NOTE TO USERS

This reproduction is the best copy available.

UMI[®]

Design and Construction of a Gas Turbine Combustor Test Rig for Alternative Fuel Testing

by

Crystal Marie Murphy

B. Eng, Carleton, 2001

A thesis submitted to the Faculty of Graduate Studies and Research

In partial fulfillment of the requirements for the degree of

Master of Applied Science

Ottawa-Carleton Institute for Mechanical and Aerospace Engineering

Department of Mechanical and Aerospace Engineering

Carleton University

Ottawa, Ontario

Canada

September 2004

© 2004 Crystal Murphy

Library and
Archives Canada

Bibliothèque et
Archives Canada

Published Heritage
Branch

Direction du
Patrimoine de l'édition

395 Wellington Street
Ottawa ON K1A 0N4
Canada

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

ISBN: 0-612-97429-4

Our file Notre référence

ISBN: 0-612-97429-4

The author has granted a non-exclusive license allowing the Library and Archives Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

PAGINATION ERROR.

TEXT COMPLETE.

ERREUR DE PAGINATION.

LE TEXTE EST COMPLET.

ABSTRACT

Current power generation methods rely primarily on the combustion of fossil fuels, such as coal, oil, and natural gas. Interest in green power technologies has recently led to the direct combustion of biomass-derived liquid fuels in gas turbine engines. The difference in properties of these fuels compared to conventional fuels has lead to some design challenges and modifications in fuel storage and delivery systems for these turbine engines.

The scope of the work presented as part of this thesis is focused on the design, construction, and validation of a gas turbine combustor test rig for alternative fuel testing. Design of the test rig has incorporated the capability to bleed 0.5 kg/s of compressed air from an Allison 250-C20B gas turbine engine for high-pressure tests as well as the option to use an electric blower to supply air at atmospheric pressure. The fuel skid design for the combustor test rig includes control valves and a separate fuel pump to permit mixtures of alternative fuels with diesel for testing purposes.

Preliminary testing of the assembled test rig was conducted to demonstrate the functionality of the design. Results from these tests were analyzed to provide recommendations for changes in the design as well as for the future use of the combustor test rig.

ACKNOWLEDGEMENTS

I would like to thank Dr. Donald Gauthier for challenging me to go beyond what I knew and whose vision, patience, and advice were essential. The assistance of the Carleton University Mechanical and Aerospace Department staff in almost every stage of this project is also gratefully acknowledged.

Thank-you to the AMES group of Orenda Aerospace whose experience, encouragement, and support were integral to the completion of this work. I would especially like to thank Get Nunez for his advice and support throughout the entire project. Patrick Boisvert's expertise with Pro/Engineer and his assistance in the assembly and testing of the combustor test rig were also greatly appreciated.

This work would not have been possible without the support of the staff at Environment Canada. A special thank-you to Jim Fearn and Fred Hendren: I am grateful for the amount of time and effort they put into helping me accomplish the goals of this project. I would also like to thank Chris Kelsey whose expertise with Allison engines was greatly appreciated, as was the assistance of Marcel Fournier from the NRC who was able to fill in for Chris on short notice at a critical time in the project.

Several companies also offered their expertise and advice. I appreciate the time and effort they took to help me with this project, especially Charles Bouchard and Dominic

Vaillancourt of QIP Equipment, Cam Hubbs at DCH Process Dynamics, and the staff at Crane Supply.

The work that comprises this thesis project is part of a joint project between Orenda Aerospace Corporation and Carleton University and would not have been possible without the financial support by Materials and Manufacturing Ontario (MMO).

Finally, I would like to thank my husband Glenn and the rest of my family and friends for their understanding, support and encouragement.

TABLE OF CONTENTS

Abstract.....	iii
Acknowledgements	iv
Table of Contents	vi
List of Tables	x
List of Figures.....	xii
Nomenclature	xvii
1 Introduction.....	1
1.1 Need For Alternative Fuels	1
1.1.1 Fossil Fuels and Greenhouse Gases	1
1.1.2 Green Power.....	3
1.1.3 Summary of Alternative Fuels	8
1.2 Biomass Fuels and Gas Turbines.....	9
1.2.1 Biomass Fuel Production	9
1.2.2 Biofuel Properties	13
1.2.3 Previous work	16
1.3 Overview of Gas Turbine Combustion	18
1.3.1 Droplet Evaporation and Combustion	18
1.3.2 Equivalence Ratio	20
1.3.3 Flammability Limits.....	21
1.3.4 Flame Types.....	22
1.3.5 Combustion Equation.....	23
1.4 Need For Test Rig	24
1.4.1 Test Methods.....	24

1.4.2	Thesis Objectives	28
1.4.3	Gas Turbine Combustor Test Rig Overview	28
1.4.4	Thesis Outline	31
2	Gas Turbine Combustor Test Rig Design.....	32
2.1	Specifications for the Gas Turbine Combustor Test Rig	32
2.2	Gas Turbine Combustor Test Rig Overview.....	34
2.2.1	Test Rig Summary	34
2.2.2	Low-Cost System.....	37
2.3	Design and Component Selection	38
2.3.1	Environment Canada Facility	38
2.3.2	Air Supply and Exhaust	42
2.3.2.1	Engine Bleed Design.....	42
2.3.2.2	Pressure Losses in a Pipe	46
2.3.2.3	Flow Control	49
2.3.2.4	Critical Area Calculation	53
2.3.2.5	Material Selection	55
2.3.2.6	Thermal Expansion of Air System.....	59
2.3.3	Test Combustor.....	60
2.3.3.1	Fuel Mass Flow Calculations.....	61
2.3.3.2	Fuel Nozzle Selection	63
2.3.4	Fuel Skid	65
2.3.4.1	Fuel Heat Transfer	67
2.3.4.2	Pump Selection	75
2.3.4.3	Valve Selection	77

2.3.4.4	Filters	80
2.3.4.5	Fuel Mixing.....	84
2.3.4.6	Miscellaneous	85
2.3.5	Data Acquisition System.....	88
2.3.5.1	Data Collection and Storage	88
2.3.5.2	Temperature Measurement	92
2.3.5.3	Pressure Measurement	94
2.3.5.4	Air Flow Measurement	96
2.3.5.5	Fuel Flow Measurement	99
2.4	Hazards Analysis.....	102
2.5	Chapter Summary	103
3	Combustor Test Rig Performance.....	105
3.1	Instrumentation Verification Tests	106
3.1.1	Data Collection System.....	106
3.1.2	Thermocouples.....	107
3.1.3	Pressure Transducers	111
3.1.4	Fuel Flowmeters and Flow Control	115
3.1.5	Airflow Control and Measurement	117
3.2	Combustor Test Rig Shakedown	120
3.2.1	High-Pressure Air Bleed Test	120
3.2.2	Fuel Subsystem	125
3.3	Ignition Testing	129
3.3.1	Ignition Testing Procedure.....	130

3.3.2	Ignition Test Results	132
3.4	Summary.....	136
4	Recommendations and Conclusions.....	139
4.1	Rationale for Design Changes.....	139
4.2	Recommendations	140
4.3	Conclusions.....	143
5	References	144
APPENDIX A:		
Frequently Asked Questions About the Use of Pyrolysis Oil (Biofuel) for Gas		
	Turbine Operation	148
APPENDIX B:		
	MSDS Sheets.....	162
APPENDIX C:		
	Combustor Test Rig Parts.....	174
APPENDIX D:		
	Specification Sheets for Selected Combustor Test Rig Components	178
APPENDIX E:		
	Custom Part Drawings	244
APPENDIX F:		
	Task Hazard Analysis for Combustor Test Rig.....	251
APPENDIX G:		
	Sample Calculations and Test Data.....	257

LIST OF TABLES

Table 1-1	Effects of typical greenhouse gases and pollutants produced through gas turbine combustion [1, 2, 3].....	2
Table 1-2	Examples of Canadian renewable energy applications [4]	2
Table 1-3	Quality of wind for various wind speeds [7]	5
Table 1-4	Productivity of oils from various oil seed plants [16].....	12
Table 1-5	Properties of biofuel and diesel [10].....	13
Table 1-6	Flammability limits for various fuels [23]	22
Table 2-1	Specifications of the Allison 250-C20B turboshaft gas turbine engine [25, 26].....	39
Table 2-2	Examples of minor loss coefficients [28]	47
Table 2-3	Pressure drop estimates for the bleed and exhaust systems of the combustor test rig.....	48
Table 2-4	Pressure drop estimates for the butterfly valve at standard conditions and conditions expected with high-pressure bleed air from the Allison 250 gas turbine engine	52
Table 2-5	Test combustor pressures for various orifice plate diameters assuming an airflow of 0.5 kg/s	54
Table 2-6	Dimensions of seamless and welded Schedule 10 stainless steel pipe [32].....	57
Table 2-7	Dimensions of stub-ends and flanges for Schedule 10 stainless steel pipe [33,34]	57

Table 2-8	Expected change in length of pipes due to thermal expansion	60
Table 2-9	Nozzle pressures required for a combustor pressure of 709.3 kPa	64
Table 2-10	Summary of fuel skid components and their purpose.....	66
Table 2-11	Effect of glycol temperature on length of coiled tubing required for the fuel heat exchanger	69
Table 2-12	Pressure drop estimates for diesel and biofuel.....	70
Table 2-13	Comparison of mesh sizes and opening diameters [40].....	83
Table 2-14	Summary of combustor test rig data measurements	89
Table 2-15	Channel assignments for 7708 module	91
Table 2-16	Thermocouple types and temperature ranges [44].....	92
Table 2-17	Specifications for pressure transducers and power supplies [45]	95
Table 2-18	Summary of identified hazards and recommended actions	103
Table 3-1	Pressure transducer ranges for pressure and output voltage	112
Table 3-2	Data trace summary	130

LIST OF FIGURES

Figure 1-1	Glazed flat-plate (left) and parabolic trough (right) solar collectors [6]	4
Figure 1-2	Horizontal and vertical axis wind turbines [6].....	5
Figure 1-3	Average wind speed in Canada [7]	5
Figure 1-4	DynaMotive pyrolysis process [14].....	10
Figure 1-5	Application of biofuel to gas turbine engines [15]	11
Figure 1-6	Change in fuel droplet temperature after injection into combustion environment [1].....	19
Figure 1-7	Droplet evaporation followed by combustion [22].....	19
Figure 1-8	Rate of droplet evaporation for two different fuels [1].....	19
Figure 1-9	Comparison of drop evaporation rates for various initial diameters [23].....	19
Figure 1-10	Adiabatic flame temperature and major products of combustion for propane in air at 101.3 kPa [23].....	24
Figure 1-11	Minor products of combustion for propane in air at 101.3 kPa [23]	24
Figure 1-12	Concept of gas turbine combustor test rig	27

Figure 2-1	Allison 250-C20B engine at Environment Canada.....	35
Figure 2-2	Schematic of test rig fuel skid.....	36
Figure 2-3	Allison control station (left). A close-up of the computer display is shown on the right.....	39
Figure 2-4	Allison gas turbine 250-C20B engine in its test cell at Environment Canada (shown with bleed pipe).....	40
Figure 2-5	Control system for dynamometer (left), and monitor showing Allison engine test cell (right)	40
Figure 2-6	Layout of rooms used by Allison engine and combustor test rig	41
Figure 2-7	Original bleed design (top left) and its location on the Allison 250 engine (top right). Warping from the welding procedure caused alignment problems for leak-free assembly to the Allison engine (bottom).....	44
Figure 2-8	Top view of the clearance between air discharge tube and turbine section of Allison 250 engine	45
Figure 2-9	Air bleed chamber shown mounted on the compressor discharge air tube. Side view (left), close-up between bleed and turbine section seen from top.....	45
Figure 2-10	Original butterfly valve used to control bleed air from Allison 250 engine.....	50
Figure 2-11	Jamesbury 815W butterfly valve used to control bleed air from Allison 250 engine.....	50
Figure 2-12	The characteristic flow curve for the Jamesbury 815W butterfly valve [30].....	51
Figure 2-13	Orifice plate machined out of Hastelloy-X.....	54
Figure 2-14	Welded pipe with straight section and elbow	56
Figure 2-15	Top view (left) and front view (right) of the air pipe design between the Allison 250 test cell and the combustor test rig room	58

Figure 2-16 Side views of air pipes for combustor test rig (left), and Allison engine (right)	58
Figure 2-17 Labeled view of the test combustor	61
Figure 2-18 Allison nozzle (top left), L48 nozzle with adaptor (bottom left), and XAAD nozzle (right)	64
Figure 2-19 Schematic design of heat exchanger concept.....	67
Figure 2-20 Heat exchanger coils and support frame	71
Figure 2-21 Fuel flow splitter	71
Figure 2-22 Drum heaters placed around the barrel of the heat exchanger. Insulation is also placed around the heat exchanger to minimize heat loss (right).	74
Figure 2-23 PID temperature controller for a heat exchanger band heater	75
Figure 2-24 Pump sizing chart for Hydra-cell diaphragm pumps from Wanner website [37].....	77
Figure 2-25 Pressure regulating valve and schematic of operation.....	78
Figure 2-26 Schematics for a needle valve (left) [38] and a check valve (right) [39].....	79
Figure 2-27 Labeled view of valves on cart	79
Figure 2-28 Strainer meshes used in Y-strainer	82
Figure 2-29 Filter assembly for biofuel	84
Figure 2-30 Threaded fittings [41]	86
Figure 2-31 Cart for fuel skid with pumps on the bottom and control valves on the top	87
Figure 2-32 Barrels for storage of biofuel [42]	88
Figure 2-33 Keithley Integra data system [43]	90

Figure 2-34	Keithley 2700 data acquisition system front and rear views	91
Figure 2-35	40-channel 7708 module.....	91
Figure 2-36	Air temperature thermocouple placement. Numbers refer to data acquisition channel.....	93
Figure 2-37	Pressure transducers PX242 (top left), PX-181 (bottom left) and PST power supply (right) [45].....	95
Figure 2-38	Mounting locations for KLFlo sensors [46].....	97
Figure 2-39	Schematic of averaging Pitot tube (left), actual Pitot tube (right)	98
Figure 2-40	Effect of Pitot alignment errors on pressure measurement [28]	99
Figure 2-41	A turbine flowmeter [47]	101
Figure 2-42	Schematic of oval gear flowmeter operation [48].....	101
Figure 2-43	Flowmeters used for combustor test rig fuel skid.....	102
Figure 3-1	Equipment used for thermocouple verification at Environment Canada....	108
Figure 3-2	Comparison of thermocouple readings with two display devices	108
Figure 3-3	Thermocouple verification test setup for computer recorded tests.....	110
Figure 3-4	Comparison of temperature readings based on thermocouple type setting.....	110
Figure 3-5	Results from averaging 60s of data from Integra software.....	111
Figure 3-6	Water manometer at Carleton University	112
Figure 3-7	Comparison of pressure readings from a water manometer and a PX242A pressure transducer	113

Figure 3-8	Comparison of pressure readings from a water manometer and the PX181 pressure transducer	113
Figure 3-9	Extrapolation for a PX181 pressure transducer up to 300 psig (2068 kPa)	114
Figure 3-10	Allison nozzle mass flow vs. needle valve position	116
Figure 3-11	Atmospheric blower mass flow vs. butterfly valve position.....	117
Figure 3-12	Averaging Pitot test set-up at Carleton	119
Figure 3-13	Comparison of air velocity measurements using the blower at Carleton and the data from the averaging Pitot tube	119
Figure 3-14	Air pressures for the high-pressure bleed test from the Allison 250 gas turbine engine	123
Figure 3-15	Air temperatures for the high-pressure bleed test from the Allison 250 gas turbine engine	123
Figure 3-16	Pressure measurements of water pumped through the biofuel pump to the L40 nozzle.....	126
Figure 3-17	Pressure measurements of water pumped through the diesel pump to the L40 nozzle.....	126
Figure 3-18	Diesel pressures and mass flow rates with a priming pump to supply the diesel fuel.....	127
Figure 3-19	Three nozzle water spray patterns at atmospheric pressure.....	128
Figure 3-20	Cracked gear shaft of oil pump assembly	129
Figure 3-21	Comparison of fuel flow rate to combustion temperature for diesel fuel through the Allison nozzle.....	132
Figure 3-22	Allison nozzle ignition test	134
Figure 3-23	Unsuccessful L40 nozzle ignition test	134
Figure 3-24	L40 test with unsustained combustion.....	135

NOMENCLATURE

A	Area
A^*	Critical area
C	Heat capacity
C_v	Valve coefficient
d	Diameter
f	Friction factor
g	Acceleration due to gravity (9.81 m/s^2)
h	Convective heat transfer coefficient
h_f	Head loss due to friction
h_m	Minor losses
k	Conductive heat transfer coefficient
K	Dimensionless loss coefficient
L	Length
$\dot{m}$	Mass flow rate
N1	Allison gas generator speed (rpm)
N2	Allison power turbine speed (rpm)
Nu	Nusselt number
p	Pressure
Q	Quantity of heat
$\dot{Q}$	Heat transfer rate

R	Gas constant for air ($R=287 \text{ J/kg}\cdot\text{K}$)
Re	Reynolds number
S.G.	Specific gravity (S.G. of water = 1)
T	Temperature
v	Velocity
$\dot{V}$	Volumetric flow rate

Greek Symbols

α	Coefficient of thermal expansion
Δp	Change in pressure
ΔT	Change in temperature
ε	Pipe roughness
ν	Kinematic viscosity
Φ	Equivalence ratio
ρ	Density

Subscripts

0	Stagnation
a	Air
b	Barrel
bf	Biofuel
df	Diesel fuel

<i>f</i>	Fuel
<i>g</i>	Glycol
<i>i</i>	Initial condition
<i>s</i>	Static
<i>w</i>	Wall

Acronyms

HDPE	High-Density Polyethylene
MMO	Materials and Manufacturing Ontario
PID	Proportional-Integral-Derivative
RTV	Room Temperature Vulcanizing
SFC	Specific Fuel Consumption
SMD	Sauter Mean Diameter

1 INTRODUCTION

1.1 Need For Alternative Fuels

1.1.1 Fossil Fuels and Greenhouse Gases

Current power generation methods rely primarily on the combustion of fossil fuels, such as coal, oil, and natural gas. These resources are either mined (e.g., coal) or extracted through the use of wells (e.g., oil or natural gas). Since these fuels are non-renewable, they will eventually become depleted.

When combusted, fossil fuels produce pollutants such as carbon monoxide (CO), sulphur oxides (SO_x), and nitrogen oxides (NO_x) [1]. Carbon dioxide (CO₂), a product of complete combustion, can also be harmful through its role as a greenhouse gas. Effects of common greenhouse gases and pollutants produced through combustion are summarized in Table 1-1.

To reduce dependence on fossil fuels, research into renewable forms of energy production is being done. In addition, recent ratification by the Canadian government of the Kyoto Protocol has encouraged development and implementation of technologies to reduce greenhouse gas emissions. Some Canadian examples are listed in Table 1-2. In addition to being renewable, some of these power sources also produce few or no

pollutants and thus have less impact on the environment. These sources of power are known as 'green power'.

Table 1-1 Effects of typical greenhouse gases and pollutants produced through gas turbine combustion [1, 2, 3]

Gas	Source(s)	Effects
CH ₄ Methane	Natural gas, fossil fuel production, anaerobic decomposition in landfills, agriculture, fuel combustion	Methane is the second largest contributor to the greenhouse effect. It is removed by reaction with OH radicals and is converted to CO ₂ .
CO Carbon Monoxide	Incomplete combustion	A toxic ambient air pollutant that oxidizes to form CO ₂ .
CO ₂ Carbon Dioxide	Naturally occurring, combustion processes	The largest contributor to the greenhouse effect.
H ₂ O Water Vapour	Naturally occurring, combustion processes	Forms clouds that absorb and reflect both solar and terrestrial radiation.
N ₂ O Nitrous Oxide	Naturally occurring, agricultural soils, industry and waste management, combustion of fossil fuels and biomass	A less common greenhouse gas than CO ₂ but more effective at trapping heat in the atmosphere.
NO _x Nitrogen Oxides	Lightning, soil microbial activity, biomass burning, fuel combustion, degradation of N ₂ O (in stratosphere)	A toxic ambient air pollutant. It is a precursor to chemical smog and contributes to depletion of stratospheric ozone.
O ₃ Ozone	Naturally occurring, reaction of pollutants such as NO _x and volatile organic compounds	Stratospheric ozone shields the Earth from harmful UV radiation. At tropospheric (ground) level, ozone is an ambient air pollutant.
SO ₂ Sulphur Dioxide	Volcanoes, fossil fuel combustion, biological decay, smelting, waste incineration	An ambient air pollutant that can be both toxic and corrosive

Table 1-2 Examples of Canadian renewable energy applications [4]

Renewable Energy Source	Location	Year	Project
Biomass	Waterloo, Ontario	1998	Toromont Energy Ltd. uses landfill gas to produce electricity
Hydro-electric	Almonte, Ontario	1996	Build small hydroelectric site for local power grid using existing dam
Solar	Oshawa, Ontario	1991	Solar wall provides heated air for building ventilation system at GM Canada

1.1.2 Green Power

Green power refers to electricity generated using renewable energy resources that have a low impact on the environment. Example sources include solar, wind, low-impact hydro-electricity and biomass. These are sustainable sources of power, which can generally be replaced within the relatively short period of time, and are essentially non-polluting. Applications using these sources of green power are briefly discussed here.

Solar

Solar energy is a source whose quantity and intensity can vary on an hourly, daily or seasonal basis (e.g., clouds, day/night, summer/winter, etc). Solar energy is commonly used for heating and cooling applications as well as for electricity production. This form of energy production does not produce any emissions and is only dependent on the amount and angle of sunlight available [5]. Solar energy is obtained through the use of collectors, which can vary in design based on the application. For example, the glazed flat-plate collector is generally used for heating applications where the desired temperature range is 30°C-70°C while the parabolic trough is used to concentrate the solar energy to obtain temperatures high enough to generate steam for electricity production (Figure 1-1) [6].

Figure 1-1 Glazed flat-plate (left) and parabolic trough (right) solar collectors [6]

Wind

Wind energy is a naturally occurring, pollution free and, infinitely sustainable form of energy that is produced through the movement of air due to thermal gradients. Kinetic energy from wind sources can be used to mechanically turn a wind turbine (Figure 1-2) to generate electricity. Changes in topography such as mountains or oceans can affect the intensity of the wind as shown in Figure 1-3. Sites that are ideal for power generation using wind tend to have average wind speeds over 6.5 m/s with a yearly capacity of 20-40% for the generators [5].

Costs for wind energy can vary depending on the initial cost and size of the installation as well as the amount of energy produced. Typical costs for wind energy can vary from about \$1500 per kilowatt for larger wind farms with arrays or up to \$3000 per kilowatt for smaller, individual installations [6].

Figure 1-2 Horizontal and vertical axis wind turbines [6]

Figure 1-3 Average wind speed in Canada [7]

Table 1-3 Quality of wind for various wind speeds [7]

> 8 m/s	(> 29 km/h)	Excellent
6 - 8 m/s	(21.5 - 29 km/hr)	Good
5 - 6 m/s	(18 - 21.5 km/hr)	Average
4 - 5 m/s	(14.5 - 18 km/hr)	Fair
< 4 m/s	(< 14.5 km/h)	Poor

Low-Impact Hydroelectric

Hydroelectric power is generated by converting the kinetic energy of fast-moving or falling water such as waterfalls, rapids, and river bends into electricity using turbines and generators. In the case of larger hydroelectric sites, a dam or an impoundment is used to store water that is not needed during high flow periods for periods where the water flow is lower. These reservoirs sometimes flood a surrounding area or involve alterations to the river. Low-impact hydroelectric sites attempt to have a minimal effect on the environment by using only fast-flowing streams or existing dams [5]. The disadvantages with the low-impact sites are that only a portion of the water flow for a river may be available and there is less storage for water.

Biomass

Biomass-derived fuels are those that are derived from plant materials or animal waste [8]. These fuels are considered to be greenhouse gas neutral: when the biomass is consumed as fuel, it releases only the amount of carbon dioxide that was absorbed during growth [9]. In addition, biomass fuels have virtually no sulphur content, and produce about half the nitrogen oxide (NO_x) emissions as diesel oil [10].

One of the most important characteristics of biomass fuels compared to fossil fuels is that the feedstock used to create them is renewable. That is, it can be replaced in a very short period of time (i.e., decades) compared to the millions of years required to create fossil fuels. The feedstock for the biomass-derived fuels can either be cultivated specifically

for use as a fuel source, or obtained in the form of “waste”. Examples of biomass feedstock include [11]:

- ♦ Wood and wood residues
- ♦ Straw and grasses
- ♦ Sugar cane residuals (e.g., bagasse and cane trash)
- ♦ Rice husks
- ♦ Palm, peanut and coconut shells
- ♦ Waste paper and sludges

Biomass fuels have the ability to be integrated into systems where fossil fuels are being used currently. They can provide a sustainable solution for energy production, especially in remote areas where fossil fuels are not as available and with large amounts of agricultural waste that would otherwise fill up landfill sites or be combusted without providing any useful energy. When organic matter breaks down it produces methane (CH_4), which has 20 times more impact as a greenhouse gas than CO_2 during its atmospheric life [3]. When the waste is combusted, methane is no longer able to escape into the atmosphere and at the same time power is produced [5].

In Canada, a common example of waste biomass is produced by sawmills in the form of sawdust, shavings and bark. For a gas turbine generating power by combusting wood waste, approximately 30% of the heat from the exhaust can be used to dry the waste wood for combustion, while the remaining 70% can be used to dry the sawdust and bark that can be sold as value-added products. In addition, this energy is “free” since it does

not have to be purchased from the power grid [12]. In Chapleau, Ontario a co-generation system exists at a sawmill where the wood waste is combusted in a boiler to produce steam for a 7.2-megawatt condensing extraction turbine that is used to heat the entire mill and lumber kilns [4].

1.1.3 Summary of Alternative Fuels

Current power generation methods rely primarily on combustion of fossil fuels, which are a non-renewable resource and whose use has a negative impact on the environment. To reduce our dependence on these fuels, research into the use of environmentally friendly, sustainable energy sources, known as green power, is becoming more important.

Green power sources include solar, wind, low-impact hydroelectric, and biomass. Due to the potential of biomass-derived fuels to displace fossil fuels in some gas turbines engines for energy production, research is required into the effects of these fuels in gas turbine systems. The gas turbine combustor test rig being designed for this thesis project is designed to test the delivery and combustion of a liquid biomass-derived fuel in a gas turbine combustor as well as the effects of the products of combustion on downstream components.

1.2 Biomass Fuels and Gas Turbines

1.2.1 Biomass Fuel Production

In addition to combusting solid biomass, the feedstock material can be processed into gaseous or liquid forms in order to increase the energy density of the fuel. It is these forms that are of interest for direct combustion in gas turbine engines.

Gasification

Solid biomass can be converted into a gas with a low heating value through a multi-stage process called gasification. In this process, dried biomass is heated, then oxygen or air is introduced to partially combust the biomass and create combustible products such as CO, H₂, CH₄, as well as some fine dust and tar [13]. One of the main disadvantages to gasification is that the products are difficult to store and transport and are therefore generally burned as they are created. This implies that if gasification is used to supply fuel for a gas turbine, it is hooked up directly to the engine and any changes in the flow of feedstock into the gasifier will also have an impact on the flow of fuel for the engine.

Pyrolysis

Fuels produced through a process called pyrolysis are quickly heated to high temperatures in the absence of an oxidizer until the biomass forms combustible solid, liquid, and gas products. Rapid cooling then preserves the products from further decomposition [14]. The proportions of these products can vary depending on the type of

feedstock. In general, the combustible by-products are approximately 10-25 wt% solids, 60-75 wt% liquids, and 5-15 wt% gases [11]. In the process used by DynaMotive Technologies, a Canadian producer of liquid biomass fuels, the gases are used to heat and burn the feedstock (Figure 1-4).

Figure 1-4 DynaMotive pyrolysis process [14]

The liquid fuel derived from the pyrolysis process is similar to petroleum-based products in that it can be stored, pumped and used as a fuel for gas turbines. This liquid is known by several different names: biofuel, bio-oil, pyrolysis oil, liquid wood, etc. [11]. In the

scope of this project, it will be referred to as biofuel. A schematic of the combustion process using biofuel for energy generation is shown in Figure 1-5 [15].

Disadvantages of biofuel include a high water content, high viscosity, and lower calorific value compared with conventional fuels, which makes pumping, ignition, and combustion more difficult. Acidity, ash and alkali metal content also introduce design challenges when using these fuels for gas turbine combustion. A description of these properties and their effect on gas turbine combustion is described in Section 1.2.2.

Figure 1-5 Application of biofuel to gas turbine engines [15]

Biodiesel

Another form of biomass-derived fuel, commonly referred to as biodiesel, can be produced through screw extraction of dried seeds from certain plants such as canola, corn, and flax [6]. Some examples of oils and quantities that can be extracted from various oil seed plants are shown in Table 1-4.

Table 1-4 Productivity of oils from various oil seed plants [16]

Species	Mass Fraction of Oil, %
Castor	45 – 50
Jatropha	50 – 60
Mohua	35 – 40
Sal	10 – 12
Linseed	35 – 45
Neem	20 – 30
Pongomia	30 – 40
*	10 - 50

**Jute plant seed, mango kernel, flame of the forest tree nuts, Indian coral, kokum butter tree nuts, Ink nut, soap nut, milk weed, watermelon, yellow oliander, tamane oil tree nuts, crotan oil tree seeds, palm, prickly poppy, wild walnut, almond, kamal, tung oil tree, silk cotton, bullet wood tree nuts, iron wood tree nuts, bastord sandal nuts, pilu nus, kamal nuts, foon tree seeds*

Extracted oils are filtered to remove any particulate matter. Both edible and non-edible oils can form biodiesel, although the edible oils are usually used for human consumption unless they are available in excess. The type of oil refers to the type of seed from which the oils are derived [17]. For example, edible oils would include coconut oil or peanut oil while non-edible oils include rapeseed oil, and pongemia oil.

Some advantages to using biodiesel over fuels derived from pyrolysis is that their properties, such as calorific value, are almost the same as that for diesel fuel (85-95%). They also do not have the same difficulties with ignition that are experienced by biofuel [17].

1.2.2 Biofuel Properties

Some differences in the combustion of biofuel, compared to conventional fuels such as diesel lead to some design challenges and modifications in the fuel storage and delivery system. A comparison of properties between biofuel and diesel is listed in Table 1-5.

Table 1-5 Properties of biofuel and diesel [10]

	Biofuel	Diesel
Calorific Value (MJ/kg)	15-20	42.0
Kinematic Viscosity (mm ² /s)	3-9 @80°C	2-4 @20°C
Acidity (pH)	2.3-3.3	5
Water (wt%)	20-25	0.05 v% (combined)
Solids (wt%)	<0.1	
Ash (wt%)	<0.02	0.01
Alkali (Na + K) (ppm)	5-100	<1

Calorific Value: The calorific value of a fuel refers to the amount of energy that is released per unit mass as the fuel is combusted. Biofuel provides about half the energy that is available with a comparable amount of diesel [10]. This means that, in order for a turbine to produce the same amount of energy, the flow rate of the biofuel must be increased to approximately double the rate that would be used for diesel.

Kinematic Viscosity: Combustion in a gas turbine is highly dependent on the atomization of fuel droplets. The higher the viscosity of a fuel, the longer it will take for the fuel to break up into smaller drops and thus more difficult for it to atomize into a fine mist [1].

To overcome the difficulties of high viscosity at lower temperatures, biofuel is preheated prior to delivery in the combustion chamber to reduce its viscosity. However, it is

recommended that the preheat temperature should not exceed 90°C in order to avoid rapid decomposition of the biofuel [18].

Acidity: Fuel acidity is an important characteristic for materials selection due to the potential for corrosion. In order to minimize the effects due to fuel acidity, materials must be selected that are compatible with the fuels used [17]. Based on their experience with biofuel, Orenda has determined that for biofuel-wetted areas, 300 series stainless steels are acceptable metals while high-density polyethylene (HDPE) or fluorinated HDPE are acceptable polymers [10].

Water Content: Variations in the water content of a fuel can have both positive and negative effects. Advantages include a reduction in fuel viscosity as well as the peak combustion temperature and thus the amount of thermal NO_x production. This is believed to be the reason why biofuel has lower NO_x emissions than diesel even though there is nitrogen present in biofuel [11]. The disadvantage however, is that a high water content contributes in part to lower calorific values [11].

The combination of low calorific value, high water content and high viscosity of biofuel makes ignition much more difficult than for diesel fuel. It also causes an increase in the time required for complete combustion. In order to facilitate the ignition process, diesel fuel is used to establish the combustion zone. Biofuel is preheated to reduce viscosity and then introduced into the combustion chamber. The amount of diesel fuel used is then reduced until only biofuel is being combusted [10].

Solids Content: Solids in fuels are undesirable because of the longer time needed for combustion. In addition to this, the solids can stick to the hot gas path components, which in turn decreases gas turbine efficiency and may also contribute to corrosion of hot section components. To remove the deposits, on-line or off-line cleaning methods are required. In order to prevent corrosion, additives can be used to mitigate these effects by reacting with corrosive elements in the fuel and preventing them from forming a liquid during combustion [11].

Ash and Alkali Content: Ash content of fuel is another characteristic that is undesirable. Ash represents a component of the fuel that cannot be combusted and it reduces gas turbine efficiency when it deposits onto components in the hot gas path. In addition, traces of alkali metals are often found in ash. These include sodium and potassium, which facilitate hot corrosion mechanisms in the hot gas path components. Additives have traditionally been used to mitigate these effects in fossil fuels [10, 11].

The solution to the presence of ash in biofuel and its subsequent deposition on turbine hot gas path components is through one of two washing methods [10, 11]. The first involves an online process using an abrasive media to scrub the deposits from the turbine blades. The second method is used during engine downtime. It loosens the deposits through the introduction of a cleaning solution and removes them when the engine is started [10].

In order to mitigate the corrosion-related effects of the alkali metals, the amount present in the fuel is reduced through the use of additives and the hot section component materials are protected using advanced coating techniques [11].

1.2.3 Previous work

Although combustion of biomass has previously been used for energy production, it has been through the use of established technologies such as fluidized bed and grate combustors to generate a steam cycle [19]. Direct combustion of biofuel in gas turbine engines has only recently been attempted.

Orenda Aerospace packages the OGT 2500 gas turbine engine and has collaborated with DynaMotive Technologies to develop an industrial power generation system that uses a liquid biomass fuel. In an August 2000 article “Fuelling the future” [10] a first generation fuel and combustion system is described. This system was used for testing purposes and to demonstrate the capability of the gas turbine to run on liquid biomass fuels. During these tests, the OGT 2500 ran for 10 hours where about 5 hours was spent running at 100% biofuel, and a diesel-biofuel mix was used for the remainder of the time [11]. Results indicated that the engine efficiency while running on biofuel was comparable to that obtainable with diesel fuel [11]. The article concludes with a description of future areas of development required to create a commercial system. These include a focus on performance (combustion system optimization) and durability

(long-term testing, coatings development, and fuel treatment) [10]. Orenda has compiled a series of frequently asked questions and answers about using biofuel in gas turbine applications which can be found in Appendix A [11].

More recently, Carleton University, and Orenda Aerospace have collaborated on Masters thesis projects such as “A Model of Bio-Oil Evaporation for Combustion Simulation” by Thomas Lederlin [20], which was funded by Materials and Manufacturing Ontario and “Selection and Evaluation Testing of Protective Coatings for Biofuel-Powered OGT 2500 Gas Turbine Hot Section” by Feng Gao [21].

A follow-on project was proposed by Orenda Aerospace to design a gas turbine combustor test rig to conduct fuel testing, durability testing, and computer model validation.

1.3 Overview of Gas Turbine Combustion

The intent of this section is to provide a brief background on some of the terminology used and processes that occur during gas turbine combustion.

1.3.1 Droplet Evaporation and Combustion

According to Lefebvre [1], a simple definition for combustion is “an exothermic reaction of a fuel and an oxidant”. The resultant flame can be described as “an interface between the burned gases and the unburned mixture”.

Combustion of liquid fuels involves an injection of fuel into the combustor chamber in the form of a spray. The droplets in this spray then evaporate to form a combustible vapour [1]. The rate of droplet evaporation, and thus the time required for combustion, are dependent on several factors including the droplet size, velocity, composition of the fuel, the rate of heat and mass transfer between the droplet and its environment, as well as the ambient temperature and pressure.

When a fuel droplet enters the high temperature environment of the combustion zone, it initially heats up until it reaches a constant temperature where steady state evaporation occurs as shown in Figure 1-6 [1]. The vapour that forms then diffuses out into the combustion zone where it reacts with the oxygen present in the air (Figure 1-7). The period of time for complete droplet evaporation and combustion is referred to as the

residence time. This time can vary depending on the composition of the fuel. The amount of time required for a droplet to evaporate with respect to its composition and initial size is shown in Figures 1-8 and 1-9.

Figure 1-6 Change in fuel droplet temperature after injection into combustion environment [1]

Figure 1-7 Droplet evaporation followed by combustion [22]

Figure 1-8 Rate of droplet evaporation for two different fuels [1]

Figure 1-9 Comparison of drop evaporation rates for various initial diameters [23]

In order to make the droplets as small as possible, the fuel is atomized either by the differential pressure between the delivered fuel and that inside the combustion chamber (pressure atomization), or through the introduction of compressed air to the fuel inside a specially designed fuel nozzle (air blast atomizer).

Droplet sizes are commonly referred to by an average diameter known as the Sauter mean diameter (SMD), which is defined as “the diameter of a drop within the spray whose ratio of volume to surface area is the same as that of the whole spray” [1].

1.3.2 Equivalence Ratio

If there were exactly enough air to completely combust a given amount of fuel, the fuel-to-air ratio would be described as stoichiometric. Often however, combustion in gas turbines occurs at conditions other than stoichiometric. A common way of describing the fuel-to-air ratio relative to stoichiometric conditions is through the equivalence ratio (Φ) [1].

The equivalence ratio is a ratio of the actual fuel-to-air ratio in the mixture to the stoichiometric fuel-to-air ratio. If $\Phi < 1$, the mixture is described as lean, while for mixtures with $\Phi > 1$, the mixture is considered rich.

The equivalence ratio has an effect on the temperature of the flame. For lean mixtures ($\Phi < 1$), all fuel is consumed, but the excess air reduces the flame temperature. At rich equivalence ratios, the flame temperature is also reduced but this is due to the cooling effects of excess fuel rather than air. Temperatures are highest near stoichiometric conditions ($\Phi = 1$) because there is no excess fuel or air to cool the flame [22].

1.3.3 Flammability Limits

While a fuel mixture may have any equivalence ratio, the mixture must have certain minimum percentages of fuel or air for it to be flammable. The lower, or lean limit defines the minimum equivalence ratio at which a fuel-air mixture will burn. At the upper, or rich limit of the range, there is more fuel available for combustion, but only the minimum amount of air required. Some flammability limits for various fuels are shown in Table 1-6.

Although flammability limits are largely dependent on the equivalence ratio of the fuel-air mixture, an increase in the pressure of a system can widen the limits for gases and vapours. To a lesser extent, increased temperature can also increase the range in which a fuel is flammable [1].

For liquid fuels, temperature also plays a role in determining the flammability of a mixture through its impact on the fuel vapour pressure. Below the lower temperature limit, insufficient fuel vapour exists to form a combustible mixture. For temperatures past the upper temperature limit, the concentration of fuel vapour exceeds the rich limit and there is no longer sufficient air in the mixture for it to be flammable [1].

Table 1-6 Flammability limits for various fuels [23]

Fuel	$\Phi_{\min}$ (Lean or Lower Limit)	$\Phi_{\max}$ (Rich or Upper Limit)	Stoichiometric Mass Air–Fuel Ratio
Acetylene, C_2H_2	0.19	∞	13.3
Carbon monoxide, CO	0.34	6.76	2.46
<i>n</i> -Decane, $C_{10}H_{22}$	0.36	3.92	15.0
Ethane, C_2H_6	0.50	2.72	16.0
Ethylene, C_2H_4	0.41	> 6.1	14.8
Hydrogen, H_2	0.14	2.54	34.5
Methane, CH_4	0.46	1.64	17.2
Methanol, CH_3OH	0.48	4.08	6.46
<i>n</i> -Octane, C_8H_{18}	0.51	4.25	15.1
Propane, C_3H_8	0.51	2.83	15.6

1.3.4 Flame Types

In gas turbine combustion, flames are usually in one of two categories: diffusion flame, or premixed flame. The type of flame is dependant on where the fuel and air are mixed.

For a diffusion flame, the fuel and air are mixed in the combustion zone as the combustion process occurs (e.g., a candle). Diffusion flames are typically described as stable (flame stays lit), but have a tendency toward higher NO_x emissions because they tend to occur close to stoichiometric conditions [22].

When the fuel and air are mixed prior to entering the combustion zone, the flame is referred to as premixed. This type of flame tends to have lower NO_x emissions because there is more control over the fuel and air ratios. However, the flame is also usually less stable and has the risk that the flame will travel upstream from the combustion zone to

the area where the fuel is mixed (flashback). To avoid flashback, the mixture velocity must be higher than the flame speed [22].

1.3.5 Combustion Equation

In most cases, gas turbine combustion occurs with a lean hydrocarbon fuel mixture where air is the oxidant. Assuming complete combustion, this reaction can be written as

where
$$x = \alpha + \frac{\beta}{4} - \frac{\gamma}{2}$$

At high flame temperatures, dissociation of the major products of combustion occurs to form a number of minor species such as H, H₂, O, CO, OH, and NO as shown in Figures 1-10 and 1-11 [23]. To reduce the concentration of these species, and therefore the emission of undesirable species, lean fuel-air mixtures are used.

Figure 1-10 Adiabatic flame temperature and major products of combustion for propane in air at 101.3 kPa [23]

Figure 1-11 Minor products of combustion for propane in air at 101.3 kPa [23]

1.4 Need For Test Rig

1.4.1 Test Methods

Testing of fuels leads to a better understanding of the ignition, flame stability, and emissions characteristics of the fuel. Testing can also be used to determine materials compatibility and durability when exposed to either the fuel or its products of

combustion. In the case of biofuel, testing will also reveal the impact on fuel properties due to variations in the types of feedstock used to produce the fuel.

There exist many procedures for evaluating fuels and materials for a gas turbine environment. These methods can be divided into three categories: laboratory bench tests, burner rig tests, and engine tests.

Engine testing is the most reliable means of testing fuels and determining durability of engine components and coatings. It also allows testing of the fuel handling, delivery, and ignition systems. However, testing with real engines is both expensive and requires at least two years of accumulated test time [24]. Due to the time and cost investment involved, engine testing is not often used for tests that could damage the equipment.

Burner rigs, or combustor test rigs, are a compromise between laboratory and field tests. They are flexible and allow the simulation of effects such as oxidation, corrosion, erosion, and thermal cycling. In order to rank materials and coatings for high temperature applications in gas turbine engines, simulated service conditions using burner rigs are considered the most powerful [24]. Depending on the design, these rigs can also provide information on the fuel ignition characteristics, flame stability and emissions. Combustor test rigs can approximate service conditions in engines but at less cost than is required for field tests [24]. This is in part due to the absence of downstream engine components such as turbine blades.

Laboratory bench testing includes crucible and furnace testing, which are used to determine materials compatibility and durability. These tests are easily reproducible and tend to have lower costs than either engine or burner rig tests. However, they are not necessarily as realistic because they do not simulate the variation in temperatures, velocities or gas compositions that occur under actual service conditions [24].

In Mr. Gao's research [21], new protective coatings for the OGT 2500 gas turbine were selected and evaluated by exposing test coupons to the corrosive products from biofuel combustion. For these tests, coupons were exposed to a biofuel combustion environment using a large atmospheric combustor and were later exposed to biofuel ash in a hot furnace environment. Some important characteristics of the testing methods used for this evaluation include:

- 1) Testing carried out under hot, corrosive conditions,
- 2) Reducing the amount of biofuel burned during the tests,
- 3) Testing carried out at atmospheric pressure, and
- 4) Using simulated combustion products.

While the testing described above has some benefits, such as a reduction in the amount of fuel required, the combination of the final two characteristics make the results less representative than testing with an actual gas turbine combustor fuelled with biofuel.

A combustor test rig can be built in order to carry out testing under atmospheric conditions or the more representative gas turbine conditions of high temperature, high

pressure, and high velocity. Air at atmospheric pressure can be provided by a blower while high-pressure air can be provided to this gas turbine combustor test rig by bleeding air from an actual turboshaft gas turbine engine. The advantage to using a separate combustor is that the engine downstream components will not be exposed to the products of biofuel combustion. Also, because the combustor test rig would use only a fraction of compressed air available from the turboshaft engine, the fuel flow through the test combustor will be lower than if testing was conducted in a full gas turbine engine. This concept is shown in Figure 1-12.

Figure 1-12 Concept of gas turbine combustor test rig

1.4.2 Thesis Objectives

The scope of the work presented as part of this thesis is focused on the design, construction, and validation of a gas turbine combustor test rig for alternative fuel testing that will be capable of:

- Testing combustion using atmospheric or high-pressure air,
- Combusting various fuels,
- Performing durability testing of materials and coatings exposed to the products of combustion,
- Performing hot corrosion and erosion testing of materials and coatings exposed to the products of combustion,
- Measuring temperature profiles of combustor exhaust for validation of computer simulations, and
- Measuring emissions.

1.4.3 Gas Turbine Combustor Test Rig Overview

A gas turbine combustion research lab has been set up at Environment Canada's River Road facility in Ottawa using a 300 kW Allison 250-C20B turboshaft gas turbine engine. This engine is jointly operated by Carleton University and Environment Canada in Ottawa.

The scope of the work for this thesis comprises the design, construction and validation of a new gas turbine combustor test rig. For the design and construction stages, this work was broken down into four subsystems: air supply and exhaust system, test combustor, fuel skid, and data acquisition.

Air Supply and Exhaust System

The Allison 250-C20B turboshaft gas turbine engine compressor is capable of providing air at a pressure ratio of approximately 7:1 with a mass flow rate of approximately 1.5 kg/s. The amount of compressed air available for the combustor test rig is limited by the amount that can be safely bled from the Allison 250 engine, which is approximately 0.5 kg/s.

The design of the air supply system was mainly concerned with regulating the flow of air between the Allison 250 engine and the combustor test rig. A bleed air chamber was designed and placed on the compressor discharge air tube on one side of the Allison 250 gas turbine engine. A butterfly valve controls the flow of air from the Allison 250 gas turbine engine to the combustor test rig. Exhaust gases from the combustor test rig are vented to the same exhaust stack used by the Allison 250 gas turbine engine.

An atmospheric blower was also adapted to hook up to the air pipes. The motivation for using atmospheric air was to allow testing in the combustor test rig even when high-pressure air is not available from the Allison 250 gas turbine engine.

Test Combustor

The test combustor is the actual ‘test area’ of the rig where the fuel is atomized and burned. The combustor test rig is made from a modified Allison 250 combustor liner and casing. In addition, extensions of the liner and casing have been incorporated.

The combustor test rig can use any one of four different nozzles for testing. These include the original Allison nozzle, two pressure-atomizing nozzles and an air-atomizing nozzle. Since the new nozzles were not designed for the Allison combustor, adaptors were designed so that they could be placed in the test combustor.

Fuel Skid

The fuel skid includes the filtering, pumping, and heating systems required to deliver biofuel to the combustor test rig. In addition to supplying biofuel to the test combustor, the fuel skid is capable of delivering diesel fuel or a combination of both diesel and biofuel. In the scope of this work, the diesel fuel is used to establish combustor test rig performance. For tests with biofuel, diesel will be used to start the biofuel combustion process, and to flush the biofuel from the fuel system after testing.

Data Acquisition

In any test system, measurements must be taken. In addition, thought must be given to the quantity of data desired and its method of collection. For the gas turbine combustor test rig, temperature, pressure, and flow measurements were taken for both the air and fuel supplied to the test combustor. Most of this data was collected by a digital data acquisition system, although some measurements were taken manually.

1.4.4 Thesis Outline

The initial task in the design of the gas turbine combustor test rig is to gain an understanding of alternative fuels and the challenges associated with using them in gas turbine combustion. This chapter outlines the need for alternative fuels and discusses briefly the production and combustion of biomass-derived fuels. It concludes by defining the scope of this thesis.

Chapter 2 begins with a list of specifications for the design of the gas turbine combustor test rig. Before going into the details of the design, a system overview of the test rig is given. In addition, the strategy used to reduce costs is outlined. A detailed description is then given for the design and selection of components for the gas turbine combustor test rig, which is completed with a hazards analysis of the designed system.

The third chapter focuses on validating the gas turbine combustor test rig. This is done through a series of functionality tests for the instrumentation as well as the air and fuel subsystems. As a final demonstration of the capability of the gas turbine combustor test rig, ignition testing was conducted. The chapter concludes with a summary of the demonstrated capabilities of the gas turbine combustor test rig design.

The final chapter discusses some recommended design changes based on the results from all validation tests. It also highlights recommendations for future work.

2 GAS TURBINE COMBUSTOR TEST RIG DESIGN

The design of the gas turbine combustor test rig will be discussed in this chapter beginning with the design specifications. An overview of the test rig design is then described before going into the details for each subsystem. Finally, a brief hazards analysis will be performed on the described design.

2.1 Specifications for the Gas Turbine Combustor Test Rig

The design of a gas turbine combustor test rig that forms this thesis project is expected to meet the following specifications:

- It must be representative of a gas turbine combustor. That is, it must be capable of combusting fuel in an environment with temperatures and pressures comparable to those found in actual gas turbine combustors.
- It must be possible to control the flow of fuel and air into the test combustor.
- It must be adaptable to a variety of liquid fuels and allow mixtures of fuels during test rig operation.
- It must be instrumented to collect various forms of data such as temperature, pressure, or emissions data.
- It must be modular. That is, it should be possible to add or remove portions of the rig depending on the types of tests or fuels used. An

example system is the ability to use air from an atmospheric blower instead of compressed air to run preliminary tests.

- It must be capable of running long-duration tests such as materials durability, or erosion/corrosion tests.
- It must contain a fuel skid capable of handling poor quality fuels. The baseline fuel envisioned for this system is diesel fuel. A “poor” quality fuel is defined as any fuel which has characteristics that are worse than those for diesel in the following areas:
 - Viscosity
 - Acidity
 - Heating value
 - Particulate concentrations
 - High concentrations of undesirable elements such as sulphur, or alkali metals
- It must be a low-cost system. Due to the nature of the fuels to be tested (i.e., poor quality fuels), it is expected that some portions of the rig will need to be replaced/sacrificed as part of the test program. Because of this, parts should be low-cost. Since this rig is terrestrial, components do not need to be airworthy and can therefore be purchased as scrap from aerospace repair and overhaul shops.

2.2 Gas Turbine Combustor Test Rig Overview

2.2.1 Test Rig Summary

The gas turbine combustor test rig was conceptualized as a stand-alone gas turbine combustor that bleeds up to one third of the compressed air from an existing gas turbine engine. The gas turbine engine used in this project is an Allison 250-C20B turboshaft engine capable of delivering 300 kW of power.

To test functionality of this combustor test rig without running the Allison engine, an atmospheric blower set-up has been incorporated which will allow preliminary testing of the fuel skid and test combustor. While this approach will not allow high pressure combustion testing to occur, the ability to run the combustor test rig without the requirement for an engine technician will increase the versatility of the rig, and allow fine-tuning of the test rig before longer duration, or high pressure tests are run.

In the scope of this thesis, the primary design philosophy is focused on a high-pressure system that bleeds air from the compressor discharge air tubes between the compressor and combustor of the Allison 250-C20B gas turbine engine (Figure 2-1). However, where applicable, the inclusion of an atmospheric blower in the design will also be discussed.

Figure 2-1 Allison 250-C20B engine at Environment Canada

The fuel skid for the combustor test rig considered the requirements for delivering a poor fuel to the test combustor. The poor fuel selected for test rig design and validation purposes was biofuel since it displays higher acidity, water content, and particulate characteristics than diesel fuel (Table 1-5). In addition, biofuel has a low heating value and higher viscosity than diesel, which makes it more difficult to pump, ignite, and burn. With these characteristics in mind, the fuel skid was designed as shown in Figure 2-2.

Figure 2-2 Schematic of test rig fuel skid

2.2.2 Low-Cost System

Due to the specification for a low-cost system, it was decided to use off-the-shelf components wherever possible and even to obtain used parts if they were available. It is understood that the combustor test rig components used at this stage may not be ideal for any specific type of fuel or test. One of the goals of this project is to provide a basic structure that can be later modified as required for a specific purpose. The optimization of components for specific configurations or tests is outside the scope of this work and is left for future projects.

As previously mentioned, the combustor test rig uses an air bleed from an Allison gas turbine engine compressor. The motivation for this decision is partially due to cost since renting or purchasing a compressor capable of delivering the required pressure and flow is expensive, while the Allison engine is already in place. Secondly, by using compressed air from a gas turbine engine, the conditions in the combustor test rig will be more representative of those occurring in an actual gas turbine combustor. That is, the temperature and pressure will be similar, although the airflow is reduced.

2.3 Design and Component Selection

The following section will discuss the theory, design, and selection of components for the combustor test rig that was designed as part of this thesis project. A significant part of the design of the combustor test rig was dependent on its location at the Environment Canada facility; therefore, this section will begin with a brief discussion on the facility at Environment Canada, before continuing with the description of the subsystem design. The design and selection of components for the combustor test rig is divided into four subsections, covering the air supply and exhaust, the test combustor, the fuel skid, and the data acquisition systems respectively.

Due to the decision to use off-the-shelf components, many of the parts are described in the English system of units. Where this occurs, S.I. equivalents will be included.

2.3.1 Environment Canada Facility

In partnership between Carleton University's Department of Mechanical and Aerospace Engineering and Environment Canada's Emissions Research and Measurement Division, a gas turbine combustion research lab has been set up at Environment Canada's River Road facility in Ottawa using a 300kW Allison 250-C20B turboshaft gas turbine engine. Specifications for the Allison250-C20B turboshaft engine are given in Table 2-1.

Table 2-1 Specifications of the Allison 250-C20B turboshaft gas turbine engine [25, 26]

Power (takeoff)	420 shp	313 kW
SFC (takeoff)	0.650 lb/shp·hr	395.38 mg/ W·h
Airflow (takeoff)	3.45 lbm/sec	1.56 kg/s
Pressure Ratio (takeoff)	7.1:1	
Weight (dry)	161 lb	73 kg
Compressor stages	6 axial + 1 centrifugal	
Gas producer turbine	2 axial stages	
Power turbine	2 axial stages	
Inter Turbine Temperature (ITT)	1490°F	810°C
Turbine Inlet Temperature (TIT) [27]	1825°F	996°C

The Allison engine (Figure 2-4) is controlled remotely by an operator using a manual throttle and a computer system (Figure 2-3) that monitors engine parameters such as gas generator speed (N1), power turbine speed (N2), inter-turbine temperature, cell ambient temperature, oil temperature, and oil pressure. A TV monitor is also set up to display visual information about the status of the Allison engine in its test cell and is shown in Figure 2-5. The power turbine speed (N2) is regulated through the use of a dynamometer to prevent the engine from over-speeding (Figure 2-5).

Figure 2-3 Allison control station (left). A close-up of the computer display is shown on the right.

Figure 2-4 Allison gas turbine 250-C20B engine in its test cell at Environment Canada (shown with bleed pipe)

Figure 2-5 Control system for dynamometer (left), and monitor showing Allison engine test cell (right)

The relation between the Allison test cell, its control room, and the location of the gas turbine combustor test rig are shown in Figure 2-6. For preliminary validation tests at atmospheric pressure, Environment Canada allowed minor modifications to one of their blowers, which is located in a test cell adjacent to the Allison test cell to permit connection to the bleed air pipes.

Figure 2-6 Layout of rooms used by Allison engine and combustor test rig

This figure will be used as an icon during the discussion of the design for the combustor test rig subsystems. Components of the discussed subsystem will be shown in red.

2.3.2 Air Supply and Exhaust

The amount of compressed air available for the combustor test rig was limited to the amount that could be safely bled from the Allison 250 engine. The design of the air supply system was mainly concerned with

regulating the flow of air between the Allison 250 engine and the combustor test rig. Some aspects that needed to be considered during the design of the air system (both bleed and exhaust) included thermal expansion of the pipes, pressure losses between the compressor and the test combustor, as well as checking for choked flow in the exhaust.

The main design consideration in the design of the air supply system was bleeding high-pressure air from the Allison 250 engine. Due to the absence of pressure and a lower delivery temperature the blower did not place the same demands on the design of the air supply pipes as had to be considered when bleeding high-pressure air from the gas turbine engine.

2.3.2.1 Engine Bleed Design

The Allison engine has bleed ports incorporated into the compressor. Unfortunately, they were not large enough to provide the combustor test rig with the target airflow rate of 0.5 kg/s. In addition, since the bleed is placed over the 5th-stage blades [25], it would not

deliver air at the same pressure as is available from the compressor discharge. To overcome this problem, a separate bleed system was designed to connect the bleed pipe to the compressor discharge air tube that runs between the compressor and combustor.

Joining techniques such as welding were impractical for connecting the bleed directly to the discharge air tube. This is because the discharge tube wall thickness is thin (0.7 mm) and will warp if it is overheated. The initial bleed design attempted to weld a connection directly to the discharge air tube (Figure 2-7.). The resulting part had to be replaced because it would no longer mate at both ends as shown in the bottom of Figure 2-7.

The second bleed design attempted to introduce as little heat as possible into the discharge tube by drilling holes into the duct and clamping a chamber around it. There were challenges in this option as well since there was so little clearance available between the discharge tube and the turbine section of the Allison engine (Figure 2-8).

The clamped-on bleed chamber was made of aluminium to minimize the weight as much as possible (Figure 2-9). Room temperature vulcanizing (RTV) gasket making material was used to make a custom-fitting gasket around the joints to ensure that no air leaked out of the bleed chamber, or where it attached to the discharge tube. An o-ring is used to prevent leaks from between the top of the bleed chamber and the air pipes leading to the combustor test rig.

Figure 2-7 Original bleed design (top left) and its location on the Allison 250 engine (top right). Warping from the welding procedure caused alignment problems for leak-free assembly to the Allison engine (bottom).

Figure 2-8 Top view of the clearance between air discharge tube and turbine section of Allison 250 engine

Figure 2-9 Air bleed chamber shown mounted on the compressor discharge air tube. Side view (left), close-up between bleed and turbine section seen from top.

2.3.2.2 Pressure Losses in a Pipe

As the air travels between the Allison engine and the test combustor, pressure losses will occur due to bends in the pipe, friction, and flow control devices such as valves and orifice plates.

The following relations from White [28] are used to express the change of pressure:

$$\Delta p = \rho \cdot g \cdot h_f \quad (2.1)$$

Where ρ refers to the fluid density, g is the acceleration due to gravity, and h_f represents the head loss in the pipe due to friction and is calculated based on the length-to-diameter ratio of the pipe as well as the velocity of the fluid as it flows through the pipe. The head loss can be described by

$$h_f = f \cdot L/d \cdot \frac{v^2}{2 \cdot g} \quad (2.2)$$

where f is a friction factor coefficient that can be approximated as a function of the Reynolds number and the pipe roughness-to-diameter ratio, ε/d ,

$$f = \left(\frac{1}{-1.8 \cdot \log \left(\frac{6.9}{\text{Re}_d} + \left(\frac{\varepsilon/d}{3.7} \right)^{1.11} \right)} \right)^2 \quad (2.3)$$

This frictional head loss however, only takes into account the losses experienced along a straight pipe of a given length. The elbows and valves also introduce minor pressure losses, h_m , into the system according to

$$h_m = \sum K \cdot \frac{v^2}{2 \cdot g} \quad (2.4)$$

The loss coefficients, K , are dimensionless values that are usually based on experimental data. Some common values are provided in Table 2-2.

Table 2-2 Examples of minor loss coefficients [28]

	Screwed				Flanged				
Nominal Diameter, in	1/2	1	2	4	1	2	4	8	20
Nominal Diameter, mm	12.7	25.4	50.8	101.6	25.4	50.8	101.6	203.2	508
Valves (fully open):									
Globe	14	8.2	6.9	5.7	13	8.5	6.0	5.8	5.5
Gate	0.30	0.24	0.16	0.11	0.80	0.35	0.16	0.07	0.03
Swing Check	5.1	2.9	2.1	2.0	2.0	2.0	2.0	2.0	2.0
Angle	9.0	4.7	2.0	1.0	4.5	2.4	2.0	2.0	2.0
Elbows:									
45° regular	0.39	0.32	0.30	0.29					
45° long radius					0.21	0.20	0.19	0.16	0.14
90° regular	2.0	1.5	0.95	0.64	0.50	0.39	0.30	0.26	0.21
90° long radius	1.0	0.72	0.41	0.23	0.40	0.30	0.19	0.15	0.10
180° regular	2.0	1.5	0.95	0.64	0.41	0.35	0.30	0.25	0.20
180° long radius					0.40	0.30	0.21	0.15	0.10
Tees:									
Line flow	0.90	0.90	0.90	0.90	0.24	0.19	0.14	0.10	0.01
Branch flow	2.4	1.8	1.4	1.1	1.0	0.80	0.64	0.58	0.41

Combining Equations (2.1)-(2.4) gives

$$\Delta p = \frac{1}{2} \rho \cdot v^2 \cdot \left(\frac{L}{d} \cdot \frac{1}{-1.8 \cdot \log \left(\frac{6.9}{v \cdot d} + \left(\frac{\epsilon/d}{3.7} \right)^{1.11} \right)} + \sum K \right)^2 \quad (2.5)$$

From Equation 2.5, it can be seen that the best way to reduce the amount of air pressure lost between the compressor discharge and the test combustor would be to reduce the length as much as possible, as well as to choose a large pipe diameter and long radius elbows.

For the combustor test rig, over 25 feet (7.6 m) of 4-inch (101.6 mm) nominal diameter stainless steel pipe was used for both the test combustor inlet air and the exhaust. Eight long-radius 90° elbows, and three long-radius 45° elbows were also used. Pressure drop estimates were calculated using Equation 2.5 and are listed in Table 2-3. Material selection and sizing for the air pipes is discussed in Section 2.3.2.5.

Table 2-3 Pressure drop estimates for the bleed and exhaust systems of the combustor test rig

Section	Length (m)	# Long-Radius Elbows	Pressure (kPa)	Temperature (°C)	Δp (kPa)
Bleed	4.0	3 x 45° 5 x 90°	709.3	260	0.70
Exhaust	3.6	3 x 90°	101.3	1000	6.47

2.3.2.3 Flow Control

The specifications for the Allison 250-C20B engine were shown in Table 2-1. For design purposes, the airflow rate of air available for the combustor test rig was estimated at one third of the airflow available from the Allison engine. This will permit a reasonable amount of compressed air for high-pressure combustion tests without risking damage to the Allison 250 engine.

To prevent flow from the Allison 250 gas turbine engine to the combustor test rig during start-up and to control the quantity of air diverted from the Allison engine into the combustor test rig, a valve was required in the air pipes. A 4-inch (101.6 mm) butterfly valve was initially selected because it was available at no cost from Carleton University and was the same diameter as the selected air pipes (Figure 2-10). This valve was later replaced with a 3-inch (76.2 mm) butterfly valve (Figure 2-11) because, early in the shakedown of the combustor test rig, it became apparent that the original valve did not seal well enough to permit start-up of the Allison 250 gas turbine. In addition, the smaller diameter would permit better control over the flow.

Figure 2-10 Original butterfly valve used to control bleed air from Allison 250 engine

Figure 2-11 Jamesbury 815W butterfly valve used to control bleed air from Allison 250 engine

The butterfly valve will not be required for tests using the atmospheric blower. Instead it will be fully open to allow the maximum amount of air to flow through the system.

Butterfly valves can lead to significant pressure losses if they are not fully open. For the new butterfly valve, the specification included the maximum C_v value of the valve (165), as well as the C_v values at intermediate positions (Figure 2-12). The valve coefficient, C_v , is commonly used when describing the flow characteristic of a valve. By definition, it is “the quantity of 60°F water, in gallons per minute, which will pass through a specific valve at maximum lift, at one (1) psi pressure drop” [29].

Figure 2-12 The characteristic flow curve for the Jamesbury 815W butterfly valve [30]

The valve coefficient is calculated using the following relation [31]:

$$C_v = \frac{\sqrt{V}}{\sqrt{\Delta p / S.G.}} \quad (2.6)$$

where $\sqrt{V}$ is the volumetric flow rate of the fluid through the valve in gallons per minute,

Δp is the pressure drop across the valve in psi, and S.G. is the specific gravity of the fluid.

For intermediate positions, the pressure drop across the valve can be determined by rearranging Equation 2.6

$$\Delta p = S.G. \cdot \left(\frac{\sqrt{V}}{C_v} \right)^2 \quad (2.7)$$

The pressure drop across the butterfly valve was determined assuming that 0.5 kg/s of air at standard conditions (101.3 kPa absolute pressure, air temperature of 15°C) and at conditions expected when high-pressure air is bled from the Allison 250 gas turbine

engine (709.3 kPa absolute pressure, air temperature of 250°C). Results of the calculation are shown in Table 2-4.

Table 2-4 Pressure drop estimates for the butterfly valve at standard conditions and conditions expected with high-pressure bleed air from the Allison 250 gas turbine engine

Butterfly Valve Position		Open Area		C _v	Δp			
Notch	Degrees	in ²	cm ²		101.3 kPa, 15°C		709.3 kPa, 250°C	
					psi	kPa	psi	KPa
0	0	0.00	0.0	0	-	-	-	-
1	10	0.79	5.1	8	902	6220	519	3580
2	20	1.57	10.1	17	180	1240	130	890
3	30	2.36	15.2	26	78	540	58	400
4	40	3.14	20.3	37	38	260	32	220
5	50	3.93	25.3	54	18	120	21	140
6	60	4.71	30.4	80	8	60	14	100
7	70	5.50	35.5	115	4	30	11	70
8	80	6.28	40.5	149	2	20	8	60
9	90	7.07	45.6	165	2	10	6	40

Note that for positions where the butterfly valve is mostly closed, the pressure drop is theoretically larger than the pressure available in the system. This suggests that some kind of flow restriction downstream of the combustor will be necessary to maintain pressure in the test combustor if the butterfly valve cannot be at or near the fully open position when compressed air is bled from the Allison 250 gas turbine engine.

Ideally, the butterfly valve should have been placed downstream of the test combustor to avoid such potentially large pressure losses prior to combustion. However, the valve has a maximum operational temperature of 260°C, which is much lower than the temperature of the exhaust gases, which are expected to up to 1000°C.

2.3.2.4 Critical Area Calculation

To limit the flow of air through the combustor test rig during high pressure testing without losing all pressure at the butterfly valve, an orifice plate was introduced downstream of the combustor. In addition to providing backpressure in the test combustor for high-pressure combustion, the orifice plate will provide a safety mechanism that limits the amount of air taken from the Allison engine. If properly sized, the backpressure from the orifice plate, could allow the butterfly valve to be fully opened without the risk of too much air being bled from the Allison 250 engine.

If the size of the orifice is too large, too much flow is permitted through the system. The critical area for an orifice is that area at which a given flow reaches sonic speed at the throat and chokes, or prevents additional flow. Assuming isentropic flow, the critical area can be calculated using [28]

$$A^* = \frac{\dot{m}_a}{0.6847 \cdot \rho_0 \cdot \sqrt{R \cdot T_0}} \cdot \frac{1}{\sqrt{k}} \left(\frac{k+1}{2} \right)^{\frac{k+1}{2(k-1)}} \quad (2.8)$$

where $\rho_0 = \frac{p_0}{R \cdot T_0}$, $k = 1.4$, and $R = 287 \frac{J}{kg \cdot K}$ is the gas constant.

Assuming an airflow from the Allison engine of 0.5 kg/s at 7 atm (709.3 kPa) absolute, and neglecting any upstream pressure losses, the pressure in the test combustor was calculated for temperatures of 260°C (no combustion) and 1000°C (with combustion) for several orifice diameters using Equation 2.8. Results are listed in Table 2-5.

Table 2-5 Test combustor pressures for various orifice plate diameters assuming an airflow of 0.5 kg/s

Orifice diameter		Orifice Area		Pressure (no combustion)		Pressure (with combustion)	
in	mm	in ²	cm ²	psia	kPa(a)	psia	kPa(a)
1.00	25.4	0.79	5.097	123.6	852.0	191.0	1316.7
1.10	27.9	0.95	6.131	102.2	704.1	157.9	1088.2
1.20	30.5	1.13	7.297	85.8	591.7	132.7	914.4
1.25	31.8	1.23	7.917	79.1	545.3	122.3	842.7
1.30	33.0	1.33	8.563	73.1	504.1	113.0	779.1
1.40	35.6	1.54	9.931	67.8	467.5	104.8	722.5
1.50	38.1	1.77	11.401	63.1	434.7	97.5	671.8
1.60	40.6	2.01	12.972	54.9	378.7	84.9	585.2
1.70	43.2	2.27	14.644	48.3	332.8	74.6	514.3
1.75	44.5	2.41	15.518	42.8	294.8	66.1	455.6
1.80	45.7	2.54	16.417	40.4	278.2	62.4	429.9
1.90	48.3	2.84	18.292	38.2	263.0	59.0	406.4
2.00	50.8	3.14	20.268	34.2	236.0	52.9	364.7

Two orifice plates were fabricated out of available Hastelloy-X material (Figure 2-13). The first had an orifice diameter of 1.25 in (31.8 mm), and the second had an orifice diameter of 1.5 in (38.1 mm). The smaller orifice is expected to give the maximum pressure once combustion is achieved although the airflow may be slightly reduced. The larger orifice should permit more airflow, but with a reduced combustion pressure.

Figure 2-13 Orifice plate machined out of Hastelloy-X

2.3.2.5 Material Selection

Materials selection for the air piping was based on compatibility with biofuel as well as consideration for the temperatures and pressures involved. Since pipes are rated for a combination of temperature and pressure, it was felt that the design could be simplified by using the same type of pipe for the bleed air as for the exhaust. The bleed air was a high-pressure, medium temperature fluid, while the exhaust gases were at high temperature, but low pressure. Based on the information available, Schedule 10 stainless steel was recommended by the supplier. The diameter of the air pipes was chosen to be as large as possible in order to reduce the pressure losses as the air travelled between the Allison engine and the combustor test rig. For the same reason, all elbows have a long radius.

Using flanges for each piece would ensure freedom of rotation in the joints for assembly purposes, but increase the cost of the system. While welding is less costly, it reduces the flexibility. To maintain some flexibility in the piping configuration and orientation, it was decided to weld half of the pipe joints and bolt together lap-joint stub-ends and flanges for the other half. For each pipe section, one elbow and one straight section of pipe were assembled as shown in Figure 2-14.

Figure 2-14 Welded pipe with straight section and elbow

To reduce the pipe from the inner diameter of the test combustor (7.125 in or 181.0 mm) to that of the exhaust pipes (4.26 in or 108.2 mm), a cone was fabricated out of Hastelloy-X material. This decision was made due to the material availability from another project, and its high temperature strength. It is not known at this stage what the durability of the Hastelloy-X will be when exposed to the products of combustion of biofuel, and it may need to be treated with protective coatings or replaced at a later date.

Table 2-6 shows various diameters of Schedule 10 stainless steel pipe. Information on the stub-ends and flanges is available in Table 2-7. The nominal 4-inch (101.6 mm) diameter was selected because the stub-end required for this size of pipe is 6 inches (152.4 mm) in diameter, and would thus be able to fit through the hole in the wall separating the Allison test cell from the test rig room. The flange however, would not fit through the hole, so it was cut in half and placed on the pipe after it had passed through the wall. Since the mating flange would be whole, it was felt that this would not have a

large impact on the integrity of the system. For simplicity, the same size of piping was used for the compressor air bleed as for the exhaust.

Table 2-6 Dimensions of seamless and welded Schedule 10 stainless steel pipe [32]

Nominal Pipe Size		Outside Pipe Diameter		Inside Pipe Diameter		Approximate Weight	
in	mm	in	mm	in	mm	lb/ft	kg/m
1	25.4	1.315	33.40	1.097	27.86	1.42	2.11
1½	38.1	1.900	48.26	1.682	42.72	2.10	3.13
2	50.8	2.375	60.33	2.157	54.79	2.66	3.96
3	76.2	3.500	88.90	3.260	82.80	4.37	6.50
3½	88.9	4.000	101.60	3.760	95.60	5.02	7.47
4	101.6	4.500	114.30	4.260	108.20	5.67	8.44
5	127.0	5.563	141.30	5.295	134.49	7.84	11.67
6	152.4	6.625	168.28	6.357	161.47	9.38	13.96
8	203.2	8.625	219.08	8.329	211.56	13.40	19.94
10	254.0	10.750	273.05	10.420	264.67	18.65	27.75
12	304.8	12.750	323.85	12.390	314.71	24.16	35.95

Table 2-7 Dimensions of stub-ends and flanges for Schedule 10 stainless steel pipe [33,34]

Stub End Outer Diameter		Flange Diameter	
in	mm	in	mm
2.00	50.8	4.25	108.0
2.88	73.2	5.00	127.0
3.62	91.9	6.00	152.4
5.00	127.0	7.50	190.5
5.50	139.7	8.50	215.9
6.19	157.2	9.00	228.6
7.31	185.7	10.00	254.0
8.50	215.9	11.00	279.4
10.62	269.7	13.50	342.9
12.75	323.9	16.00	406.4
15.00	381.0	19.00	482.6

The length of the stainless steel pipes was dictated by both the necessity of going to an adjacent room, and the requirements of the flow measurement system. The piping design

for the air bleed and exhaust was done with the Student Edition of Pro/Engineer 2001. The model included a model of the Allison 250 test cell and the combustor test rig room as well as the holes between the two rooms. The test combustor and air pipes were then modelled; taking into account the upstream and downstream length requirements for measurement devices. The design of the air pipes is shown in Figures 2-15 and 2-16.

Figure 2-15 Top view (left) and front view (right) of the air pipe design between the Allison 250 test cell and the combustor test rig room

Figure 2-16 Side views of air pipes for combustor test rig (left), and Allison engine (right)

2.3.2.6 Thermal Expansion of Air System

In all, there were over 25 feet (7.6 m) of straight pipe sections to direct the bleed air from the Allison engine to the combustor test rig. Due to the length of the pipe and the temperature of the air expected to pass through them, thermal expansion was considered.

The increase in length of an air pipe due to thermal expansion can be expressed as [35]

$$\delta = \alpha \cdot L \cdot (T - T_i) \quad (2.9)$$

where α is the coefficient of thermal expansion for the given pipe material, L is the length of the pipe, and T is the temperature of the air in the pipe. T_i is the temperature of the pipe when no heat is being added to the system (assumed to be 20°C). If the change in length of the pipe is large enough, then the design of the air pipes will have to include a section that will permit expansion or contraction.

Due to the number of direction changes in the pipe design, a calculation was done using Equation 2.9 to obtain the expected change in length for the longest straight pipes in the bleed air and the exhaust sections (Table 2-8). A high exhaust temperature was estimated to provide a conservative estimate for the thermal expansion. The results in Table 2-8 were given to the supplier for the pipes who included a quote on flexible pipe sections for both the inlet air and the exhaust that were installed just upstream and just downstream of the test combustor.

Table 2-8 Expected change in length of pipes due to thermal expansion

Pipe Section	Material	Coefficient of Thermal Expansion	Maximum Length	Expected Temperature	Change in Length Due to Thermal Expansion
		1/°C	m	°C	m
Bleed	Stainless Steel	17.3E-06	1.57	260	0.0065
Exhaust	Stainless Steel	17.3E-06	2.55	1000	0.0432

2.3.3 Test Combustor

The test combustor is the actual ‘test area’ of the rig where the fuel is atomized and burned. It consists of a combustor casing, a liner, an ignition system, and a fuel nozzle. It also includes areas where test coupons can

be placed, and where measurements of temperature and pressure are possible.

Most of the components for the combustor portion of the test rig were selected because of their similarity to the Allison engine. Since the combustor test rig is only a terrestrial test rig and airworthiness was not required, and several used components were available at low-cost. These parts included the combustor casing, combustor liner, exciter box, igniter plug and an Allison fuel nozzle. More details on these parts can be found in Appendix C. A labelled view of the test combustor is shown in Figure 2-17.

Figure 2-17 Labeled view of the test combustor

2.3.3.1 Fuel Mass Flow Calculations

To demonstrate the versatility of this section of the rig, it was decided that a small number of nozzle designs would be used for the validation tests. Before nozzles could be chosen however, the fuel flow rate was required.

The mass flow rate of the fuel, $\dot{m}_f$, can be calculated using the power and specific fuel consumption (SFC) of an engine. The mass flow rate of air, $\dot{m}_a$, and SFC for the Allison 250-C20B engine are given in Table 2-1.

$$\begin{aligned}\dot{m}_f &= Power \cdot SFC = 420shp \cdot 0.65 \frac{lb}{shp \cdot hr} = 273 \frac{lb}{hr} = 124 \frac{kg}{hr} \\ \dot{m}_a &= 3.45 \frac{lb}{s} = 12420 \frac{lb}{hr} = 5634 \frac{kg}{hr}\end{aligned}\quad (2.10)$$

The fuel-to-air ratio, f/a , can then be calculated by dividing the mass flow rate of the fuel by the mass flow rate of the air

$$f/a = \dot{m}_f / \dot{m}_a = 124 / 5634 = 0.022 \quad (2.11)$$

For the test combustor, only one third of the available air will be available. Therefore, for diesel fuel,

$$\begin{aligned}\dot{m}_a &= 5634 \frac{kg}{hr} \cdot 1/3 = 1878 \frac{kg}{hr} = 0.52 \frac{kg}{s} \\ \text{and} \\ \dot{m}_{df} &= f/a \cdot \dot{m}_a = 0.022 \cdot 0.52 \frac{kg}{s} = 0.011 \frac{kg}{s}\end{aligned}\quad (2.12)$$

To obtain similar energy from biofuel, the difference in calorific value between diesel and biofuel needs to be taken into account. From Table 1-5, the calorific value of diesel is 42 MJ/kg while for biofuel it is between 15-20 MJ/kg. That is, the ratio of the amount of energy available for the two fuels is

$$\frac{42}{17.5} = 2.4 \quad (2.13)$$

Therefore, for biofuel, the mass flow rate would be

$$\begin{aligned}\dot{m}_{bf} &= 2.4 \cdot \frac{f}{a} \cdot \dot{m}_a = 2.4 \cdot 0.022 \cdot 0.52 \frac{\text{kg}}{\text{s}} \\ \dot{m}_{bf} &= 0.027 \frac{\text{kg}}{\text{s}}\end{aligned}\tag{2.14}$$

2.3.3.2 Fuel Nozzle Selection

The first non-Allison components selected as part of the test combustor section were additional fuel nozzles. Three nozzles were initially selected based on:

- 7 atm assumed combustor pressure
- Desired droplet SMD less than 100 μm
- 90° hollow cone spray pattern

Fuel flow rates were based on an estimate of 0.5 kg/s, approximately 1/3 of the airflow available from the Allison engine:

- Max biofuel flow: 0.027 kg/s
- Max diesel flow: 0.011 kg/s

The first two nozzles were pressure atomization nozzles with slightly different nozzle sizes (L40 and L48 nozzles). The third nozzle used air atomization (XAAD nozzle). All three of these additional nozzles were made out of stainless steel for compatibility with biofuel. Fuel pressures for the various nozzles are listed in Table 2-9.

Table 2-9 Nozzle pressures required for a combustor pressure of 709.3 kPa

Nozzle name	Atomization Method	Flow rate of fuel (kg/s)	Fuel Pressure at Nozzle	
			(psi)	(kPa)
L40	Pressure	0.027	242	1669
		0.011	126	869
L48	Pressure	0.027	170	1172
		0.011	114	786
XAAD	Air	0.027	108 (+ 111 air)	745 (+ 765 air)
		0.011	108 (+ 116 air)	745 (+ 765 air)
Allison	Pressure	0.027	203	1400
		0.011	203	1400

For the XAAD nozzle, the fuel pressure will need to be decreased by a small amount so that the air pressure is greater than the fuel pressure, thus permitting proper atomization of the fuel.

Since most nozzles were not designed for the Allison combustor, adaptors had to be designed and manufactured. These are shown in Figure 2-18.

Figure 2-18 Allison nozzle (top left), L48 nozzle with adaptor (bottom left), and XAAD nozzle (right)

Also included in the combustion section of the test rig, was an extension that was initially intended as an extension to the Allison engine in order to validate a CFD model of the Allison combustion process. It was later decided to mount it on the combustor test rig to include a longer residence time for complete combustion, and a quick disconnect system for the combustor.

Finally, a power supply was required to power the exciter box for the igniter. The power requirement for the exciter box was 5 A at 28 V, or 140 W. An RKW 28-12K (300 W) power supply was ordered to meet this requirement. Specifications can be found in Appendix D.

2.3.4 Fuel Skid

The fuel skid portion of the test rig includes any parts that are involved with transporting, controlling, and measuring the flow of the fuel to the combustor section of the rig. This includes pumps, filters, valves, and storage devices.

The selection of components for the fuel skid was one of the more challenging tasks undertaken as part of this project. This was especially true for biofuel-wetted parts, where options were somewhat limited when trying to find affordable off-the-shelf components that met the materials compatibility requirements. In addition, there were a

number of different types of parts that were needed to handle the fuel from the fuel supply tank to the fuel nozzle in the test combustor. Some examples are listed in Table 2-10.

Table 2-10 Summary of fuel skid components and their purpose

Component	Purpose
Filter	Limits the maximum particle size that can travel through the system
Heat Exchanger	Preheats fuel going into the test combustor to aid atomization
Pipe	Connects all components of the fuel skid together
Pumps	Increases fuel pressure up to the required amount for atomization in the fuel nozzle for combustion
Static Mixer	Mixes fuels before entry into the test combustor
Valves	
Check	Ensures flow moves only in the 'forward' direction
Flow Regulating	Controls the mass flow rate through the system
Pressure Regulating	Sets the maximum pressure through the system, excess fuel is returned to the supply tank
Pressure Relief	Safety valve that ensures that pressure does not exceed a set maximum
Solenoid	Quick method of turning on/off fuel flow, can be used as a safety shut-off switch (normally closed)
Three-Way	Permits switching between two separate flow paths

Some components were available from a previous biofuel heat exchanger experiment done by Orenda. These included a filter assembly, two 0.5-inch (12.7 mm) diameter flexible hoses, the heat exchanger barrel (with glycol), and heaters. The remainder of the fuel skid components for combustor test rig were either purchased as off-the-shelf components, or as materials that were easily assembled into the required components.

2.3.4.1 Fuel Heat Transfer

Due to the high viscosity of biofuel, it must be preheated prior to combustion to atomize properly in the combustor. To accomplish this, a heat exchanger module was designed for inclusion into the fuel system. The design of the heat exchanger is a length of tubing coiled inside a barrel full of fluid as shown in Figure 2-19. This fluid is stirred and heated to a temperature that will ensure that the fuel passing through the tubing exits the heat exchanger at the desired temperature for combustion.

Figure 2-19 Schematic design of heat exchanger concept

To obtain a rough estimation of how much tubing would be required in the heat exchanger, assumptions were made with respect to the heat transfer mechanisms occurring:

- The fuel temperature is constant across the diameter of the tubing
- Convection is the main mechanism for heat transfer from the heat exchanger fluid to the fuel temperature

Equations and derivations for the calculation of the fuel heat transfer were based on information from the book on heat transfer by Holman [36]. The heat transfer rate, $\dot{Q}$, required is determined from the mass flow rate, $\dot{m}_f$, heat capacity of the fuel, C_f , and the required change in temperature of the fuel, ΔT .

$$\dot{Q} = \dot{m}_f \cdot C_f \cdot \Delta T \quad (2.15)$$

The heat transfer from the fluid in the barrel can be represented by convection of the fluid relative to the tubing due to stirring.

$$h \cdot A \cdot (T_w - T) = \dot{m}_f \cdot C_f \cdot \Delta T \quad (2.16)$$

The Nusselt number is a non-dimensional parameter that relates the convective heat transfer coefficient, h , to the conductive heat transfer coefficient, k .

$$Nu_d = \frac{h \cdot d}{k} \quad (2.17)$$

By substituting this relation into Equation 2.16 and expressing the area of heat transfer in terms of the diameter of the barrel, the resulting equation is

$$\begin{aligned} \frac{Nu \cdot k}{d} \cdot \pi \cdot d \cdot dx \cdot (T_w - T) &= \dot{m}_f \cdot C_f \cdot dT \\ \text{or} & \\ Nu \cdot k \cdot \pi \cdot dx &= \dot{m}_f \cdot C_f \cdot \frac{dT}{(T_w - T)} \end{aligned} \quad (2.18)$$

Integrating each side, and solving for the length of the tubing, x , gives a relation for the amount of tubing required based on the expected temperature difference of the fuel and its heat transfer characteristics.

$$x = \frac{\dot{m}_f \cdot C_f}{Nu \cdot k \cdot \pi} \cdot \ln \left(\frac{T_w - T_{in}}{T_w - T_{out}} \right) \quad (2.19)$$

To preheat biofuel from 20°C to 80°C using glycol, the length of the tubing is highly dependent on the difference between the desired temperature and the temperature of the heat exchanger fluid (glycol). Table 2-11 shows the length of tubing required for various glycol temperatures for a mass flow rate of biofuel of $\dot{m}_f = \dot{m}_{bf} = 0.027 \text{ kg/s}$, the heat capacity of the biofuel is $C_f = 3.00 \text{ kJ/kg} \cdot \text{K}$ [21], and the thermal conductivity of the glycol is $k = 0.26 \text{ W/m} \cdot \text{K}$ [36]. The Nusselt number for the glycol is assumed to be low ($Nu = 10$) because the fluid movement in the barrel is just enough to maintain a uniform temperature and is therefore not considered turbulent.

Table 2-11 Effect of glycol temperature on length of coiled tubing required for the fuel heat exchanger

Initial Fuel Temperature	Final Fuel Temperature	Glycol Temperature	Required Length
°C	°C	°C	m
20	80	90	19.3
20	80	85	25.4
20	80	83	30.2
20	80	82	34.1
20	80	81	40.8
20	80	80.1	63.5
20	80	80.01	79.4
20	80	80.001	109.1

A temperature of 80°C was chosen as the desired fuel exit temperature to ensure that the viscosity at the fuel nozzle comparable to diesel. It also has the benefit of being below the 90°C temperature limit where rapid biofuel decomposition occurs. To reduce the risk of biofuel overheating and decomposing prior to combustion, it is desirable to have the glycol as close as possible to the fuel outlet temperature. A coil length of 50 m was selected which results in a glycol temperature between 80.1°C and 81°C.

Due to the length of the tubing, the diameter of any piping or tubing used will have a direct impact on the pressure losses in the system and thus on the delivery pressure required by the pumps. The pressure drop in a commercial steel pipe was calculated according the Equation 2.5 with the following assumptions:

- the length of the fuel system from the pump outlet to the fuel nozzle in the test combustor is approximately 75 m
- constant viscosity based on the room temperature viscosity of the fuel
- minor losses are neglected

Table 2-12 Pressure drop estimates for diesel and biofuel

Pipe Diameter		Diesel	Biofuel	Pipe Length	75 m
(in)	(mm)	ΔP (kPa)	ΔP (kPa)		
0.250	6.35	61.78	932.65	Pipe Roughness	0.0457 mm
0.375	9.53	9.79	171.68	<u>Diesel Properties</u>	
0.500	12.70	2.69	53.92	S.G.	0.85
0.625	15.88	1.03	22.68	Viscosity	3 mm ² /s
0.750	19.05	0.48	11.45	Mass Flow	0.011 kg/s
0.875	22.23	0.21	6.62	<u>Biofuel Properties</u>	
1.000	25.40	0.14	4.14	S.G.	1.2
				Viscosity	6 mm ² /s
				Mass Flow	0.027 kg/s

A half-inch (12.7 mm) diameter was selected for having the largest effective area that was still easily bendable and had a reasonable pressure drop. A combination of Swagelok tubing and unions were used to make the coils to ensure that no leaks occurred in the heat exchanger. The coiled tubing was attached to a support frame to allow circulation of the glycol around the tubing (Figure 2-20). Before entering the heat exchanger, the flow was split into two streams using a 'Y' and brought back together into one stream after exiting (Figure 2-21). The reasons for splitting the flow are to reduce the flow through each path and leave a margin of error in case fouling occurs along the inside edges of the tubing thus reducing its effective inner diameter, and to provide an alternate path for fuel in the case where a blockage occurs.

Figure 2-20 Heat exchanger coils and support frame

Figure 2-21 Fuel flow splitter

As mentioned previously, heaters were available from a previous project with Orencia Aerospace. These heaters consisted of one 8000 W immersion heater and maintained by four drum heaters, each capable of up to 1500 W. The power requirements for the heat

exchanger of the gas turbine combustor test rig fuel skid was determined by two separate calculations: the amount of power needed to warm up the heat exchanger prior to testing, and the amount of power required to maintain the heat exchanger temperature once fuel was flowing through it.

The heat exchanger warm-up calculation was done assuming that the glycol would need to be heated from room temperature (20°C) to approximately 80°C in one hour. The amount of heat, Q , required to heat the glycol and the barrel from 20°C to 80°C is

$$Q = m \cdot C \cdot \Delta T \quad (2.20)$$

The heat exchanger barrel is approximately 1 m tall and 0.3 m in diameter and weighs about 7 kg. It holds approximately 150 L, or 160 kg of glycol. The heat capacities of the steel barrel and glycol are 0.47 kJ/(kg·K) [36] and 2.56 kJ/(kg·K) [36] respectively. Calculating the heat required reveals that

$$\begin{aligned} Q_b &= 7\text{kg} \cdot 0.47 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \cdot (80^\circ\text{C} - 20^\circ\text{C}) = 210 \text{ kJ} \\ \text{and} \\ Q_g &= 160\text{kg} \cdot 2.56 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \cdot (80^\circ\text{C} - 20^\circ\text{C}) = 24576 \text{ kJ} \end{aligned} \quad (2.21)$$

If the heat exchanger must be at 80°C in one hour, then the heating rate required would be

$$\frac{(Q_b + Q_g)}{1 \text{ hour}} = \frac{(210 + 24576) \text{ kJ}}{3600 \text{ s}} = 6.88 \text{ kW} \quad (2.22)$$

In addition to the amount of power required to bring the heat exchanger up to temperature, heat losses must be taken into account as well. If laminar free convection is assumed, then the convective heat transfer coefficient for a vertical cylinder can be given by [36]

$$h = 1.42 \cdot \left(\frac{\Delta T}{\text{height}} \right)^{1/4} \frac{W}{m^2 \cdot K} \quad (2.23)$$

and the power required to make up for the heat loss can be calculated as

$$Q = h \cdot A \cdot \Delta T \quad (2.24)$$

$$Q = 1.42 \cdot \left(\frac{\Delta T}{\text{height}} \right)^{1/4} \cdot \left(2 \cdot \frac{\pi}{4} \cdot (0.3 \text{ m})^2 + 2 \cdot \pi \cdot \frac{0.3 \text{ m}}{2} \cdot 1 \text{ m} \right) \cdot (80^\circ \text{C} - 20^\circ \text{C})$$

$$Q = 257 \text{ W}$$

Thus the total power required to heat the glycol from 20°C to 80°C would be 7.1 kW. With a safety factor of 25%, the amount of power required will increase to approximately 9 kW. The immersion heater is capable of supplying up to 8 kW of power with the remainder being supplied by a drum heater.

To maintain a temperature of 80°C in the heat exchanger while fuel passes through the system, power will also be required. This power can be calculated using Equation 2.15 and will yield the following result with biofuel

$$\dot{Q} = \dot{m}_f \cdot C_f \cdot \Delta T$$

$$\dot{Q}_{bf} = 0.027 \frac{\text{kg}}{\text{s}} \cdot 3.00 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \cdot (80^\circ\text{C} - 20^\circ\text{C})$$

$$\dot{Q}_{bf} = 4.9 \text{ kW}$$

With the same factor applied, approximately 6 kW will be required to maintain the temperature in the heat exchanger at 80°C. Since each of the four band drum heaters (Figure 2-21) is capable of up to 1500W, the large immersion heater will not be required once the glycol has reached 80°C.

Figure 2-22 Drum heaters placed around the barrel of the heat exchanger. Insulation is also placed around the heat exchanger to minimize heat loss (right).

To maintain the temperature of the heat exchanger at 80°C, one of the drum heaters was plugged into a PID temperature controller. The controller reads the glycol temperature with a thermocouple and adjusts the power supplied to the heater accordingly. Only one controller is required, because with the heating requirements of the system, three heaters can provide up to 4.5 kW of the required heating power and the final drum heater will only need to supply heat to ensure that the final amount of heat is supplied as required. The controller is shown in Figure 2-23.

Figure 2-23 PID temperature controller for a heat exchanger band heater

2.3.4.2 Pump Selection

Pumps are required to deliver fuel from storage containers, such as barrels or totes, to the fuel nozzle at a sufficient pressure to ensure atomization of the fuel into droplets small enough for complete combustion. The delivery pressure required by the pumps is dependant on the magnitude of the pressure drop, Δp , experienced throughout the fuel system.

As mentioned in the design of the combustor test section, the highest delivery pressure required by the selected fuel nozzles is the L40 nozzle 242 psi (1669 kPa). Using the 0.5-inch (12.7 mm) diameter tubing selected for the heat exchanger, the pump would need to deliver at least 250 psi (1724 kPa) before taking into account the losses introduced by the fuel valves. To account for these losses, and include a safety factor in the pump size, it was decided to look for a pump in the range of 350–400 psi (2400–2750 kPa).

Several types of pumps were considered: gear pumps, plunger pumps, and diaphragm pumps. Gear pumps were originally considered to avoid pressure fluctuations, but the costs were high for the combination of high pressure and low flow rate. In addition, pumps that met these requirements did not necessarily meet the materials requirements of biofuel-wetted areas. Plunger pumps were a possibility, but to reduce the pressure fluctuations, a pulsation dampener would have been required which would have increased the cost of the pump assembly. Most diaphragm pumps also had pressure fluctuations, but some models included multiple pistons, which reduced these effects.

The most practical compromise between the many requirements of flow rate, pressure, materials, and cost ended up being a Hydra-Cell diaphragm pump with multiple pistons to reduce pressure fluctuations. The sizing chart for these pumps is shown in Figure 2-24. The F-20 and M-03 (shown as the D-03 pump on the chart) pump models were selected for diesel and biofuel respectively. The M-03 pump has the multiple pistons behind the diaphragm due to its larger size. In addition, it was possible to get all wetted components in biofuel-compatible materials (stainless steel and Teflon).

Figure 2-24 Pump sizing chart for Hydra-cell diaphragm pumps from Wanner website [37]

2.3.4.3 Valve Selection

Valve selection was based on the fuel skid configuration and requirements for pressure and flow regulation. Quotes were requested for both stainless steel and brass valves. In many cases, brass was selected due to lower cost. Some less expensive components were available for the diesel fuel, because they used the more common viton seals. For the biofuel-wetted components however, Teflon seals were required.

Pressure-regulating valves were offered by the same supplier as the fuel pumps (Figure 2-25). This type of valve controls the pressure in the fuel line by lifting a diaphragm that opens the bypass line. The pressure required to lift the diaphragm is proportional to the force exerted by the spring above it. Tightening or loosening the screw on the top of the valve can adjust the force on the spring that must be overcome before the valve opens.

Figure 2-25 Pressure regulating valve and schematic of operation

A manually operated stainless steel needle valve was recommended as a means of flow control, while maintaining low cost. A needle valve regulates the volume of flow with a conical needle that, based on its position, controls the size of the opening through which the fluid flows. An example of a needle valve is shown in Figure 2-26.

In systems such as the combustor test rig fuel skid where two fuel lines are combined, it is important that the fuel from one line does not enter the other. One way to accomplish

this is through the use of check valves (Figure 2-26). Check valves are self-actuating valves that only permit flow in one direction. When the flow is in the desired direction, the valve opens; when the flow is reversed, the valve is forced shut by the flow. Two check valves were placed in the fuel skid, one on the diesel line, and the other in the biofuel line as shown in Figure 2-27.

Figure 2-26 Schematics for a needle valve (left) [38] and a check valve (right) [39]

Figure 2-27 Labeled view of valves on cart

Solenoid valves were placed in each fuel line. Solenoid valves use current running through a coil to either open or close a valve. The selected valves were normally closed (closed when there is no power) and would shut off the flow of fuel from the pumps to the remainder of the system. Since the solenoid valve is capable of stopping fuel flow through the system, there is no need to close the needle valve after each test. This is an advantage with the manually controlled needle valves because they can be set to the desired fuel flow rate and left in position between tests ensuring that the same fuel flow rate exists next time the solenoid valve is opened.

2.3.4.4 Filters

Filters are used to trap particulates over a certain size and prevent them from travelling downstream through the fuel line. Diesel fuel is a relatively clean fuel, with low viscosity, so finding a filter for the diesel portion was easy.

For the biofuel filter, which has a higher particulate content, several options were considered: filters (both manual and self-cleaning) as well as strainers. Strainers are similar to filters for removing particles, but they are more economical. Part of the reason is that they cannot remove particles below a certain size and are therefore less efficient at removing particulates.

Initial considerations in the selection of a filter or strainer were the maximum particle size that would be permitted downstream. The smallest nozzle size was about 0.040 inches (1.02 mm) in diameter, and the filter should be capable of removing particles large enough to clog the nozzle. It was decided to go as small as possible without incurring too large a pressure drop or cost.

To avoid downtime, a two-filter system was proposed where the flow could be switched from one filter and another with a three-way valve if the first one became inefficient due to clogging of the holes. This would allow the system to continue running while the filter was cleaned out or replaced. Automated, self-cleaning systems do exist, but they are costly so a manual system was chosen.

When trying to size the filters, some concern was raised regarding the rate at which they would need to be switched. A manufacturer of custom-made screens was contracted to make a series of screens of different mesh sizes to fit into a Y-strainer used by Orenda for a biofuel heat exchanger experiment. The mesh sizes chosen were: 60-mesh, 100-mesh, 150-mesh, 200-mesh, and 300-mesh (Figure 2-28). A chart showing the relation between mesh sizes and the opening size in inches and microns (μm) is shown in Table 2-13.

*Figure 2-28 Strainer meshes used in Y-strainer
(all finer meshes were placed inside a 20-mesh screen for support)*

The 300-mesh screens were placed in the Y-strainer and observed for a fifteen-minute period while biofuel was pumped through. No significant pressure drop, or change in fuel flow rate was noted during that time which suggested that the screens were not clogging too quickly. Based on the results, it was decided to use the Y-strainer assembly as part of the combustor test rig fuel skid. In addition to those previously mentioned, two smaller screens were also ordered: a 500-mesh screen, and a 17-micron screen (smallest screen available from the manufacturer).

The filter assembly for the combustor test rig, including a three-way valve to permit switching between the two strainers is shown in Figure 2-29.

Table 2-13 Comparison of mesh sizes and opening diameters [40]

Meshes/Lineal inch US and ASTM Std. Sieve No.	Actual Opening		Meshes/Lineal inch US and ASTM Std. Sieve No.	Actual Opening	
	<u>Inches</u>	<u>Microns</u>		<u>Inches</u>	<u>Microns</u>
10	.0787	2000	170	.0035	88
12	.0661 1/16	1680	200	.0029	74
14	.0555	1410		.0026	65
16	.0496 3/64	1190	230	.0024	62
18	.0394	1000	270	.0021	53
20	.0331 1/32	840		.0020	50
25	.0280	710	325	.0017	44
30	.0232	590		.0016	40
35	.0197 1/64	500	400	.00142	36
40	.0165	420		.00118	30
45	.0138	350	550	.00099	25
50	.0117	297	625	.00079	20
60	.0098	250		.00059	15
70	.0083	210	1,250	.000394	10
80	.0070	177	1,750	.000315	8
100	.0059	149	2,500	.000197	5
120	.0049	125	5,000	.000099	2.5
140	.0041	105	12,000	.0000394	1

Figure 2-29 Filter assembly for biofuel

2.3.4.5 Fuel Mixing

Diesel and biofuel do not mix without effort. In order to ensure good mixing between the two fuels, a mixer was needed in the fuel line just upstream of the nozzle. The proximity to the nozzle prevents the fuels from separating before they enter the test combustor. A 0.5-inch (12.7 mm) Omega FMX 8482 static mixer was selected because of low cost, material compatibility, and ease of installation.

In order to size the length required for the static mixer, the Reynolds number for the fluid was required. Assuming that the fuel passing through the mixer was 100% biofuel, due to its higher viscosity, the Reynolds number would be

$$\text{Re}_d = \frac{v \cdot d}{\nu} = \frac{\left(\frac{\dot{m}}{\rho \cdot A} \right) \cdot d}{\nu} \quad (2.25)$$

$$\text{Re}_d = \frac{\left(\frac{0.027 \text{ kg/s}}{1200 \text{ kg/m}^3 \cdot \frac{\pi}{4} \cdot (0.0127 \text{ m})^2} \right) \cdot 0.0127 \text{ m}}{9 \text{ cSt}} = 251$$

Based on the sizing for the static mixer, 16-24 elements are required for Reynolds numbers between 10-500. The selected mixer came with an option of either 6 or 12 mixing elements. Two 12-element mixers were selected because additional length would ensure longer mixing of the fuels, and the difference in cost was low.

2.3.4.6 Miscellaneous

In addition to the pumps, valves, filters, mixers, and heat exchanger, other components were required for the test rig fuel skid that did not involve a lot of calculation, but were nonetheless required. They are mentioned here for completeness.

Fittings were required to connect all of the previously mentioned components together. Many of these components had NPT connections, so it was decided to connect the fuel valves and pumps using NPT fittings (Figure 2-30). Due to the number of connections, these parts were placed on a cart with trays that could catch any potential fuel leaks (Figure 2-31).

Screwed/Threaded Fittings

Figure 2-30 Threaded fittings [41]

Figure 2-31 Cart for fuel skid with pumps on the bottom and control valves on the top

To reduce the chance of fuel leaking for the remainder of the fuel system it was decided to use Swagelok tubing and fittings. A flexible stainless steel hose with a quick-connect connection was also incorporated between the static mixers and the fuel nozzle to accommodate the connection angles required by the different fuel nozzles.

To store the biofuel, 45-gallon (170 L), 0.8 mm-thick steel barrels were purchased (Figure 2-32). From previous experience handling biofuel, it was discovered that the biofuel degrades the lining of fuel barrels and this lining could enter the fuel system in

the form of additional particulates that would need to be filtered; therefore unlined barrels were ordered.

Figure 2-32 Barrels for storage of biofuel [42]

2.3.5 Data Acquisition System

2.3.5.1 Data Collection and Storage

In any test system, measurements must be taken. For the combustor test rig, these measurements are summarized in Table 2-14. Details of specific measurement devices and how they were selected are discussed later in this section.

Table 2-14 Summary of combustor test rig data measurements

Measurement Type	System	Locations	Range	Device
Temperature	Air	Upstream of combustor	0 - 300 °C	Thermocouple
		Exhaust	0 - 1000 °C	
	Fuel	Pump discharge	0 - 50 °C	
		Upstream of filter	0 - 50 °C	
		Upstream of heat exchanger	0 - 50 °C	
		Downstream of heat exchanger	0 - 100 °C	
		Upstream of combustor	0 - 100 °C	
	Heat Exchanger	Glycol temperature	0 - 100 °C	
Pressure	Air	Upstream of butterfly valve	0 - 100 psig (0-690 kPa)	Transducer 1-6 Vdc
		Downstream of butterfly valve	0 - 100 psig (0-690 kPa)	
	Fuel	Pump inlet	-30 inHg - 30 psig (-100-200 kPa)	Dial Gauge
		Downstream of pressure regulator	0 - 300 psig (0-2068 kPa)	Transducer 1-5 Vdc
		Upstream of filter	0 - 300 psig (0-2068 kPa)	
		Upstream of heat exchanger	0 - 300 psig (0-2068 kPa)	
		Upstream of combustor	0 - 300 psig (0-2068 kPa)	
	Flow	Air	Upstream of butterfly valve	2 Pressure Transducers 1-6 Vdc
Fuel		Diesel line	79 - 795 L/hr	Digital Display Flowmeter
		Upstream of heat exchanger	15 - 500 L/hr	
		Upstream of combustor	0.2 - 23 kg/min	

To effectively record the amount of data that is simultaneously available from the combustor test rig, it was decided to use a device capable of handling multiple inputs. Keithley Instruments offers multimeter and data acquisition systems capable of acquiring temperature, voltage, current and frequency inputs, depending on the modules installed. They are also easily interfaced to a computer using Ethernet, GPIB, or RS-232 connections. A typical system is shown in Figure 2-33.

Typical Integra Series System Diagram

Figure 2-33 Keithley Integra data system [43]

For the combustor test rig application, the Keithley 2700 data acquisition system was selected with a 7708 module, capable of measuring 40-channels with voltage and temperature inputs (Figures 2-34 and 2-35). The second slot in the 2700 remains available for expansion, if it is later required. The software used to record the data is the Integra Up&Running software, which is a demonstration software package, that records all data and can plot up to eight channels in real-time. It was installed on a laptop computer and connected to the Keithley instrument using a PCM GPIB controller card.

All temperature and pressure transducer measurements are recorded with the Keithley data acquisition system. Channel assignments in the 7708 module are listed in Table 2-15. The flowmeters were purchased before the Keithley system and were therefore not selected with integration into this system in mind. For the fuel flow measurements, data will need to be recorded manually.

Table 2-15 Channel assignments for 7708 module

Channel #	Measurement Type	Device	Measurement Location
1	Air Temperature	Thermocouple (°C)	Upstream of Combustor
2	Air Temperature	Thermocouple (°C)	Downstream of Combustor
3	Air Temperature	Thermocouple (°C)	Downstream of Combustor
4	Air Temperature	Thermocouple (°C)	Downstream of Combustor
5	Air Temperature	Thermocouple (°C)	Downstream of Combustor
6	Glycol Temperature	Thermocouple (°C)	Heat Exchanger Barrel
7-12	Unassigned		
13	Fuel Temperature	Thermocouple (°C)	Downstream of Diesel Pressure Regulator
14	Fuel Temperature	Thermocouple (°C)	Downstream of Biofuel Pressure Regulator
15	Fuel Temperature	Thermocouple (°C)	Upstream of Filter
16	Fuel Temperature	Thermocouple (°C)	Upstream of Heat Exchanger
17	Fuel Temperature	Thermocouple (°C)	Downstream of Heat Exchanger
18	Fuel Temperature	Thermocouple (°C)	Upstream of Nozzle
19-24	Unassigned		
25	Fuel Pressure	Transducer (1-5 V)	Downstream of Diesel Pressure Regulator
26	Fuel Pressure	Transducer (1-5 V)	Downstream of Biofuel Pressure Regulator
27	Fuel Pressure	Transducer (1-5 V)	Upstream of Filter
28	Fuel Pressure	Transducer (1-5 V)	Upstream of Heat Exchanger
29	Fuel Pressure	Transducer (1-5 V)	Upstream of Nozzle
30-31	Unassigned		
32	Air Pressure	Transducer (1-6 V)	Pitot Stagnation Pressure
33	Air Pressure	Transducer (1-6 V)	Pitot Static Pressure
34	Air Pressure	Transducer (1-6 V)	Upstream of Combustor
35-40	Unassigned

Figure 2-34 Keithley 2700 data acquisition system front and rear views

Figure 2-35 40-channel 7708 module

2.3.5.2 Temperature Measurement

Thermocouples were used to determine the temperature at various locations in the combustor test rig. Thermocouples are made of two pieces of wire made from two different metals that are joined together at one end. Increasing the temperature at the joined end causes a change in the voltage between the two wires that can be measured at the open end.

Thermocouples are available in a number of different metal combinations depending on the temperature range expected for the application as shown in Table 2-16.

Table 2-16 Thermocouple types and temperature ranges [44]

Thermocouple Type	Metals	Temperature Range (°C)
T	Copper vs. Copper-Nickel	-200 – 350
J	Iron vs. Copper-Nickel	0 – 750
E	Nickel-Chromium vs. Copper-Nickel	-200 – 900
K	Nickel-Chromium vs. Nickel-Aluminium	-200 – 1250
N	Nickel-14.2%Chromium-1.4%Silicon vs. Nickel-4.4%Silicon-0.1%Magnesium	-270 – 1300
S	Platinum-10%Rhodium vs. Platinum	0 – 1450
R	Platinum-13%Rhodium vs. Platinum	0 – 1450
B	Platinum-30%Rhodium vs. Platinum-6%Rhodium	0 - 1700

As previously discussed, biofuel temperatures cannot safely exceed 80°C without risk of degradation. A high temperature limit is therefore not required on the thermocouples and T-type thermocouples were selected for all fuel temperature measurements.

The temperature controller for the heat exchanger required a J-type thermocouple for its feedback system. For the air system, incoming air is at a much lower temperature than the exhaust air (250°C vs. 1000°C), and a J-type thermocouple was also selected.

For the exhaust gas temperature measurement, thermocouples were placed downstream of the Hastelloy-X reducing cone. As thermocouples experience the stagnation temperature of a fluid, the temperature for at least one portion of the probe is expected to be up to 1000°C, so K-type thermocouples were selected. Four thermocouples were placed together in the exhaust in case of a thermocouple failure during testing. Two thermocouples were placed near the centre of the pipe, while the other two were placed closer to the pipe wall as shown in Figure 2-36. The reason for the varied placement of the thermocouples is because the exhaust gas temperatures are expected to be higher near the centre of the flow, but in case of thermocouple failure in the centre, the outer thermocouples are expected to survive. In addition, the thermocouple placement will give the opportunity to determine if the flow out of the combustor is symmetrical.

Figure 2-36 Air temperature thermocouple placement. Numbers refer to data acquisition channel.

2.3.5.3 Pressure Measurement

Pressure measurements are taken in several places in the combustor test rig. They are used to determine air pressure in the combustor as well as the airflow rate. Pressure measurements in the fuel skid are used to determine the settings for the fuel pressure regulating valves, and can be used to provide an indication of where flow restrictions occur, such as identifying if filters need to be cleaned.

It was decided to use pressure transducers to measure the pressures in the combustor test rig because the pressures could then be recorded by the data acquisition system during tests. To minimize costs however, it was decided to use available dial gauges if they had a suitable pressure range.

Several Omega pressure transducers and a power supply were available from a previous thesis project. These included Omega PX242A-G100V pressure transducers, and an Omega PST-8 power supply, shown in Figure 2-37. Some specifications are outlined in Table 2-17. These were suitable for the air pressure measurements, but the pressure range and materials were not suitable for the fuel skid.

Pressure transducers for the fuel system were purchased to be compatible with biofuel. The selected pressure transducer was Omega's PX181-300G5V corrosion resistant pressure transducer in a stainless steel case (Figure 2-37). To provide the excitation voltage to the pressure transducer, an Omega PST-15 power supply was purchased.

Figure 2-37 Pressure transducers PX242 (top left), PX181 (bottom left) and PST power supply (right) [45]

Table 2-17 Specifications for pressure transducers and power supplies [45]

Pressure Transducers			Power Supplies	
	PX242A-G100V	PX181-300G5V	PST-8	PST-15
Range	0-100 psig (0-690 kPa)	0-300 psig (2068 kPa)	8 Vdc	15 Vdc
Excitation	8 Vdc	12-25 Vdc	300 mA	200 mA
Output	1-6 Vdc	1-5 Vdc		

Dial gauges were included with the pumps for both the inlet and outlet. The gauge supplied for the inlet was used as part of the fuel skid. The gauge for the outlet however, had too large a pressure range for use in the combustor test rig so it was decided to replace the dial gauge with a pressure transducer that could be recorded by the data acquisition system.

2.3.5.4 Air Flow Measurement

Due to a combination of temperature, size, and cost considerations, an averaging Pitot tube was selected to measure the airflow into the combustor and placed in the straight pipe upstream the butterfly valve used to control the airflow into the combustor.

This Pitot tube, sized for the pipe diameter, required the flow to be undisturbed for several pipe diameters upstream of the measurement point and again downstream of the Pitot tube in order to ensure that the flow is fully developed and symmetrical. According to Figure 2-38, the minimum length for the pipe configuration shown in Figure 2-16 would need to take into account one 90° elbow upstream, and a butterfly valve downstream. The averaging Pitot tube was placed in the pipe with ten diameters of straight pipe upstream, and five diameters downstream.

The selected averaging Pitot tube was a KLFlo KL model for welding into 4-inch, schedule 10 stainless steel pipe and is shown in Figure 2-39. It measures both the stagnation pressure, and static pressure of the air. The Pitot tube has several ports along each side to measure the fluid pressure at different points in the flow profile. The attached pressure transducer measures the average pressure from these points.

RECOMMENDED MIN. STRAIGHT PIPE RUNS FOR UPSTREAM

Figure 2-38 Mounting locations for KLFlo sensors [46]

Figure 2-39 Schematic of averaging Pitot tube (left), actual Pitot tube (right)

The difference between these two pressures can be used to determine the fluid flow.

Assuming no friction around the Pitot tube and incompressible flow, air velocity may be determined by using the Pitot formula [28],

$$v = \left[\frac{2(p_0 - p_s)}{\rho} \right]^{1/2} \quad (2.27)$$

where ρ is calculated using

$$\rho = \frac{p}{R \cdot T} \quad (2.28)$$

The velocity can then be used to calculate the mass flow rate

$$\dot{m}_a = \rho \cdot V \cdot A \quad (2.29)$$

In addition to the cost advantage of this type of flowmeter, it also provides a pressure measurement for the air upstream of the test combustor. One disadvantage however, is that in order to measure the flow accurately, the Pitot tube must be aligned with the flow

direction. A small misalignment can lead to large errors in pressure measurement as shown in Figure 2-40.

Figure 2-40 Effect of Pitot alignment errors on pressure measurement [28]

2.3.5.5 Fuel Flow Measurement

When the fuel skid was designed, it was decided that there should be a flowmeter in each fuel line, and a third near the end of the fuel line, just upstream of the fuel nozzle for purposes of comparison. A turbine flowmeter was available for loan from Environment Canada for use with diesel fuel only. Orenda had a mass flowmeter that had been purchased for other experiments with biofuel, therefore only one additional flowmeter suitable for the test rig fuel skid was required.

When considering a flow measurement device for biofuel, the primary factors in the selection of the flowmeter were the abilities to handle the low flow rate and higher viscosity of the biofuel.

Some experiments done by Orenda with the mass flowmeter using biofuel before assembly of the combustor test rig fuel skid indicated that it had difficulty measuring flows at lower flow rates. To counter this limitation, it was decided to place this flowmeter just upstream of the fuel nozzle since the fuel from both lines would be present, and thus have a higher volume. Also, it was decided to remove the meter from the biofuel-only section of the fuel skid and place it in a combined flow position as well. This would allow two separate measurements of the flow, and guarantee some redundancy.

Options considered for the biofuel flowmeter included a turbine flowmeter and an oval gear flowmeter. A turbine flowmeter is in the category of velocity meters and is shown schematically in Figure 2-41. The turbine meter rotor blades create a frequency signal that can be sensed magnetically as they spin and the volume flow rate is directly proportional to the speed of rotation. Limitations of turbine flowmeters are that they are better with low-viscosity fluids [47].

Figure 2-41 A turbine flowmeter [47]

An oval gear flowmeter is a positive displacement measurement device where the amount of flow can be determined based on the rotation of the gears. As shown in Figure 2-42, the oval gears displace a fixed amount of fluid with every rotation. The amount of flow through the flowmeter is then proportional to the rate of rotation of the gears.

Figure 2-42 Schematic of oval gear flowmeter operation [48]

An oval flowmeter was chosen because it was not sensitive to viscosity changes with changes in temperature. Its measurement of flow is dependent a finite displacement of liquid between the gears. The placement chosen for the flowmeter was before the heat exchanger, because of the increased viscosity aids in the rotation of the oval gears.

The three flowmeters used in the fuel skid for the combustor test rig are shown in Figure 2-43. Performance of the fuel flowmeters is discussed in Chapter 3.

*Figure 2-43 Flowmeters used for combustor test rig fuel skid
Diesel turbine flowmeter (left), Oval gear flowmeter (center), Mass flowmeter (right)*

2.4 Hazards Analysis

For reasons relating to occupational health and safety, Environment Canada requires a Task Hazard Analysis (THA) to be completed for any projects that are conducted within their facility. A hazards analysis was done with the combustor test rig to identify any hazards that might be present to operators and also to devise actions that could mitigate these hazards. Table 2-18 summarizes some of the main concerns for the combustor test rig along with actions or solutions that were taken to resolve the identified/potential problems (risks). A more detailed hazards analysis is included in Appendix F.

Table 2-18 Summary of identified hazards and recommended actions

Hazard	Recommendations
Heat radiation (pipes and combustor)	Place heat shield around the combustor
	Label pipes 'HOT'
Hot air leaks (pipes and combustor)	Place gaskets in all joints
	Check piping for air-tightness before running the engine
	Place heat shield around the combustor
	Wear protective clothing if required to be near the pipes or combustor
Fire from combustor	Place heat shield around the combustor
	Stop fuel flow to combustor with solenoid
	Wear protective clothing if required to be near pipes or combustor
	Fire extinguisher will be placed near the combustor test rig
Mechanical failure	Engine room doors closed during engine tests
	No one in engine room while Allison engine is running
	Air piping is supported to prevent damage to engine from weight of pipes
Uncontrolled fuel ignition	Airflow will begin before fuel flow in the combustor test rig
	Airflow will stop after fuel flow in the combustor test rig
	Test combustor casing will be drained after every test
	Fuel will be stored safely away from the combustor test rig

2.5 Chapter Summary

A low-cost test rig was designed to operate in a mode representative of a gas turbine combustor by bleeding air from an Allison 250-C20B gas turbine, or at atmospheric conditions using an electric blower. The versatility of this test rig will allow testing with mixtures of two different liquid fuels.

As part of the design process, a bleed design was incorporated onto the compressor discharge air tube of the Allison gas turbine engine. Design of the air piping system

considered the system temperatures and pressures, as well as pressure losses, methods of flow control, thermal expansion, and material properties and compatibility with the test environment.

Many hardware components, such as pumps, valves, filters, mixers, and nozzles were researched for the fuel handling and delivery systems. Selection of these components required determination of fuel mass flow rates, knowledge of fuel properties, as well as theory relating to pressure losses and heat transfer.

Instrumentation of the test rig considered the collection and storage of data. Measurement of temperatures, pressures, and flow of both the air and fuel were also discussed. Finally, a task hazards analysis was done for the assembled combustor test rig at Environment Canada prior to conducting any testing.

3 COMBUSTOR TEST RIG PERFORMANCE

To demonstrate the functionality of this new gas turbine combustor test rig and form a basis for the evaluation of the design, it was decided to run a short series of tests. The testing was an opportunity to determine the strengths and weaknesses of the current configuration and to provide suggestions for future iterations of the design or optimization of the test rig performance.

Due to the number of new parts, it was decided to test individual subsystems where possible before attempting to run the entire test rig. Verification tests of the data acquisition system and instrumentation are discussed in Section 3.1 while a series of subsystem tests referred to as the Test Rig Shakedown are discussed in Section 3.2.

After verification of the functionality of the subsystems, a short series of ignition tests was conducted using diesel fuel to demonstrate the combustor test rig functionality with a ‘normal’ fuel. These tests are summarized in Section 3.3. Tests with biofuel had originally been planned, but were later set aside due to problems experienced during the ignitions tests with diesel. The chapter concludes with a summary of the combustor test rig.

3.1 Instrumentation Verification Tests

Verification of the data acquisition components of any test system is required in order to have a reasonable level of confidence in the data collected during a test. Basic tests were conducted on all instrumentation to demonstrate functionality of the measurement devices. The scope of the current work was focused mainly on the design and construction of the test rig therefore a detailed calibration to determine the accuracy of the measurements is left for future work with this test rig.

3.1.1 Data Collection System

The data recorded with the Keithley 2700 was verified by comparing the values recorded for temperature and pressure with other verification tests, which are discussed in Sections 3.1.2 and 3.1.3 respectively.

Using a laptop computer as the data storage device caused difficulties when connecting to the Keithley 2700. It typically took three or four attempts before communication was established between the two devices. Once established however, no further problems were encountered unless the connection was maintained for extended periods of time (over 2 hours).

Discussions with the Keithley supplier resulted in the recommendation to use a desktop computer for data collection and storage. Connecting the Keithley 2700 to a desktop computer through a PCI slot will allow the data channel to be assigned on computer start-up rather than when the GPIB card is inserted into its slot on the laptop. This hardware controlled channel assignment would reduce the problems with the computer attempts to locate the Keithley 2700. A desktop computer will also not heat up as much as a laptop. It is believed that the loss of communication over an extended time between the Keithley 2700 and the laptop is caused by the GPIB card overheating.

3.1.2 Thermocouples

Thermocouples from the air system were used to verify the functionality of both the thermocouples and the capability of the Keithley data acquisition system. The equipment used for these tests was an Omega model CLL22 thermocouple calibrator with a temperature range of 30°C-500°C as well as the front panel display of the Keithley 2700 and an Omega DP462 digital thermocouple display (Figure 3-1).

The verification method initially consisted of placing the thermocouples individually in the calibrator and recording the temperature shown on the Keithley display then on the Omega display. The purpose of the two readings was to enable a comparison between the values of each display. Results for this test are shown in Figure 3-2.

Figure 3-1 Equipment used for thermocouple verification at Environment Canada

Figure 3-2 Comparison of thermocouple readings with two display devices

The readings for both the Keithley and Omega displays were in good agreement with each other. The K-type thermocouple readings were also in good agreement with the set point on the thermocouple calibrator. The J-type thermocouple however was off by a large amount. Investigation into the settings with the Keithley display revealed that the front panel is capable of displaying temperature for only one thermocouple type at a time. Both the Omega display and the Keithley front display were configured for K-type thermocouples.

When the Integra Up&Running software is used however, it is possible to define the thermocouple type for each channel individually. Having determined good agreement between the Omega thermocouple calibrator, the Keithley unit, and the Omega display, it was decided to continue the remainder of the thermocouple verification tests (300°C – 500°C) with only the Keithley unit recording the temperatures using the Integra software. In addition, since the software was capable of taking all measurements simultaneously, all thermocouples were placed in the calibrating unit together. The setup for these tests is shown in Figure 3-3.

A comparison of the temperature readings based on measurement setting for the J-type thermocouple (#1) is shown in Figure 3-4. The measured results for this thermocouple are in good agreement with the set values in the calibrator when the J-type thermocouple setting is used. Figure 3-5 shows a comparison for all thermocouples along the calibrator range of 300°C to 500°C. Plotted points are an average of 60 seconds data measured for each thermocouple

Figure 3-3 Thermocouple verification test setup for computer recorded tests

Figure 3-4 Comparison of temperature readings based on thermocouple type setting

Figure 3-5 Results from averaging 60s of data from Integra software

3.1.3 Pressure Transducers

Two different models of pressure transducers are used in the combustor test rig and they are listed in Table 3-1. They operate similarly, but have different pressure ranges and output voltages. The verification that was performed with these transducers was mainly to demonstrate that the pressures calculated from the output voltages were in agreement with the actual pressure being measured.

Table 3-1 Pressure transducer ranges for pressure and output voltage

Transducer model	Fluid Measured	Pressure Range		Output Voltage V
		psig	kPa	
PX242A-G100V	Air	0 – 100	0-600	1 – 6
PX181-300G5V	Fuel	0 – 300	0-2068	1 - 5

The apparatus used for this determination was a water manometer. The one shown in Figure 3-6 has a pressure range of up to 16 inches of water (3.98 kPa). Measurements were taken for each two inches of pressure increase (498 Pa) in the manometer. Comparisons between the water level in the manometer and the results for the gauge pressure measured by the transducers are shown in Figures 3-7 and 3-8.

Figure 3-6 Water manometer at Carleton University

Figure 3-7 Comparison of pressure readings from a water manometer and a PX242A pressure transducer

Figure 3-8 Comparison of pressure readings from a water manometer and the PX181 pressure transducer

The main disadvantage with using a water manometer to measure pressures on the transducers is that its range is only a small fraction of what the transducer can measure. Based on the information collected, it is difficult to predict how much difference there will be between the two measurements at 100 psig (600 kPa) or 300 psig (2068 kPa). Figure 3-9 shows an extrapolated pressure difference for a 300 psig (2068 kPa) pressure transducer is 200kPa. As mentioned previously however, the aim of the exercise here is to verify the functionality of the components used for the combustor test rig fuel skid, and not to calibrate the measurement device. For future calibration of the pressure transducer over its entire range, another method must be used.

Figure 3-9 Extrapolation for a PX181 pressure transducer up to 300 psig (2068 kPa)

3.1.4 Fuel Flowmeters and Flow Control

The fuel skid for the combustor test rig contains three flowmeters connected in series: one in the diesel line (turbine flowmeter), the second upstream of the heat exchanger (oval gear flowmeter), and the third downstream of the heat exchanger and upstream of the fuel nozzle (mass flowmeter). Functionality testing of the flowmeters was conducted by comparing the results output from the three flowmeters connected in series.

A correlation done in Excel indicates good agreement between the oval gear flowmeter and the mass flowmeter results as shown in Figure 3-10. Readings have been converted into a mass flow rate. Results from the turbine flowmeter did not appear on its display. Verification of the flow range for the FTB-101 flowmeter supplied by Environment Canada revealed that the linear flow range was 0.35-3.5 gpm (79.5-795 L/hr) [47]. Converting the required diesel flow through fuel nozzle from 0.011 kg/s to a volume flow rate reveals that it is only 48 L/hr indicating that fuel flow for this application is too low for the flowmeter. To get a data reading of the diesel flow at this location, the flowmeter will need to be replaced with one that has a lower measurement range.

Figure 3-10 Allison nozzle mass flow vs. needle valve position

In Figure 3.10 the variation in fuel flow for a given number of valve turns is also shown. From the figure, less than $\frac{1}{4}$ of a turn of the valve is required to reach the maximum desired diesel flow (0.011 kg/s), while the valve is capable of $3\frac{1}{4}$ turns before it reaches the fully open position. The results suggest that the valve does not provide enough control over the flow. In addition, since the valve rotation is manually controlled, it is difficult to reach the desired position consistently. A smaller, electrically actuated flow control valve should be considered for future use with this test rig.

3.1.5 Airflow Control and Measurement

To have an idea of the amount of airflow in the system at various butterfly valve positions, a series of tests was conducted with the atmospheric blower to measure the flow rate at each of the ten available positions. Pressure measurements were taken for thirty seconds at every position and then averaged and used in Equation 2.29. Results are shown in Figure 3-11.

Figure 3-11 Atmospheric blower mass flow vs. butterfly valve position

The chart in Figure 3-11 shows no mass flow for butterfly valve positions up to 20 degrees open. There are two possible explanations for this result: the seal on the valve has not opened yet, or extra turbulence in the flow from a partially open butterfly valve

too close to the averaging Pitot tube. To mitigate this second problem, it is suggested that the Pitot be moved further upstream of the butterfly valve. Another option is to avoid running the combustor test rig with the butterfly valve open less than 30%. For high-pressure tests that bleed air from the Allison 250 gas turbine engine, an orifice plate can be used downstream of the combustor to provide control for the flow.

To verify that the air velocity calculated from the Pitot tube measurements was representative of the actual air velocity, a test was run at Carleton University with the averaging Pitot placed in front of a blower that also records air speed. The set-up is shown in Figure 3-12. Due to the configuration of the blower, only one static pressure port and one stagnation pressure port on the averaging Pitot tube were used. The remaining pressure ports were blocked.

Comparisons of air velocities measured by the blower system and by the averaging Pitot tube appear to be in relatively good agreement (Figure 3-13). Deviations between the two measurement systems may be the result of a small deviation in the Pitot alignment with the blower.

Figure 3-12 Averaging Pitot test set-up at Carleton

Figure 3-13 Comparison of air velocity measurements using the blower at Carleton and the data from the averaging Pitot tube

3.2 Combustor Test Rig Shakedown

The 'shakedown' of the combustor test rig was a series of small tests to verify the functionality of parts of the rig by subsystem before attempting to run tests with the whole system. It also provided the opportunity to fine tune the testing procedure.

3.2.1 High-Pressure Air Bleed Test

The combustor test rig was designed to bleed air from the compressor discharge of an Allison 250-C20B gas turbine engine. This test was to determine the effects of pressurizing the combustor test rig air pipes during the Allison 250 engine start-up and to determine the quantity of air that it was possible to safely bleed from the Allison 250 engine without causing the ITT to exceed its recommended limit of 810°C [25].

Prior to bleeding air from the compressor discharge air tube of the Allison 250 engine, the air bleed chamber was installed and capped. This was to verify that the engine setup was functional before attempting to bleed air for the combustor test rig. This test was successful.

Once normal engine operation of the engine was demonstrated with the modified compressor discharge air tube, the Allison 250 engine was shut down and the air bleed pipes were connected to the pipe section protruding from the top of the air bleed chamber. A second test was run with the butterfly valve fully closed to determine if there

were any detrimental effects to the Allison 250 gas turbine caused by pressurizing the combustor test rig air pipes during start-up.

Results from the first test of this type indicated that the engine was losing too much air in the bleed pipes to reach operational speed. The original butterfly valve was identified as a significant cause of air leakage and was replaced by a smaller one with a better seal. An orifice plate was also introduced downstream of the test combustor to assist in the generation of backpressure in the test system.

To reduce the amount of gas turbine engine time required to demonstrate system functionality, an adaptor was placed in the cap for the bleed chamber that allowed a hose of shop air to be attached and pressurize the closed pipe. This also provided the opportunity to check the pipe joints in the engine room as well as the air-tightness of the seal around the bleed attachment since the engine test cell was empty during engine operation. All flanged joints were determined to be airtight and no flow was observed past the new butterfly valve in the closed position with this method.

Due to the potential for small misalignments where the bleed pipe clamps to the bleed chamber, a small leak may exist but it is not possible to test unless the Allison engine is running. An o-ring is currently used to create a seal between the mating surfaces. In the future, a small flexible section should be considered for placement where the bleed pipe connects to the bleed chamber as this would facilitate alignment of the two parts and reduce the risk of unintentionally loading the compressor discharge air tube.

The second bleed test from the Allison 250 gas turbine was conducted using the new butterfly valve and the 1.5-inch (38.1mm) diameter orifice plate. The larger plate was selected to allow a better determination of how wide the butterfly valve could open while at the same time providing some restriction in the flow downstream of the combustor.

The procedure for bleeding air was determined through a trial and error process. A stable operating point was achieved by stabilizing the Allison 250 engine at 70% gas generator (N1) speed prior to opening the butterfly valve. The butterfly valve was opened to 20% before increasing the N1 speed to 85%. This resulted in a stable operating point with an inter-turbine temperature of 785°C. Pressure and temperature measurements taken from this test are shown in Figures 3-14 and 3-15 respectively. An average air mass flow rate of 0.58 kg/s was calculated over the period of constant pressure (75-225 s). This is just slightly over the air mass flow rate of 0.5 kg/s that was assumed during design of the combustor test rig.

For future tests involving high pressure from the Allison 250 engine, it is recommended that the smaller orifice plate be used. The should allow opening of the butterfly valve past 20 % and reduce the magnitude of the pressure drop currently experienced across the butterfly valve seen in Figure 3-14.

Figure 3-14 Air pressures for the high-pressure bleed test from the Allison 250 gas turbine engine

Figure 3-15 Air temperatures for the high-pressure bleed test from the Allison 250 gas turbine engine

The cause for the large difference between the combustor inlet and outlet temperatures is unknown. Based on results from the thermocouple verification tests in Section 3.1.2, the temperature readings should be in close agreement to the air temperature. Variations between the measured air temperatures between the combustor inlet and exhaust could be due to the thermocouples not being at steady state. Four minutes (240 seconds) after the butterfly valve is opened to bleed compressed air from the Allison engine, the thermocouples are still showing an increase in temperature. If the bleed test had run longer, perhaps a steady-state temperature would have been reached where the difference between the temperature readings would not have been as large. Placement of a thermocouple upstream of the butterfly valve would also give an indication of the temperature of the air bled from the compressor.

In addition to the thermocouples not reaching a steady state, the difference in temperature could be partly attributed to the presence of the orifice plate upstream of the exhaust thermocouples. Since the exhaust thermocouples are at atmospheric pressure and the thermocouple upstream of the test combustor is at a slightly higher pressure, the expansion of the airflow from a higher-pressure environment to a lower-pressure could explain the drop in temperature.

3.2.2 Fuel Subsystem

As part of the preliminary testing of the fuel system, water was pumped through the fuel line at pressures up to 300 psi (2068 kPa) to ensure that all joints in the fuel system were leak-free. The advantage to using water for this kind of test is that it is easily available, and does not pose any safety hazards if spilled.

In addition to verifying that the fuel system was leak-free, two tests were conducted. The first pumped water with the biofuel pump through the fuel line and the second test used the diesel pump. Water pressures were recorded at the pump outlets (just downstream of the pressure regulating valve) and just upstream of the fuel nozzle. The L40 nozzle was used and fuel was sprayed into an empty barrel.

Since the real-time graphing of the data acquisition system plots only the signal from the measurement device, it was decided to adjust the pressure regulators until the output voltage from the pressure transducers read approximately 3 V (equivalent to 1034 kPa). The data was then reduced to the results shown in Figure 3-16 for the biofuel pump and Figure 3-17 for the diesel pump to observe the magnitude of the pressure drop between pump delivery and the fuel nozzle. As was expected from Table 2-11, the pressure drop between the pump outlet and the fuel nozzle was low.

Figure 3-16 Pressure measurements of water pumped through the biofuel pump to the L40 nozzle

Figure 3-17 Pressure measurements of water pumped through the diesel pump to the L40 nozzle

Figure 3-16 shows various pressure settings where steady state was achieved with the biofuel pump. The supply lines into the diesel pump were longer however, so the pump

had difficulty pressurizing the water. The steady increase in pressure shown in Figure 3-17 is due to the gradual opening of the pressure-regulating valve until it was 100% open (approximately 180 seconds). The fuel system pressure then remained at around 1000 kPa with pressure fluctuations.

Figure 3-18 shows the increased delivery pressure from the diesel pump when a low-pressure priming pump was supplied by Environment Canada to assist in fuel delivery. The priming pump was used to supply diesel fuel once the water was purged from the fuel pipes and diesel fuel was introduced. Pressure measurements shown are for one of the flowmeter tests where each step in pressure corresponds to a fuel mass flow rate in kg/s.

Figure 3-18 Diesel pressures and mass flow rates with a priming pump to supply the diesel fuel

During verification of the fuel subsystem with water, pressure and flow regulation tests with the various nozzles were also conducted. Based on visual data of water spraying from the nozzles at atmospheric pressure (Figure 3-19), the Allison nozzle appeared to perform best since it had the finest spray pattern. The air-atomizing nozzle performed the worst, due to difficulties in getting enough air pressure from the atmospheric blower to assist with atomization. The poor atomization may also be due to the size of the nozzle, which was selected based on the flow rate and viscosity required for biofuel. The lower viscosity and flow rate required for diesel would likely result in the spray pattern shown which would cause damage to downstream components. Since biofuel combustion requires initial ignition with diesel fuel, it was decided to not use this nozzle for testing. The L40 and L48 spray patterns were similar, therefore only the L48 nozzle was shown.

*Figure 3-19 Three nozzle water spray patterns at atmospheric pressure
Allison nozzle (left), L48 nozzle (middle), air atomizing nozzle (right).*

3.3 Ignition Testing

Ignition testing was done in the combustor test rig with diesel fuel to demonstrate its functionality. Due to the discovery of a cracked shaft in the Allison engine oil pump assembly (shown Figure 3-20); high-pressure ignition tests were not conducted with the Allison 250 gas turbine engine. Repairs to the Allison 250 gas turbine are underway at the time of this writing, and were not completed early enough for inclusion of high-pressure combustion tests as part of this project. To avoid potential damage to the Allison 250 gas turbine engine, only blower-supplied air was used to conduct ignition tests in the combustor test rig.

Figure 3-20 Cracked gear shaft of oil pump assembly

3.3.1 Ignition Testing Procedure

Ignition tests with the combustor test rig and the atmospheric blower were conducted according to the following procedures.

Start-up

- 1) The fuel drain plug in the test combustor casing was removed to ensure that no fuel had accumulated in the test combustor. Once fuel was drained the plug was replaced in the casing.
- 2) Power is supplied to the data acquisition system. This includes the computer, the Keithley data acquisition system, the flowmeters, and power supplies. A short data collection test was usually run to ensure that all signals from the pressure transducers and thermocouples were being received by the system before starting data collection for a test.

With the software used, up to eight traces could be plotted as data was collected. The data plotted is summarized in Table 3-2.

Table 3-2 Data trace summary

Trace	Data Type	Axis	Range	Measurement Point	Channel
1	Fuel Pressure	Y1	0-5 V	Diesel pump outlet	25
2				Biofuel pump outlet	26
3				Upstream of nozzle	29
4	Air Temperature	Y2	0-1000°C	Upstream of test combustor	1
5				Exhaust	2
6					3
7					4
8					5

- 3) The butterfly valve was opened fully.
- 4) The exhaust vent and fan in the Allison 250 test cell were opened and started.
- 5) The igniter was started.
- 6) The fuel pumps were started (priming pump and diesel pump).
- 7) Solenoid valves were opened.
- 8) Fuel flow was adjusted as required to achieve combustion and recorded.
- 9) For tests with combustion, the igniter is stopped once a flame has been established in the combustor.
- 10) For tests where ignition was not achieved within 45-60 seconds of opening the solenoid valves, the igniter was stopped then the shutdown procedure was followed.

Shutdown

- 1) The solenoid valves are closed.
- 2) The fuel pumps are turned off.
- 3) The blower is turned off.
- 4) The butterfly valve is closed.

3.3.2 Ignition Test Results

Initial tests were conducted using the Allison fuel nozzle since it had the best spray pattern of the available nozzles. Several tests were run with this nozzle, and a number of fuel flow rates were attempted during each test. A comparison of the fuel flow rate to the measured exhaust gas temperature is shown in Figure 3-21.

Figure 3-21 Comparison of fuel flow rate to combustion temperature for diesel fuel through the Allison nozzle

There is a significant temperature difference between the four exhaust thermocouple measurements. Since the thermocouple readings were shown to be in good agreement with a calibrated source in Section 3.1.2, the differences in readings suggest that the flow

is not uniform. A characterization of the flow in the exhaust will need to be done in the future.

The second fuel nozzle tested was the L40 nozzle, because it had the second best spray pattern. Several tests were attempted, but ignition was not achieved as easily as for the Allison nozzle. It was noted during these tests that the excess fuel was not accumulating in the bottom of the combustor casing during failed ignition attempts, but rather being blown down the exhaust pipe. To avoid hazards associated with uncontrolled combustion of fuel, the Allison nozzle was used to combust any accumulated fuel in the exhaust pipe before reattempting ignition with the L40 nozzle.

Analysis of the data suggests that the difficulty in igniting fuels with the L40 nozzle may be due to insufficient pressure at the fuel nozzle. Figures 3-22 to 3-24 show an ignition test with the Allison nozzle, as well as two ignition attempts with the L40 nozzle. One of the L40 attempts was not successful, while the other test had ignition that was not sustained because it occurred after the shutdown procedure had been initiated.

Figure 3-22 Allison nozzle ignition test

Figure 3-23 Unsuccessful L40 nozzle ignition test

Figure 3-24 L40 test with unsustained combustion

The successful ignition test with the Allison nozzle in Figure 3-22 shows the increase in fuel pressure just prior to ignition. Testing with the L40 nozzle however, revealed that too much time is required for the pressure to build up sufficiently in the nozzle for ignition. In Figure 3-24, ignition occurred soon after an increase in fuel pressure at the nozzle to 140 kPa, but the flame was not sustained since the system was in the process of being shut down when ignition occurred. In addition, when ignition did occur a loud noise was heard from the exhaust stack in the Allison 250 test cell, which suggests that backfire occurred in the system. It is believed that the fuel droplets were being blown past the vertical section of the exhaust pipe and were building up in the collector that is shared with the exhaust from the Allison 250 gas turbine engine.

3.4 Summary

The objective of this thesis project was to design and build a modular gas turbine combustor test rig capable of performing a variety of tests under both atmospheric and high-pressure conditions. A short series of tests designed to demonstrate functionality of this test rig indicate that it is capable of delivering diesel fuel into a gas turbine combustor where it is atomized and combusted in the same fashion it would be in an actual gas turbine engine.

Ignition testing with the gas turbine combustor test rig was conducted using diesel fuel and air provided by an atmospheric blower. Various nozzles were considered as part of the preliminary design of the gas turbine combustor test rig: an Allison nozzle, two pressure atomizing nozzles of different sizes (L40 and L48), and an air-atomizing nozzle (XAAD). The Allison nozzle was successfully used for several ignition tests at various fuel flow rates.

Although no successful combustion tests were conducted with the remaining nozzles, valuable information was still obtained. With the XAAD air-atomizing nozzle, a high-pressure water test showed that the expected spray pattern with a lower viscosity fluid was not suited to creating the fine mist required for combustion in a gas turbine combustor environment. Ignition attempts with the L40 nozzle led to many recommendations for improvement of the design of the combustor test rig with respect to fuel handling and safety.

Although high-pressure combustion tests could not be conducted due a cracked shaft in the oil pump assembly of the Allison 250 gas turbine engine, a brief test was conducted to determine whether air could be safely bled from the Allison engine. These tests were successful in demonstrating that the predicted 0.5 kg/s of compressed air could be used by the combustor test rig without risking damage to the Allison engine.

The fuel skid design for the combustor test rig included consideration of requirements for “poor” quality fuel. A separate fuel pump and control valves were included in the fuel skid to permit mixtures of these fuels with diesel for testing purposes. In addition, materials selected for the fuel system were chosen to be compatible with a sample “poor” fuel: biofuel. A heat exchanger to preheat fuel and reduce its viscosity to aid in fuel atomization inside the test combustor was also included in the design.

The gas turbine combustor test rig data acquisition system is currently capable of monitoring pressure, temperature, and flow of both air and fuel. These measurement devices have been tested for functionality as part of this project, and several channels are still available to include additional measurements.

In keeping with the requirement for a low-cost system, most of the components used to construct the gas turbine combustor test rig are commercially available, off-the-shelf components. Components for assemblies such as the air pipes, heat exchanger coils, and support stands were purchased from vendors and then assembled at Carleton University. Exceptions to the use of off-the-shelf components include the adaptors used to integrate

the L40, L48, and XAAD nozzles into the test combustor, and the Hastelloy cone which were custom-made.

A modular approach was also used when designing and assembling the gas turbine combustor test rig. The system can currently use compressed air from the Allison 250 engine, or atmospheric air from an electric blower. The assembly of the air pipes is another example of where the modular approach of the system can be applied. Since pipe sections are bolted together at intervals, only the individual sections of pipe need to be removed. For example, for CFD validation tests, the pipes could remain in their configuration, with the possible addition of pressure and temperature measurement devices. For a materials durability test to be conducted however, a portion of the current exhaust piping would be removed and replaced with another pipe designed to hold material test coupons.

4 RECOMMENDATIONS AND CONCLUSIONS

4.1 Rationale for Design Changes

Due to the backfire incident, Environment Canada has placed all combustion testing with the combustor test rig on hold. While no one was injured and no damage was done to any equipment during this particular ignition test, the risk of backfire from the system is a hazard that needs to be addressed before testing can resume. At the time of this writing, steps were being taken by Environment Canada staff to install a separate stack for the combustor test rig, rather than sharing the exhaust collector and stack with the Allison engine.

The design of the fuel handling system for the combustor test rig is also being evaluated. Proposed changes include placing a solenoid valve closer to the fuel nozzle. This would provide a faster shut-off for fuel and also permit the fuel to be fully pressurized before it reaches the nozzle.

It has also been decided to move the control and data acquisition systems for the combustor test rig to the Allison 250 control room to increase the safety of the test rig operators. To implement this design change, electric actuators will be needed for various valves such as the fuel flow control valves and the butterfly valve. Relays will also need to be introduced for control of the power to the pumps, power supplies, igniter, etc. A

system for remote flowmeter data collection will also be required. This could be done by mounting a camera near the display to transmit the information to the control room, or by increasing the length of the signal wires between the meters and their displays so that the displays can be placed in the control room.

While these changes are being made to the fuel skid, it is also recommended to replace all wooden structures with metal to reduce the fire hazard near the gas turbine combustor test rig.

4.2 Recommendations

During the assembly and preliminary testing of the gas turbine combustor test rig, several recommendations were suggested. These are listed here:

- Implementation of an electric actuator for the butterfly valve. This will enable increased control over the airflow compared to the ten discrete positions offered by the manual lever control. It will also increase user safety during test rig operation since it can be remotely actuated.
- Implementation of a flexible section for attachment of the bleed pipes to the Allison engine. This would make alignment of the air pipes with the bleed chamber easier, and reduce the risk of unintentional loading of the bleed chamber and compressor discharge air tube by the piping.

- A specimen holder and test area should be designed for the gas turbine combustor test rig. The exhaust piping can be shortened to accommodate extra combustor length if required.
- Nozzles designed for lower fuel flow rates and viscosities should be considered.
- Implementation of smaller, electrically actuated fuel control valves. Smaller valves will give more control over the fuel flow. Electrically actuated valves will allow remote operation of the fuel flow and also provide a repeatable valve position that can be correlated to fuel flow rate.
- Implementation of a normally closed solenoid valve placed in the fuel system just upstream of the fuel nozzle. This will allow a quicker fuel shut-off to the test combustor, prevent leaks from the fuel system when nozzles are changed, and permit pressurization of the fuel line up to the nozzle, thus reducing the amount of fuel accumulating in the exhaust pipe.
- Replacement of wooden structures in the fuel skid with metal or some other non-flammable material.

- The laptop should be replaced with a desktop computer for data storage. This should solve the communications issues between the Keithley data acquisition system and the storage device.
- Implementation of a system for remote flowmeter data collection to transmit the information to the control room.
- A thermocouple should be placed upstream of the butterfly valve in order to get a measurement of the temperature of the compressed air before the butterfly valve is opened.
- The placement of the averaging Pitot tube relative to the butterfly valve should be revisited to determine the location with the best flow characteristics for Pitot measurements.

4.3 Conclusions

With respect to the specifications outlined in Section 2.1, as well as the results discussed in Chapter 3, the following conclusions can be drawn for the gas turbine combustor test rig:

- High-pressure air can be safely bled from the Allison 250 gas turbine engine for use in the gas turbine combustor test rig.
- Atmospheric air can be used to run preliminary tests with the gas turbine combustor test rig.
- The gas turbine combustor test rig is capable of initiating and sustaining combustion in an atmospheric environment using diesel fuel.
- Optimization of the fuel system is required to improve fuel delivery pressure at the fuel nozzle.
- Modifications of the gas turbine combustor test rig are needed to increase safety while the test rig is in operation.
- The gas turbine combustor test rig has the potential to be a valuable tool for research relating to gas turbine combustion both for conventional and alternative fuels.

5 REFERENCES

- 1) A.H. Lefebvre, *Gas Turbine Combustion*, Second Edition; Taylor & Francis, 1999.
- 2) J. Sills (2002), *Global Warming*, Date accessed: January 20, 2004. <http://www.fabianglobalforum.net/knowledge/article009.html>
- 3) U.S. Environmental Protection Agency, Office of Atmospheric Programs (2002), *Greenhouse Gases and Global Warming Potential Values, Excerpt from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000*, Accessed Jan. 20, 2004. [http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/SHSU5BUM9T/\\$File/ghg_gwp.pdf](http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/SHSU5BUM9T/$File/ghg_gwp.pdf).
- 4) CanREN (2000), *Renewable Energy in Action*, Natural Resources Canada, Date accessed: Feb. 26, 2004. http://www.canren.gc.ca/renew_ene/index.asp
- 5) Ontario Power Generation (2003), *Green Power – Frequently Asked Questions*, Date accessed: July 19, 2004. http://www.opg.com/envComm/E_greenPower_FAQs.asp
- 6) CanREN (2000), *Technologies and Applications*, Natural Resources Canada, Date accessed: Feb. 26, 2004. http://www.canren.gc.ca/renew_ene/index.asp
- 7) CanREN (2000), *Resource Assessment*, Natural Resources Canada, Date accessed: Feb. 26, 2004. http://www.canren.gc.ca/resou_asse/index.asp
- 8) Merriam-Webster (2003), “Biomass”, *Merriam-Webster Online Dictionary*, Date accessed: July 30, 2003. <http://www.m-w.com/cgi-bin/dictionary?book=Dictionary&va=biomass>
- 9) R.G. Andrews, D. Fuleki, S. Zukowski, P.C. Patnaik, “Results of Industrial Gas Turbine Tests Using a Biomass-Derived Fuel”, in *Proceedings of the Third Biomass Conference of the Americas: Making a Business from Biomass in Energy, Environment, Chemicals, Fibers and Materials*, Volume 1, 1997. Pages 425-435.
- 10) K. Morris, R. Thamburaj, “Small Gas Turbines: Fuelling the Future”, *Power Engineering International*, V. 8, N. 7, 2000. Page 31.
- 11) Advanced Materials and Energy Systems, *Frequently Asked Questions About the Use of Pyrolysis Oil (Biofuel) for Gas Turbine Operation*, Orenda Aerospace Corporation, 2003.
- 12) V. de Biasi, “Alfalfa-Fuel 75 MW Plant on Track for 2002 Operation”, *Gas Turbine World*, V. 28, N. 4, 1998. Pages 26-30.

- 13) Anonymous, *Technology of Biomass Gasification*, Combustion, Gasification and Propulsion Laboratory, Department of Aerospace Engineering, Indian Institute of Science, Date accessed: August 13, 2003. <http://cgpl.iisc.ernet.in/np2.pdf>.
- 14) DynaMotive, *BioOil Technology*, DynaMotive, Date accessed: May 25, 2003. <http://www.dynamotive.com/biooil/technology.html>.
- 15) Magellan Repair, Overhaul, and Industrial (2004), *AMES – Biofuel*, Magellan Aerospace Corporation, Date accessed: July 19, 2004. http://www.magellanroi.com/AMES/AMES_Biofuel/ames_biofuel.html.
- 16) H.S. Mukunda, *100% of Energy from Renewables – Is this an Achievable Goal or an Improbable Slogan?*, Combustion, Gasification and Propulsion Laboratory, Department of Aerospace Engineering, Indian Institute of Science, Date accessed: August 13, 2003. http://cgpl.iisc.ernet.in/hsm_paper7.pdf.
- 17) Anonymous, *A Techno-Economic Comparison of Liquid Fuels from Biomass*, Combustion, Gasification and Propulsion Laboratory, Department of Aerospace Engineering, Indian Institute of Science, Date accessed: August 11, 2003. http://cgpl.iisc.ernet.in/liq_fuels_biomass.html.
- 18) R.G. Andrews, D. Fuleki, S. Zukowski, P.C. Patnaik, “Feasibility of Firing an Industrial Gas Turbine Using a Biomass-Derived Fuel”, presented at the Developments in Thermochemical Biomass Conversion conference in Banff, Alberta, May 20-24, 1996.
- 19) A. Wiese, E. Von Hermann, M. Drosch, “Will the Biomass Market Outgrow its Fuel Supply?”, *Modern Power Systems*, September 2003, p. 34-36.
- 20) T. Lederlin, *A Model of Bio-Oil Evaporation for Combustion Simulation*, Thesis (M. App. Sc.), Carleton University, 2003.
- 21) F. Gao, *Development of Protective Coatings for Biofuel-Powered OGT 2500 Gas Turbine Engine*, Thesis (M. App. Sc.), Carleton University, 2003.
- 22) J.E.D. Gauthier, *Course Notes for Gas Turbine Combustion*, 2002.
- 23) S.R. Turns, *An Introduction to Combustion: Concepts and Applications*, Second Edition, McGraw-Hill, 2000.
- 24) A.K. Gupta, T. Terada, P.C. Patnaik, J.P. Immarigeon, “Evaluation of High Temperature Protective Coatings for Gas Turbine Engines Under Simulated Service Conditions”, in *High Temperature Surface Interactions*, AGARD conference proceedings No. 461, 1989.

- 25) Allison Engine Company, *250-C20 Series Operation and Maintenance Manual*, Sixth Edition, Third Revision, July 15, 1999.
- 26) Rolls-Royce (2002), *Model 250 Fact Sheet*, Rolls-Royce Corporation, Date accessed: May 31, 2004,
http://www.rolls-royce.com/civil_aerospace/downloads/helicopters/model250.pdf.
- 27) Avon Aero (2000), Allison Model T63-A-700 (250-c18) Gas Turbine Engine, Avon Aero Supply, Inc., Date accessed: July 13, 2004.
<http://www.avonaero.com/allison.htm>
- 28) F.M. White, *Fluid Mechanics*, Third Edition; McGraw-Hill, 1994.
- 29) Check-All (2003), *Technical Data*, Check-All Valve Manufacturing Company, Date accessed: May 11, 2004.
<http://www.checkall.com/PDF%20files/technical%20data.pdf>
- 30) Jamesbury Bulletin W101-6 (2003), *Series 815 ANSI Class 150 and Series 830 ANSI Class 300 Wafer-Sphere ® High Performance Butterfly Valves*, Metso Automation, Date accessed: May 12, 2004.
<http://www.jamesbury.com/public/publicdocs/Docs/Bulletin%20W101-6%2011-03.pdf>
- 31) W. Ulanski, *Valve and Actuator Technology*, McGraw-Hill, Inc., 1991. Page 89.
- 32) Metal Supermarkets (2001), "Product: Stainless Steel, Shape: Stainless Steel Pipe, Grade: Seamless and Welded Schedule 10", *Metal Supermarkets Catalogue*, Date accessed: July 11, 2003.
<http://www.metalsupermarkets.com/cust/default.htm?PageType=Product>
- 33) CCTF, "Forged Stainless Steel Flanges", in *Pipe Fittings & Flanges* catalogue.
- 34) CCTF, "Stainless Steel Welding Fittings", in *Pipe Fittings & Flanges* catalogue.
- 35) P.P. Benham, R.J. Crawford, C.G. Armstrong, *Mechanics of Engineering Materials*, Second Edition; Longman, Harlow, Essex, England, 1996. Page 70.
- 36) J.P. Holman, *Heat Transfer*, Eighth Edition, McGraw-Hill, 1997.
- 37) Hydra-Cell Pumps, "Selection Guide for Diaphragm Pumps", Wanner Engineering, Date accessed: May 17, 2004. <http://web2share.net/action.lasso?-database=wan&-response=wan%2fds%2fWA000/WA0002c.lasso&-layout=web000&-search&pcode=1152>
- 38) Valve Manufacturer's Association of America, "Multi-Turn Valves or Linear Motion Valves", *Valves and Actuators Online*, Date accessed: May 20, 2004.
http://www.vma.org/multi_turn_valves_or_linear_motion_valves.html

- 39) Valve Manufacturer's Association of America, "Self-Actuated Valves", *Valves and Actuators Online*, Date accessed: May 20, 2004.
http://www.vma.org/self_actuated_valves.html
- 40) Shelco Filters, "Mesh – Inch – Micron Conversion Chart", *Units of Measurement Equivalents*, Shelco Filters, Date accessed: May 20, 2004.
http://www.shelco.com/HTML/units_equivalents.htm
- 41) Online Pipe, *Standard Fitting Types: Screwed/Threaded Fittings*, Bakersfield Pipe & Supply, Date accessed: June 3, 2004. <http://www.onlinepipe.com/thdfittings.html>
- 42) Jos. Le Bel (2003), "Products: Drums: Steel Drums: New, Open Top, 45 Gal", Les Contenants Jos. Le Bel Containers, Date accessed, June 3, 2004.
http://www.joslebel.com/indiv_product_info.php?id=50&catid=8
- 43) Keithley Instruments (2003), *Integra Series: Technical Data*, Keithley Instruments, Inc., Date accessed: June 1, 2004.
<http://www.keithley.com/servlet/Data?id=9951&jsession=946971090269216291>
- 44) Omega Engineering, *The Temperature Measurement Handbook and Encyclopedia*, Volume MM, 2000.
- 45) Omega Engineering, *The Pressure, Strain and Force Measurement Handbook and Encyclopedia*, Volume MM, 2000.
- 46) Anonymous, *Installation Instructions for Pitot Tubes*, KFlow Meters Inc., St. Laurent, Quebec, Canada.
- 47) Omega Engineering, *The Flow and Level Measurement Handbook and Encyclopedia*, Volume MM, 2000.
- 48) Cross Instrumentation (2002), *A Flow Measurement Primer – Oval Gear Meters*, Cross Instrumentation, Date accessed: May 21, 2004.
http://www.crossinstrumentation.com/ga/mfg/Flow/ovalgear_meters.htm.

APPENDIX A:
**FREQUENTLY ASKED QUESTIONS ABOUT THE USE OF
PYROLYSIS OIL (BIOFUEL) FOR GAS TURBINE OPERATION**

What terms are used to describe pyrolysis oil?

Pyrolyzed biomass converted to a liquid product can be referred to as: Pyrolysis Oil, Bio-Oil, Bio-Crude, Liquid Wood, Wood Tar or Biofuel. Orenda uses the term Biofuel.

What is biofuel and how does a biomass feedstock gets converted to liquid?

Biofuel is a combustible liquid produced from biomass through a process called pyrolysis. The complex structures of the biomass feedstocks (lignin, cellulose and hemicellulose) are broken into useful fuel or chemical “building blocks” by intense thermal action achieved by very rapid heating and a short (fraction of a second) processing time. This chemical process involves division of the large molecules and their reformation. In the biomass community, this is better known as “fast pyrolysis”. In the petroleum industry this is usually called “rapid cracking”. Rapid cooling then preserves the initial decomposition products. This prevents the valuable components from degrading into non-reactive or low value residues. Maximum liquid yields are obtained at high heating rates, at reaction temperatures around 500°C and with short vapour residence times to minimize secondary reactions. Most biomass forms give maximum liquid yields of up to 80% (wt%) on a dry feedstock basis at reactor temperatures of 500-520°C with vapour residence times not more than 1 second. Very short residence times can result in incomplete depolymerization of the lignin macromolecule resulting in a less homogeneous liquid product. Alternatively, longer residence times can cause secondary cracking of the primary products, reducing yield and adversely affecting the properties of the biofuel. The process parameters are therefore adjusted to provide the best balance of heating rate, maximum temperature, residence time and cooling rate to ensure acceptable fuel properties are attained.

What types of pyrolysis processes are there?

The generic method by which pyrolysis occurs is described above, but there are many different ways by which this can be achieved. Below is a table providing some examples of various pyrolysis systems (both fast and slow) that exist.

PYROLYSIS REACTORS, HEATING METHODS AND HEATING RATES

Reactor Type	Method of Heating	Heat Transfer	Heating Rate	Organization
Canadian				
Transported bed (Commercial)	Hot sand	Direct	High	Ensyn
Vacuum (Commercial)	Molten Salt	Indirect	High	Pyrovac
Fluid bed (commercial planned)	Heated recycle gas	Indirect	High	Dynamotive
Ablative plate (Commercial)	Wall heating	Indirect	High	Enervision
Multiple hearth (research scale)	Hearth heating	Direct	Low	U. Laval
International				
Ablative cone	Wall and sand heating	Indirect	High	U. Twente
Ablative mill	Wall (disc) heating	Indirect	High	CSM
Ablative plate	Wall heating	Indirect	High	U. Aston, U. Nancy
Ablative vortex	Wall heating	Indirect	High	NREL, Interchem
Auger kiln	Wall heating	Indirect		U. Tubingen, WTC
Circ. fluid bed	Partial gasification	Direct	High	CRES
Entrained flow	Combustion products	Direct	High	Egemin, GTRI
Fixed bed	Combustion products	Direct	Low	Bio-Alternative
	Partial gasification	Direct	Low	Alten
Fluid bed	Heated recycle gas	Direct	Low	CPERI, U. Leeds, INETI, NREL, U. Aston, Union Fenosa, U. Waterloo
	Partial gasification	Direct	High	U. Sassari Worthing
	Fire tubes	Indirect		Alten, MTCI
Horizontal bed	Fire tubes	Direct	Low	Pyrosol
Rotary Kiln	Wall Heating	Indirect	Low	Deutsche Babcock, KWU, PKA, Stenau
Stirred bed	Partial Gasification	Direct	High	Alten

What are the outputs of the pyrolysis reactor?

The products from a reactor vary on the type of pyrolysis process used and the feedstock. However, in general there are three combustible by-products. Their yield normalized with respect to the feedstock (typically dried to 10-15 wt% moisture) input are: liquid pyrolysis oil 60-75 wt%, solid charcoal 10-25 wt% and non-condensable pyrolysis gases 5-15 wt%.

How much feedstock is required to run the OGT2500 engine?

For a combined cycle installation (3 OGT2500 turbines) generating 15 MW of electrical power, approximately 200 tonnes/day (@15% moisture) of feedstock would be required. This provides an order of magnitude number, however, the actual requirement will vary depending on factors such as feedstock heating value and reactor yields.

What type of feedstocks could be used?

In general, any biomass containing lignin, cellulose or hemi-cellulose can be pyrolyzed. Below is a list of various feedstocks that have been pyrolyzed.

- a) Wood and wood residues (including hardwood, softwood and bark),
- b) Sugar cane residuals (e.g. bagasse and cane trash),
- c) Straw and grasses,
- d) Rice Husks,
- e) Palm, peanut and coconut shells,
- f) Crude oil,
- g) Heavy oils,
- h) Asphalt and bitumen,
- i) Heavy distillates from petroleum refining,
- j) Tire crumb,
- k) Waste paper and,
- l) Sludges

What are typical biofuel properties and how do they compare with diesel fuel?

Parameter	Units	Bio-Fuel	Diesel
<i>Net Calorific Value</i>	<i>MJ/kg</i>	<i>18-22</i>	<i>42.0</i>
<i>Flash Point</i>	<i>°C</i>	<i>60-90</i>	<i>35-60</i>
<i>Viscosity (60 °C)</i>	<i>cSt</i>	<i>33-76</i>	<i>6.0</i>
<i>Moisture</i>	<i>wt%</i>	<i>15-30</i>	<i>0</i>
<i>Density (25° C)</i>	<i>g/ml</i>	<i>1.1-1.2</i>	<i>0.84</i>
<i>Surface Tension</i>	<i>mN/m</i>	<i>35-39</i>	<i>29</i>
<i>Acidity</i>	<i>pH</i>	<i>2.4-2.8</i>	<i>5</i>
<i>Solids</i>	<i>wt %</i>	<i>0.4-0.6</i>	<i>-</i>
<i>Ash</i>	<i>wt %</i>	<i>0.04-0.4</i>	<i>0.01</i>

The range of properties is based on data obtained in literature for wood feedstocks.

What is the effect of the water content in the fuel?

The water or moisture content is a part of the fuel make-up and not a separate phase. This is true for water contents up to 25 wt%, however, above this value, phase separation will typically occur. For a gas turbine engine, this water content is still quite small. For NO_x control, some gas turbines use steam or water injection in which the flow rates can be up to 100-200 wt% of the fuel. The effect is to reduce the peak combustion temperatures and lower the rate of NO_x production. This is the likely reason biofuel has lower NO_x emission levels when compared to diesel fuel even though it contains fuel bound nitrogen.

The effect of the water is a decrease in the heating value of the fuel. As the heating value decreases, the fuel flow rate has to be increased such that the energy input rate remains constant. However, it is advantageous to have water in the fuel to reduce the viscosity, which allows for better flow and atomization characteristics. As well, fuel bound water can assist in atomization by a process called micro-burst. This occurs when the fuel enters the hot combustion chamber, which causes the water to vapourize. This causes a rapid expansion and assists in breaking up the atomized biofuel droplets.

What is the source of ash and its effects?

Plants and trees draw up minerals from the soil during their growth. It is these inorganic elements that form the ash in the feedstock. During the pyrolysis process, these minerals are primarily found within the char particles, which if not separated out of the vapour phase; carry through to the liquid phase (biofuel) during condensation. Therefore, a fuel's quality is often determined by the ability of the pyrolysis process to prevent the entrainment of char in the vapour phase.

Any ash that is in the liquid fuel will carry through to the engine. The effect is that the ash will deposit on the components downstream of the fuel injection point. This can result in both a build-up of material deposited material (similar to dust particles) on the airflow surfaces which will reduce performance along with the formation of liquid phases resulting in increased corrosion.

Although these are detrimental effects, there are technologies available to mitigate their impact. Firstly, the corrosive effects can be reduced by the addition of selected elements to the fuel, which preferably react with the corrosive elements and increase their melting point such that they do not form a liquid during combustion. This eliminates the condensation of these compounds on the components and thereby dramatically reducing their reactivity. In addition, hot section coatings can be modified to better suit the biofuel combustion products. Secondly, deposition will occur however, as with high ash bearing fuels commonly used for gas turbine power generation, they can be washed off. This process can be performed online using an abrasive media or off-line using a liquid based solution. Both these processes remove the deposits and regain performance.

How safe is biofuel to handle?

In general, biofuel does not require any unusual handling precautions. In a study sponsored by the National Renewable Energy Lab, it was concluded that biofuel can be safely handled wearing gloves, goggles and protective clothing such as coveralls. Dermal exposure to biofuel will result in a tanning of the skin, however, the toxicity of the oil to the skin is low. The eyes and respiratory tract are sensitive to biofuel vapours and therefore, NIOSH approved masks should be worn when being exposed to high levels of vapours.

What are the difficulties in using biofuel in a gas turbine and how can they be overcome?

High Viscosity	- fuel preheat, combustion system modifications.
Acidic	- materials and coating selection.
Ash content	- processing modifications.
Lower heating value	- fuel and combustion system modifications.
Poor Ignition	- ignition on conventional fuels.
Alkali content	- reduction by post fuel processing and the use of advanced protective coatings.

What are the green house gas and other emission benefits of biofuel?

The primary drive for the use of this type of fuel is because it is a carbon neutral fuel. The carbon released during combustion (in the form of CO₂) is retrieved during the growth of the biomass. The release of CO₂ is considered to be the main contributor to global warming which makes this type of fuel to be very attractive. For each OGT2500 (2.5 MWe) engine operating on biofuel, CO₂ emissions would be reduced by approximately 17,000 tons per year compared to operating on diesel fuel for base load conditions of 8000 hrs/year.

In addition, there are only trace levels of sulphur in the fuel, which is a major contributor to the creation of SO_x, which results in acid rain. As well, the water content in the fuel has been shown to reduce the NO_x emission levels in about half when compared to diesel fuel.

What is the difference between a gas turbine simple cycle, combined cycle and co-generation?

- a) Simple Cycle: A gas turbine operated independently where the heat in the exhaust is not recovered
- b) Combined Cycle: A gas turbine operated with a heat recovery steam generator (HRSG), which extracts heat from the engine's exhaust to produce steam. This steam is then expanded through a steam turbine for additional mechanical power extraction.
- c) Co-generation: A gas turbine set-up as a combined cycle but rather than sending the steam to a steam turbine, it is utilized in for industrial plant process or heating applications.

What is the advantage of a gas turbine over a boiler?

Efficiency. Currently, the available technology to convert biomass into electricity is a boiler and steam turbine cycle. However, the efficiency of energy conversion is much more favourable for the combine cycle gas turbine configuration. This is apparent from a study carried out by Pyrovac International where the electrical energy output of a combined cycle turbine was compared to that of a boiler, see table below. This analysis examines three different energy conversion scenarios using an equivalent fuel energy input of 200 (@15% moisture) t/day or 45.6 MW of bark residues. Scenario A examines the direct firing of the residues in a boiler/steam turbine configuration assuming a 26% efficiency, which generates a total of 11.8 MW of electricity. Scenario B examines the use of a pyrolysis reactor to convert the bark residues to the pyrolysis fuel products of charcoal, oil and gas. This fuel is then fed into a boiler/steam turbine configuration, which produces electricity at the same 26% efficiency as in Scenario A. However, 3.1 MW power draw is required by the pyrolysis process. This produces a net yield of 8.7 MW of power with an overall efficiency of 19%.

However, the improvement is dramatic when the pyrolysis reactor is married with a combined cycle gas turbine rather than a boiler, which results in a significant increase in output power and overall efficiency. In this configuration, scenario C, liquid pyrolysis oil is fed into the gas turbine, which is connected to a generator to produce electricity. The exhaust from the engine is then passed through a heat exchanger (Heat Recovery Steam Generator) to produce steam, which is expanded in a steam turbine for additional power generation. The efficiency of this combined cycle is assumed to be 40%. Additional fuel energy is also available from the pyrolysis wood charcoal which is combusted in a solid fuel boiler to produce steam and is combined with that produced from the gas turbine. As with scenarios A and B, the efficiency of this boiler/steam configuration is assumed to be 26%. The 3.1 MW power requirement for the pyrolysis process is met by combusting the pyrolysis gas and a small portion of the pyrolysis oil. As a whole, this configuration produces 14 MW of power with an overall efficiency of 31% showing a significant improvement in efficiency that can be gained by the use of a gas turbine, combine cycle installation. This superior efficiency results in higher profit associated with the sale of the electricity and maintaining approximately the same pay back period as a boiler configuration as illustrated in the figure below. This illustrates how the technical advantages of the gas turbine combined cycle translates into economic advantages.

	Scenario A	Scenario B*	Scenario C*
Total Energy Input	Bark Residues: 164,160 MJ/hr (45.6 MW)		
Fuel	Bark Residues	Biofuel	Biofuel
	19MJ/kg@15% water	32.2 MJ/kg@1.4% water	32.2 MJ/kg@1.4% water
Energy Input	164,160 MJ/hr	82,000 MJ/hr	76,636 MJ/hr
Energy Conversion	Boiler/Steam turbine	Boiler/Steam turbine	Gas Turbine Combined Cycle
Efficiency	26%	26%	40%
Power Output	11.8 MW	5.9 MW	8.5 MW
Fuel		Wood Charcoal	Wood Charcoal
Energy Input		76,000 MJ/hr	76,000 MJ/hr
Energy Conversion		Boiler/Steam turbine	Boiler/Steam turbine
Efficiency		26%	26%
Power Output		5.5 MW	5.5 MW
Fuel		Pyrolysis Gas	Pyrolysis Gas
Energy Input		5,662 MJ/hr	(used for pyrolysis process energy requirements)
Energy Conversion		Boiler/Steam turbine	
Efficiency		26%	
Power Output		0.4 MW	
Process Energy Requirement		(3.1 MW)	Pyrolysis gas & some biofuel used to meet process needs
Total Power Output	11.8 MW	8.7 MW	14.0 MW
Overall Efficiency	26%	19%	31%

Scenario A: Direct combustion of biomass in boiler

Scenario B: Application of pyrolysis oil & charcoal to boiler

Scenario C: Application of pyrolysis oil & charcoal to boiler and combine cycle gas turbine

**Small amount of energy for the bio-treatment of the aqueous phase was considered to be negligible*

*PAYBACK TIME AND PROFIT FOR BOILER/STEAM TURBINE INSTALLATION COMPARED WITH
COMBINED CYCLE GAS TURBINE INSTALLATION¹*

What is the advantage of pyrolysis over gasification?

Gasification technology is the conversion of biomass into a low heating value gas which is then filtered and fed into a gas turbine. This technology has received a significant amount of international attention with several large demonstration level projects under way. However, these projects have encountered many technical difficulties in achieving continuous operation and have yet to reach a viable commercial state. Besides the technical issues, there are some fundamental differences between the use of gasified biomass when compared to pyrolyzed biomass. In gasification, it is not possible to store any significant amounts of fuel because it is in a gaseous form. Therefore, the engine must be directly hooked up to the gasifier. This means, any interruption in the flow of the fuel will affect the supply to the engine for combustion. Therefore, any element in the gasification process that requires downtime will interrupt the power generation. This is a fundamental problem in working with a gas. As previously discussed, the fuel to be used for the OGT2500 is a liquid fuel derived from the pyrolysis process. Using a liquid allows for the capability for both storage and transportation of the fuel. This is key in continuous operation where interruptions in the fuel production side can be accommodated by drawing from stored reserves. Drawing from a storage vessel also improves the homogeneity of the fuel. Fuel properties can vary with feedstock which means that fuel characteristics can vary from one load of biomass to another. The OGT2500 biofuel installation will accommodate this range of properties however, a

¹ M.A. Gabra and B.O. Kjellstrom, "Evaluation of new process options for co-generation in the sugar Industry", American Society Mechanical Engineers, 1996, 96-GT-301.

critical factor is how severe is the change in properties and how quickly does the system have to respond. Mixing in the storage facility allows for damping of these variations and smoothes out the required response from the engine and controls system. If a direct connection were made with the fuel supply, then the system would have to respond to a larger deviation and potential result in more complex control systems and a higher probability of unstable operation. In addition to the storage capabilities with liquids fuel, it is transportable which means the engine and fuel system can be in two different geographical locations. In gasification, the engine must be directly linked to the gasifier. It is due to these advantages that Orenda is pursuing the use of liquid pyrolysis fuel.

What is a typical cost of fuel?

The cost of electricity is the critical cost parameter for the cost effectiveness of a power generating installation. However, often enquires are made as to the cost per gallon since this is a more tangible parameter for most people. The cost of pyrolysis oil however, depends on the cost of the feedstock.

What is the advantage of a gas turbine over a reciprocating engine operating on biofuel?

The application of biofuel to diesel piston engine operation is another area of biomass fuelled power production that is being developed. As with the use of pyrolysis fuel for a gas turbine, it is necessary to ignite on a conventional fuel and transition to biofuel. For the gas turbine, this entails starting on diesel and transitioning to biofuel for continuous operation. However, for piston engine applications, each power stroke of the piston requires ignition on diesel fuel followed by the injection of biofuel. This therefore means that a significant amount of diesel fuel must be combusted with the biofuel resulting in the need for a continuous supply of fossil fuels during operation. As well, the injection pressures are extremely high and the fuel nozzle passages very small making it difficult to pump this very viscous fuel into the combustion chambers. These are some of the key technical difficulties in the application of pyrolysis fuel to diesel piston engine operation. Although the efficiency of a diesel engine is comparable to a combine cycle gas turbine installation, it does not have the capability of producing steam. This is important for applications in which steam is either required for processes such as in industrial applications or for heating requirements. It is the ability to use the energy with in the exhaust gas of the gas turbine, which provides flexibility in the application of gas turbines and is advantageous over the use of a diesel engine.

What is a sample price for a complete installation?

The economic size of a pyrolysis reactor is the controlling factor. We have been working on commercial project designs in the order of 200 tons per day of biofuel throughput. This size of installation includes the pyrolysis reactor, 3 Orenda packages as well as equipment to recover the waste heat from the turbine and the equipment to use the charcoal produced by the pyrolysis process. The cost of the installation is likely to be more economical for cases where one large fuel processing unit supplies several gas turbines in a distributed energy systems

What would the cost of electricity be for a biofuel-powered plant?

This cost is site specific depending on the feedstock since in many cases, it will have a negative cost since there are often disposal charges associated with excess biomass. Therefore the cost of electricity is given over a range of feedstock costs in the graph below.

What are the typical size ranges for Orenda's biofuel installations?

The development work to date has been on the 2.5 MW engine, the OGT 2500. In simple and combined cycle applications, the installed power generating capabilities can range from 2.5 to 25 MW. These are the typical values most customers are seeking.

What testing has been carried out and what were the results?

A Mashproekt industrial gas turbine engine was modified by Orenda, the OGT2500, to operate on pyrolysis oil. It was successfully operated from 1 to 2.65 MW using 100% flow rate bio-fuel. Total operational time on bio-fuel was in the order of 10 hours where 5 hours was at 100% biofuel and the other 5 on a bio-fuel, diesel mix. A total of 13,000 litres of bio-fuel was consumed with the engine efficiency comparable for biofuel and diesel fuel. For most of the measured emission products, similar values were approached for bio-fuel and diesel as power was increased. The emission characteristics of operation on bio-fuel relative to diesel were very positive with lower NO_x, and SO₂ emissions and equivalent total hydrocarbon and methane emissions. The higher particulate emissions were offset by the lower soluble organic fraction found with the bio-fuel particulates.

What work is being planned for the future?

Future work is focussed on commercializing the technology by further fuel optimization and engine systems development as well as rigorous testing with the following objectives:

- I. Develop, integrate and test commercial level systems for engine operation on biofuel.
- II. Optimize the combustion system and determine engine operating and emission characteristics using various biofuels.
- III. Optimize components and systems for long term operation with bio-fuel.
- IV. Develop specifications for the fuel and a commercial level package.

The tasks associated with achieving these objectives are outlined below.

- I. Redesign of the GT2500 gas turbine fuel handling and hot section hardware to deal with the viscosity, ash, acidity and particulate content of the bio-fuel, as well as accept multiple fuel types (e.g. various pyrolysis techniques and feedstocks).
- II. Full scale performance and emission tests using re-designed engine combustion and auxiliary systems.
- III. Further process optimization of bio-fuel for operation on the GT2500 engine through adjustment of fuel production and development of post production processing techniques.

MAGELLAN
AEROSPACE CORPORATION

Orenda Aerospace Corporation

- IV. Coupon and rig testing to improve and quantify component operational and endurance characteristics.
- V. Development of warranties and specifications for the fuel, engine, auxiliary and fuel handling systems for commercial application.

APPENDIX B: MSDS SHEETS

BIOFUEL

DIESEL

GLYCOL

BIOFUEL**MATERIAL SAFETY DATA SHEET****Section I Product Identification and Use**

Manufacturer:	Emergency Phone Numbers:
DynaMotive Technologies Corporation	(604)267-6000
105 - 1700 West 75 th Avenue	CANUTEC (613)996-6666
Vancouver, B.C.	
V6P 6G2	

Product Name:	BioOil
Synonyms:	Pyrolysis oil, biomass pyrolysis oil
UN number:	UN1993
TDG Shipping Name:	Flammable Liquid N.O.S. (lignin solution)
TDG Classification/Packing group:	Class 3.3, Packing Group III
Use:	Applications as a liquid fuel or raw material for industrial processes

Section II Ingredients

Water:	25%
Lignins:	25%
Other Oxygenated Compounds	50%

Section III Physical Data

Physical State:	liquid
Appearance:	dark brown liquid
Odour:	charred odour
Odour Threshold:	not applicable
Vapour Pressure:	not available
Vapour Density:	not available
Evaporation Rate:	not available
Boiling Point:	not available
Freezing Point:	not available
pH:	2.2 to 3.5
Specific gravity:	1.1 to 1.25
Coefficient of Water/Oil Distribution:	not available

Section IV Fire or Explosion Hazard

Conditions of flammability:	WHMIS Class B, Division 3. Combustible liquid. Flammable at extremely high temperatures. May react with strong oxidants.	
Extinguishing media:	water, foam, dry chemical. Fire fighters should wear self-contained breathing apparatus.	
Flash point/method:	44°C/PMCT	
UEL:	not available	
LEL:	not available	
Auto-ignition temperature:	not available	
Hazardous Combustion Products:	COx	
Explosion Data - sensitivity to mechanical impact:	no	
- sensitivity to static discharge:	no	

Section V Reactivity Data

Conditions of Instability: normally stable

Incompatibilities: oxidizers

Conditions of Reactivity: temperatures above 160°C may generate highly flammable acetone

Hazardous Decomposition Products: acetone, carbon dioxide, carbon monoxide

Section VI Toxicological Properties/Health Hazard Data

Route of Entry:

Skin contact: may irritate

Skin absorption: no information available

Eye contact: may irritate

Inhalation: may irritate

Ingestion: may irritate

LC₅₀: not available

LD₅₀: not available

Exposure limits: not established

Effects of Acute Exposure: Coughing or mild breathing difficulties may result. If ingested, large doses may irritate the gastrointestinal tract

Effects of Chronic Exposure: no information available

Irritancy: no experimental information available

Sensitizing capability: no information available

Carcinogenicity: no information available

Reproductive toxicity: no information available

Teratogenicity: no information available

Mutagenicity: no information available

Toxicologically Synergistic Products: no information available

Section VII First Aid Measures

Skin: flush the contact area with lukewarm running water for at least 15 minutes. Remove contaminated clothing, taking care not to spread the chemical. If contamination is extensive, remove the clothing under running water. Discard or decontaminate clothing before use. Unless contact has been slight, seek medical attention. Seek medical attention if irritation persists.

Eye: flush the contaminated eye(s) for at least 15 minutes with lukewarm running water, holding the eyelids open. Take care not to rinse contaminated water into the non-affected eye. Always seek medical attention for accidents involving the eyes.

Inhalation: Take proper precautions to ensure your own safety before attempting rescue. Remove source of contamination or move victim to fresh air. If breathing has stopped, trained personnel should begin artificial respiration, or if the heart has stopped, cardiopulmonary resuscitation (CPR) immediately. Seek medical attention.

Ingestion: Never give anything by mouth if victim is rapidly losing consciousness, or is unconscious or convulsing. Rinse mouth thoroughly with water. Do not induce vomiting. Have victim drink 200 to 400 mL of water to dilute. If breathing has stopped, trained personnel should begin artificial respiration, or if the heart has stopped, cardiopulmonary resuscitation (CPR) immediately.

Section VIII Preventive Measures

- Engineering Controls:** Engineering control measures to reduce hazardous exposures are preferred. Methods include mechanical ventilation (dilution and local exhaust), control of personnel exposure, control of process conditions and process modification. Administrative controls and personal protective equipment may also be required.
- Personal protective equipment:**
- Gloves:** neoprene, latex or equivalent
- Respiratory protection:** fume hood or NIOSH/MSHA approved organic vapour respirator as appropriate
- Eye protection:** chemical safety goggles
- Clothing:** plastic apron, sleeves and boots as appropriate
- Storage Requirements:** Store in suitable labeled containers. Keep containers tightly closed when not in use and when empty. Protect from damage. Store in a cool, dry, well ventilated area, out of direct sunlight. Store away from oxidants.
- Handling Procedures and Equipment:** Follow routine safe handling procedures.
- Leak or Spill Cleanup:** Before dealing with spills take necessary protective measures, inform others to keep at a safe distance and shut off all possible sources of ignition when the oil is at temperatures above 160°C. Mix with sand, transfer carefully to container and arrange removal by disposal company. Wash site of spill thoroughly with water.
- Disposal:** Follow all federal, provincial and local regulations for disposal. Use only licensed disposal and waste hauling companies. Disposal of small amounts of spilled material may be handled as described under "Leak or Spill Cleanup". Large spills must be dealt with separately and must be handled by qualified disposal companies.
- Special Shipping Information:** Follow all TDG regulations and see classification in Section I.

Section IX Preparation Information

Prepared by: DynaMotive Technologies Corporation, 105 - 1700 West 75th Avenue, Vancouver, B.C. V6P 6G2, phone 604-267-6000.
Date: April 3, 2000.

DIESEL

Gary-Williams Energy Corp
 370 17th Street
 Suite 300
 Denver, CO 80202

MATERIAL SAFETY DATA SHEET		October 20, 1999	MSDS NUMBER W-3035
EMERGENCY TELEPHONE NUMBERS	COMPANY 800-666-6665	CHEMICAL 800-424-9300	

I. PRODUCT IDENTIFICATION			
PRODUCT DIESEL FUEL (CLEAR)		GENERIC NAME AND SYNONYMS Petroleum Hydrocarbon Mixture, Distillate, 2- Oil # 2 Diesel Fuel, Fuel Oil #2,	
CHEMICAL FAMILY Petroleum Hydrocarbon Distillate		FORMULA C ₁₁ - C ₂₀	
National Fire Protection Association Hazard Rating Codes Flash - 0 Slight - 1 Moderate - 2 High - 3 Extreme - 4		Health Hazard (Hazardous) 0 2	Reactivity Code 0

II. SUMMARY OF HAZARDS		
<p>CAUTION! COMBUSTIBLE LIQUID AND VAPOR. HARMFUL IF INHALED AND MAY CAUSE DELAYED LUNG INJURY. CAN CAUSE NERVOUS SYSTEM DEPRESSION. ASPIRATION HAZARD IF SWALLOWED - CAN ENTER LUNGS AND CAUSE DAMAGE. Keep away from heat and flame. Avoid breathing vapor. Use ventilation adequate to keep vapor below recommended exposure limits. Avoid contact with eyes, skin and clothing. Wash thoroughly after handling.</p> <p>NIOSH, EPA, & current literature have indicated that breathing whole diesel exhaust over a working lifetime may cause cancer in humans. Animals exposed to whole diesel exhaust over a lifetime have developed lung tumors (cancer). Diesel exhaust may cause eye irritation, headache, light-headedness, nausea, vomiting, heartburn, weakness, numbness, tingling in the extremities, chest tightness and wheezing. Cough and labored breathing have been reported in garage workers without adequate ventilation (air circulation) in the garage.</p>		
Hazardous Material	Hazardous Name and Number	Hazard Code (GHS)
YES	Diesel Fuel, 3, NA1993, III	3 (Flammable Liquid)

III. HAZARDOUS COMPONENTS			
CONCENTRATION	PERCENT	RELATIVE	HAZARD
Straight Run Middle Distillate (CAS # 64741-44-2)	60 to 100 %	Petroleum Distillate TWA - 400 ppm	Combustible Acute Health Chronic Health
Light Catalytic Cracked Distillate (CAS # 64741-59-0)	0 to 40 %	Petroleum Distillate TWA - 400 ppm	

Diesel exhaust contains: Nitrogen Dioxide, Sulfuric Acid, Sulfur Dioxide, Aliphatic Aldehydes, Soot containing Polynuclear Aromatic Hydrocarbons, Carbon Monoxide, Hydrogen Sulfide.

Gary-Williams Energy Corp.
370 17th Street
Suite 5300
Denver, CO 80202

IV. HEALTH INFORMATION

EXPOSURE BY ROUTE OF ENTRY	EXPOSURE CHARACTERISTICS AND FIRST AID	
INHALATION	EFFECTS	Acute: Headache, nasal and respiratory irritation, nausea, drowsiness, breathlessness, fatigue, central nervous system depression, convulsions, and loss of consciousness.
	FIRST AID	Move exposed person to fresh air. If breathing has stopped, perform artificial respiration. Get medical attention as soon as possible.
SKIN	EFFECTS	Acute: Irritation Chronic: dermatitis
	FIRST AID	If clothing soaked, immediately remove clothing and wash skin with soap and water. Launder clothing before wearing. Get medical attention promptly.
EYES	EFFECTS	Acute: Irritation
	FIRST AID	Immediately flush eyes with water for a minimum of 15 minutes, occasionally lifting the lower and upper lids. Get medical attention promptly.
SWALLOWING INGESTION	EFFECTS	Acute: aspiration hazard, headache, nausea, drowsiness, fatigue, pneumonitis, pulmonary edema, central nervous system depression, convulsions and loss of consciousness.
	FIRST AID	Call a physician immediately. ONLY induce vomiting at the instruction of a physician. Never give anything by mouth to an unconscious person.
Medical conditions especially aggravated by exposure	N/A	
LISTED AS POTENTIALLY HAZARDOUS OR CARCINOGEN	NOT LISTED ☒ INTERNATIONAL Agency for Research on Cancer	NATIONAL TOXICOLOGY PROGRAM TEST

Gary-Williams Energy Corp
370 17th Street
Suite 5300
Denver, CO 80202

V. EMPLOYEE PROTECTION

RESPIRATORY PROTECTION: USE AN OSHA-APPROVED RESPIRATOR (SEE OSHA STD. 1910.134)

Up to 4000 ppm, half-mask organic vapor respirator. Up to 20,000 ppm, full-face organic vapor respirator or full-face supplied air respirator. Greater than 20,000 ppm, fire fighting, or unknown concentration, self-contained breathing apparatus with positive pressure

<p>Eye</p> <p>Safety glasses, chemical goggles or face shield as appropriate.</p>	<p>Skin</p> <p>Gloves: Nitrile, neoprene or other material resistant to distillate.</p>
---	---

VENTILATION

Maintain local or dilution ventilation to keep air concentration below 400 ppm. Loading, unloading, tank gauging, etc., remain upwind. Request assistance of safety and industrial hygiene personnel to determine air concentrations.

VI. FIRE PROTECTION INFORMATION

FLASH POINT AND METHOD	AUTOIGNITION TEMPERATURE ESTIMATED	FLAMMABLE LIMITS (% VOLUME IN AIR) ESTIMATED	LOWER	UPPER
Tag Closed Cup 130°F	490°F		0.7	6

FIGHTING MEDIA

Carbon dioxide, dry chemical, or foam. Water stream may spread fire, use water spray only to cool containers exposed to fire. If leak or spill has not ignited, use water spray to disperse the vapors.

HAZARDOUS DECOMPOSITION PRODUCTS

Incomplete combustion can yield carbon monoxide and various hydrocarbons.

FIRE AND EXPLOSION HAZARDS

Can form combustible mixtures with air when heated.

STORAGE

Do not store with strong oxidizers. Store as OSHA Class II combustible liquid.

HAZARDOUS POLYMERIZATION	STABILITY
WILL NOT OCCUR ☒ MAY OCCUR ☐	STABLE ☒ UNSTABLE ☐

VII. PHYSICAL AND CHEMICAL PROPERTIES

BOILING POINT	Red VAPOR PRESSURE (RVP) at 100°F	EVAPORATION (ETHYL ETHER %)
330 - 675 °F	ESTIMATED less than 0.1 pound	ESTIMATED slower
PERCENT VOL. AET BY VOLUME	AVG. MOLECULAR WEIGHT	APPEARANCE
100	N/A	May be clear to yellow-brown
COLOR	POUR POINT	ESTIMATED VAPOR DENSITY (AIR = 1)
Diesel Fuel	Pour Point -25 to +10 °F	6
SPECIFIC GRAVITY	VISCOSITY	SOLUBILITY IN FRESH WATER AT 70 °C
0.8 to 0.9	2 to 4 cs at 100°F	Negligible

Gary-Williams Energy Corp.
370 17th Street
Suite 5300
Denver, CO 80202

VIII. ENVIRONMENTAL PROTECTION

S		
P		
I		
I		
I		
S		
D		
W	I	Utilize licensed waste disposal company. Consider recycling or incineration. Utilize permitted hazardous waste disposal site or industrial waste disposal site as appropriate.
A	S	
S	P	
I	O	
I	S	
	A	
	I	

ADDITIONAL INFORMATION

The following chemicals are subject to the reporting requirements of section 313 of Title III of the Superfund Amendments and reauthorization Act of 1986 and 40 CFR Part 372:

PREPARED BY	DATE PREPARED
Jeffrey L. Ray	October 20, 1999

DISCLAIMER

The information and recommendations contained in this publication have been compiled from sources believed to be reliable and to represent the best current opinion on the subject at the time of publication. Since we cannot anticipate or control the many different conditions under which this information or our products may be used, we make no guarantee that the recommendations will be adequate for all individuals or situations. Each user of the product described herein should determine the suitability of the described product for his particular purpose and should comply with all federal and state rules and regulations concerning the described product.

ABBREVIATIONS

CAS #	Chemical Abstracts Service Number
N/A	Not Applicable
N/AV	Not Available
ppm	Parts per million
PEL	Permissible Exposure Limit
TLV	Threshold Limit Value
	Both the OSHA PEL and the American Conference of Governmental Industrial Hygienists TLV were reviewed. Where a difference existed, the more restrictive of the two was selected.
STEL	Short Term Exposure Limit
TWA	Time-Weighted Average

GLYCOL **DELTREX CHEMICALS****A Division of Campbell Brothers Limited****ABN 92 009 657 489**

7-11 Burr Court

Laverton North

3026

Postal Address:

P.O. Box 118, Newport

Victoria 3015

AUSTRALIA

Telephone: 61/3/9250-1000**PROPYLENE GLYCOL****ISSUED: FEB 28, 2000****Not classified as hazardous according to criteria of Worksafe Australia.****IDENTIFICATION**

TRADE NAME :	Propylene Glycol
OTHER NAMES :	Monopropylene Glycol; Propylene Glycol USP; 1,2 Propanediol; Methyl Glycol
U.N. NO. :	None Allocated
DG CLASS :	None Allocated
SUB RISK :	None Allocated
PACKAGING GROUP :	None Allocated
HAZCHEM :	None Allocated
POISON SCHEDULE :	None Allocated
USES :	Humectant, Refrigerants, Fragrance.

PHYSICAL DESCRIPTION/ PROPERTIES**Appearance, odour :** Clear liquid, odourless**Melting Point :** -59 °C**Boiling Point :** 188°C**Specific Gravity (20°C) :** 1.04**Vapour Density (air=1) :** 2.6**Vapour Pressure (20°C) :** Not Available

Flash Point (Closed cup) : 99°C

Flammability Limits (%) : lower limit: 2.6, upper limit: 12.5

Solubility in water (g/L) : Soluble

Autoignition Temp (°C) : 371°C

INGREDIENTS

Chemical Name CAS Number Proportion

Propylene Glycol 57-55-6 >99.5%

Other ingredients are not considered hazardous by Worksafe Australia to 100%

HEALTH EFFECTS INFORMATION

HEALTH EFFECTS

No adverse health effects expected if the product is handled in accordance with this Safety Data Sheet and the product label. Symptoms that may arise if the product is mishandled are:

ACUTE EFFECTS -

SWALLOWED: Non toxic. Ingestion of large amounts may cause some gastrointestinal disturbances.

EYE: May cause stinging and tearing.

SKIN: May cause mild irritation on prolonged contact.

INHALED: No adverse effects expected.

CHRONIC EFFECTS

No data available.

FIRST AID

SWALLOWED: If large amounts ingested give water to drink. Seek medical advice.

EYE: Immediately irrigate with copious quantities of water for at least 15 minutes. Eyelids to be held open. Seek medical advice.

SKIN: Wash with soap & water. Remove contaminated clothing, launder clothes before reuse. If irritation develops seek medical advice.

INHALED: Remove victim from exposure - avoid becoming a casualty. Rest, half upright position, remove contaminated clothing and loosen remaining clothing. Keep at rest until fully recovered. If breathing laboured ensure airways are clear. If breathing has stopped apply artificial respiration at once. Seek medical advice.

ADVICE TO DOCTOR

Treat symptomatically.

TOXICITY

ORAL LD50 (rat): 20g/kg.

LD50 SKIN (rabbit): 20.8g/kg.

PRECAUTIONS FOR USE**EXPOSURE STANDARDS**

No value assigned for this specific material by the National Occupational Health and Safety Commission (Worksafe Australia).

ENGINEERING CONTROLS

Ensure ventilation is adequate. Use a system of local or general exhaust ventilation to keep vapour or mist levels as low as possible.

PERSONAL PROTECTION

Avoid skin and eye contact and inhalation of vapour or mist spray. Wear overalls, eye protection & gloves. Use with adequate ventilation. If airborne concentration is high, use an approved respirator. Always wash hands before smoking, eating, drinking or using the toilet.

FLAMABILITY Combustible Liquid.

SAFE HANDLING INFORMATION**STORAGE AND TRANSPORT**

Not defined as a Dangerous Good by the Australian Code for the Transport of Dangerous Goods by Road and Rail.

Store in a cool place away from sources of heat or ignition. Store in well ventilated area. Store away from oxidizing agents.

SPILLS

Wear protective equipment to prevent skin and eye contamination and inhalation of vapours. Contain and recover liquid where possible. Use absorbent such as earth, sand or other non-combustible material. Collect and place into suitably labelled containers for disposal.

DISPOSAL

Refer to State Land Waste Management Authority.

FIRE/EXPLOSION HAZARDS

Combustible liquid. On burning will emit toxic fumes. Containers may explode in heat or fire. Use water to keep fire-exposed containers cool. Fire fighters to wear self-contained breathing apparatus if risk of exposure to vapour or products of combustion.

EXTINGUISHING MEDIA: Water spray, foam, dry chemical powder or carbon dioxide.

ENVIRONMENTAL IMPACT

Biodegradability: Product is biodegradable.

OTHER INFORMATION AND REFERENCES**PRINCIPAL REFERENCES**

This chemical is listed on the Australian Inventory of Chemical Substances (AICS).

CONTACT POINT

Phone: (03) 9250 1000

Phone: 1 800 628 724 (24hr - Emergency Contact)

This MSDS has been prepared from current technical data and summarises at the date of issue our best knowledge of the health and safety information of the product, and in particular how to safely handle and use the product in the workplace. Each user should read this MSDS and consider the information in the context of how the product will be handled and used in the workplace.

If clarification or further information is needed to ensure that an appropriate assessment can be made, the user should contact this company.

Our responsibility for products sold is subject to our standard terms and conditions, a copy of which is sent to our customers and is also available upon request

END OF MSDS NO 177

APPENDIX C:
COMBUSTOR TEST RIG PARTS

AIR SYSTEM

TEST COMBUSTOR

FUEL SKID

DATA ACQUISITION SYSTEM

Part	Description	Supplier
<i>Air System</i>		
	4" pipe, schedule 10, 316 SS	QIP Equipment (Montreal)
	4" 90° long-radius elbow	QIP Equipment (Montreal)
	4" 45° long-radius elbow	QIP Equipment (Montreal)
	4" butt weld stub ends, schedule 10, 316SS	QIP Equipment (Montreal)
	4" class 150 lbs, galvanized forged lap joint flange	QIP Equipment (Montreal)
	4" 304 S.S. flexible pipe	QIP Equipment (Montreal)
	4" Butterfly valve	Carleton University (Ottawa)
	Hastelloy cone	A-Line Precision Tool (Toronto)
Newco 28TFS2	1", globe valve, class 800, carbon steel body	QIP Equipment (Montreal)
	3 feet ½" Flex tubing, braided stainless steel	QIP Equipment (Montreal)
	Clamps, threaded rod, couplings for hanging pipes	Crane (Ottawa)
<i>Test combustor</i>		
L40	1/4" S.S. pressure-atomizing nozzle	BETE Fog Nozzle (Greenfield, MA)
L48	1/4" S.S. pressure-atomizing nozzle	BETE Fog Nozzle (Greenfield, MA)
XAAD 5100A	1/2" S.S. air-atomizing nozzle	BETE Fog Nozzle (Greenfield, MA)
6874959	Allison fuel nozzle	Essential Turbines (Montreal)
6870992	Allison combustor casing	Essential Turbines (Montreal)
6877518	Allison igniter plug	Essential Turbines (Montreal)
6870885	Exciter box and cable for igniter	Essential Turbines (Montreal)
23060429	Combustor liner	
6876667	Compressor discharge air tube	Essential Turbines (Montreal)
RKW 28-12K	300 W power supply for exciter box	Testforce (Ottawa)
	Nozzle adaptors (see Appendix E for drawings)	C & R Developpement (Aylmer)

Part	Description	Supplier
Fuel Skid		
F21SABTHHECG	F-20 diaphragm pump for diesel	John Brooks Company (Montreal)
M03EABJSSSCA	M-03 diaphragm pump for biofuel	John Brooks Company (Montreal)
C62AABJRREF	Pressure regulating valve	John Brooks Company (Montreal)
6ILA-03-74	Diesel fuel filter	Flow Ezy Filters (Ann Arbor, MI)
ASCO EF8210G7V	1/2" brass body solenoid valve with Viton O-rings	QIP Equipment (Montreal)
ASCO EF82232G27T	3/8" brass body solenoid valve with Teflon O-rings	QIP Equipment (Montreal)
CFF SS-12	3/4" NPT threaded needle valve, all stainless construction with Teflon seals.	QIP Equipment (Montreal)
	3/4" Newman Hattersley, all brass check valve, NPT threaded end connections, 400 PSI CWP	QIP Equipment (Montreal)
	Strainer screens (multiple mesh sizes ordered)	BG Screen Fabrication (Burlington)
BF-2003-2A	Heavy duty drum heaters (1500W)	Benchmark Thermal (Columbus, OH)
	Immersion heater (2" NPT, B=36", 220V, 8000W, Nema 1 Enclosure, Steel sheath, T. Stat 10-120°C)	National Plastic Heater Sensor and Control (London)
FMX8482S	1/2" S.S. 12-element static mixer	Omega (Laval)
	45 Gallon barrels (unlined, steel, open top)	Jos. Le Bel (Montreal)
	NPT fittings	Crane (Ottawa)
	Tube fittings	Swagelok (Ottawa)
	Cart	Tenaquip (Ottawa)

Part	Description	Supplier
<i>Data Acquisition System</i>		
2700	Keithley data acquisition system	Testforce (Ottawa)
7708	40-channel module for Keithley data acquisition system	Testforce (Ottawa)
J-116-U-316-00-6"-120"-3A-Bell Spring	J-type thermocouples (6" lead, 10 foot extension)	DCH Process Dynamics (Ottawa)
K-116-U-316-00-4"-200"-3A-Bell Spring	K-type thermocouples (4" lead, 200" extension)	DCH Process Dynamics (Ottawa)
KMTSS-062U-12	K-type thermocouples (12" leads)	Omega (Laval)
T-116-U-316-00-6"-120"-3A-Bell Spring	T-type thermocouples (6" lead, 10 foot extension)	DCH Process Dynamics (Ottawa)
T-116-U-316-00-3"-120"-3A-Bell Spring	T-type thermocouples (3" lead, 200" extension)	DCH Process Dynamics (Ottawa)
PA41602	Jack Panel for thermocouple plugs	DCH Process Dynamics (Ottawa)
	Thermocouple extension wire	DCH Process Dynamics (Ottawa)
PX242A-G100V	Pressure transducer (1-6 Vdc)	Omega (Laval)
PST-8	Power supply (8 V, 300 mA)	Omega (Laval)
PX181-300G5V	Pressure transducer (1-5 Vdc)	Omega (Laval)
PST-15	Power supply (15 V, 200 mA)	Omega (Laval)
	Averaging annular pitot tube KL model for welding into 4", schedule 10, SS pipe	DCH Process Dynamics (Ottawa)
Kobold OMP-2-I-N2-T-L	Oval gear flowmeter	DCH Process Dynamics (Ottawa)

APPENDIX D:
SPECIFICATION SHEETS FOR SELECTED COMBUSTOR TEST RIG
COMPONENTS

AIR SYSTEM

TEST COMBUSTOR

FUEL SKID

DATA ACQUISITION SYSTEM

AIR SYSTEM

Fact Sheet

Rolls-Royce

Model 250-C20B/J turboshaft engine

Features

Robust, proven, modular design

160 million fleet flight hours

Continued improvements for increased performance and reduced operating cost

Worldwide authorized repair and overhaul network

Description

The Model 250-C20B/J turboshaft engine is a proven, modular design that has been in service for over 160 million fleet flight hours.

The Model 250-C20B/J turboshaft engine is a proven, modular design that has been in service for over 160 million fleet flight hours. The engine is a modular design that can be configured for a wide range of applications, from light helicopters to heavy-lift helicopters. The engine is a modular design that can be configured for a wide range of applications, from light helicopters to heavy-lift helicopters.

The Model 250-C20B/J turboshaft engine is a proven, modular design that has been in service for over 160 million fleet flight hours. The engine is a modular design that can be configured for a wide range of applications, from light helicopters to heavy-lift helicopters. The engine is a modular design that can be configured for a wide range of applications, from light helicopters to heavy-lift helicopters.

Model 250-C20B/J

Bell Helicopter Textron 206B III

MD Helicopters MD500

Eurocopter BO-105

BLOWER INFORMATION

THE SPENCER TURBINE CO., WINDSOR, CT, USA

Preliminary Performance Curve of a Spencer Model #: 30104A3

SERIES 815 ANSI CLASS 150 AND SERIES 830 ANSI CLASS 300 WAFER-SPHERE® HIGH PERFORMANCE BUTTERFLY VALVES

Jamesbury's Wafer-Sphere high performance butterfly valves provide long lasting tight shut-off capability, excellent flow characteristics, and long service life. The following standard sizes are available:

815W - 150 Class Wafer-Sphere Valve	1 1/2" - 24"	ANSI Class 150
830W - 300 Class Wafer-Sphere Valve	2 1/2" - 60"	ANSI Class 300
815W - 150 Class Wafer-Sphere Valve	1 1/2" - 24"	ANSI Class 150
830W - 300 Class Wafer-Sphere Valve	2 1/2" - 60"	ANSI Class 300
815W - 150 Class Wafer-Sphere Valve	1 1/2" - 24"	ANSI Class 150
830W - 300 Class Wafer-Sphere Valve	2 1/2" - 60"	ANSI Class 300
815W - 150 Class Wafer-Sphere Valve	1 1/2" - 24"	ANSI Class 150
830W - 300 Class Wafer-Sphere Valve	2 1/2" - 60"	ANSI Class 300
815W - 150 Class Wafer-Sphere Valve	1 1/2" - 24"	ANSI Class 150
830W - 300 Class Wafer-Sphere Valve	2 1/2" - 60"	ANSI Class 300

The Wafer-Sphere high performance butterfly valve is available in a range of materials and seat combinations suitable for service in a wide variety of applications including NACE MR0103 and abrasive services. Also available are valves specifically prepared for chlorine, oxygen, and high vacuum applications.

FEATURES

- New Xtremic® seat provides longer life, expanded performance boundaries, and greater value
- Field-Proven Single-Piece Flexible PTFE Seat Design**
 - Lip-seal design compensates for temperature and pressure changes
 - No additional o-rings or metal parts required to maintain tightness
 - Tight shut-off in either direction
 - Longer service life with less maintenance
- Offset Shaft and Eccentric Disc**
 - No seat/disc contact in the open or intermediate position
 - Eliminates wear points at top and bottom of seats for higher cycle life
 - Reduces torque requirements, allowing for smaller operators
- Fire-Tested Version Available**
 - Fire-Tite® Wafer-Sphere valves have been tested to API 607 4th edition and BS 6755 part 2

CE Marked Versions Available

CE marked and documented valves that conform to the European Pressure Equipment Directive (PED) 97/23/EC are available in ANSI Class 150/300, both standard and Fire-Tite® construction. Operating torques, construction options and valve dimensions are exactly the same as the standard ANSI 150/300 offering. The applicable sizes for CE marked valves are shown in table to left.

Positive Shaft Retention

2-1/2" – 24" (DN 65 – 600) valves are equipped with a retaining ring at the top of the shaft to prevent movement of the top portion of the shaft past the compression ring if for any reason the shaft should break within the valve.

Easy Seat Maintenance

Simply remove body insert and replace seat – disassembly of disc and shaft is not required

Excellent for both On-Off and Control Applications

- Superior control characteristics
- Inherent flow characteristic is modified equal percentage
- Wide rangeability
- Tight shut-off even in control applications
- Standard lugged style valves are suitable for bi-directional dead-end service at the full pressure-temperature rating of the valve.

Single-Source Responsibility

Purchase valves, actuators, and accessories, completely mounted from one source

Available with electric, manual gear, and pneumatic double acting or spring return actuators and a variety of accessories including limit switches, solenoids, and positioners

OEM service available through world-wide service centers

Available in a Wide Choice of Materials for a Broad Range of Applications

Standard body materials include ductile iron, carbon steel, stainless steel, Alloy 20, and Monel®. Other materials, such as Avesta® 254SMO are available on application.

Jamesbury

Bulletin W101-6

Issue 11/2003

ADDITIONAL INFORMATION

Please refer to the bulletins listed below for additional information on other Jamesbury high-performance butterfly valves.

Wafer-Sphere polymer (soft) seat HP Butterfly valves

ASME/ANSI Class 600	W104-1
ASME/ANSI Class 150 (Process rated)	W105-1
Cryogenic Service	W130-1
Steam Service	W150-1
Chlorine Service	W150-2
Oxygen Service	W150-3
Vacuum Service	W150-4
Jacketed Valves	W151-3

SPECIFICATIONS

Valve Seat Ratings

Seat ratings, shown by the graph at right, are based on differential pressure with the *disc in the fully closed position* and refer to **seats** only. Maximum body working pressures are shown in the **Valve Body Ratings** tables below.

Valve Body Ratings

The tables below are maximum working pressure ratings of the **valve body only**. The seat ratings determine the practical pressure limitations according to actual service conditions. Test pressures are for hydrostatic test with disc open.

Series 815, Class 150 Valve Body Ratings – psi					
Temp °F	Carbon Steel*	Ductile Iron*	316 Stainless Steel*	Alloy 20*	Monel
-20 to 100	285	250	275	230	230
200	260	235	240	200	200
300	230	215	215	180	190
400	200	200	195	160	185
500	170	170	170	150	170
Test Pressure	450	400	425	350	350

Series 815, Class 150 Valve Body Ratings – bar					
Temp °C	Carbon Steel*	Ductile Iron*	316 Stainless Steel*	Alloy 20*	Monel
-29 to 38	19.7	17.2	19.0	15.8	15.8
93	17.9	16.2	16.5	13.8	13.8
149	15.8	14.8	14.8	12.4	13.1
204	13.8	13.8	13.4	11.0	12.8
260	11.7	11.7	11.7	10.3	11.7
Test Pressure	31	27.6	29.3	24.1	24.1

Series 830, Class 300 Valve Body Ratings – psi				
Temp °F	Carbon Steel*	316 Stainless Steel*	Alloy 20*	Monel
-20 to 100	740	720	600	600
200	675	620	520	530
300	655	560	465	495
400	635	515	420	480
500	600	480	390	475
Test Pressure	1125	1100	900	900

Series 830, Class 300 Valve Body Ratings – bar				
Temp °C	Carbon Steel*	316 Stainless Steel*	Alloy 20*	Monel
-29 to 38	51	49.6	41.4	41.4
93	46.5	42.7	35.9	36.5
149	45.2	38.6	32.1	34.1
204	43.8	35.5	29.0	33.1
260	41.4	33.1	26.9	32.8
Test Pressure	77.6	75.8	62	62

* Ratings correspond to ASME/ANSI B16.34-1996 for material grades shown in bills of material herein. Ductile iron ratings conform to ASME/ANSI B16.42

NOTE: 14" – 60" (DN 350 – 1500) Class 150 valves equipped with 316 stainless or Alloy 20 shafts are rated for maximum differential pressure of 150 psi (10.35 bar).

3" – 36" (DN 80 – 900) Class 300 valves equipped with 316 stainless or Alloy 20 shaft are rated for maximum differential pressure of 300 psi (20.7 bar).

These ratings are a conservative guide for general service. Previous experience in a process or new developments and alternative seat materials may permit applications at ratings above those shown. Please consult our home office for specific recommendations.

Flow Data

The tables below provide flow coefficients for Series 815 and 830 butterfly valves covered in this bulletin. The C_v values represent the number of gallons per minute of +60°F water that flows through a fully open valve at a pressure drop of 1 psi. The metric equivalent, K_v , is the flow of water at 16°C through the valve in cubic meters per hour at a pressure drop of 1 kg/cm². To convert C_v to K_v , multiply by 0.8569. C_v values for partially open valves are given below.

Series 815		
Valve Size		C_v
Inches	DN	
2-1/2	65	78
3	80	165
4	100	400
5	125	650
6	150	1,050
8	200	2,200
10	250	3,300
12	300	5,100
14	350	5,800
16	400	8,000
18	450	10,500
20	500	14,000
24	600	21,600
30	750	34,000
36	900	55,500
42	1050	82,650
48	1200	108,300
54	1350	133,500
60	1500	159,000

Series 830		
Valve Size		C_v
Inches	DN	
3	80	165
4	100	400
6	150	1,050
8	200	1,800
10	250	3,150
12	300	4,750
14	350	5,200
16	400	6,900
18	450	9,300
20	500	11,300
24	600	18,500
30	750	29,100
36	900	47,500

Flow Data (Continued)

To determine C_v values for a valve in an intermediate position: (1) determine the percent of maximum C_v from the graph at right (2) multiply the percent of maximum C_v shown on the graph by the C_v value from the appropriate **Flow Data** table on the previous page.

EXAMPLE: The C_v for a 6" (DN 150) 815 that is 70% open is:

(1) From the graph, a 6" (DN 150) 815 that is 70% open has a C_v value that is 53% of the maximum C_v .

(2) 53% of the maximum $C_v = 0.53 \times 1050 = 560$.

SEAT DESIGNS

Xtreme Performance and Value

Xtreme seats provide longer life, expanded performance boundaries, and the greatest possible value. Xtreme is a unique material that resulted from a technological breakthrough in our polymer research lab. The material is a fluoropolymer-based blend proprietary to Jamesbury that provides superior quarter-turn performance.

Standard Seats

Wafer-Sphere standard seat design, constructed of PTFE, Filled PTFE, or UHMW Polyethylene, utilizes a flexible lip, which, when distorted, will always attempt to return to its original shape and maintain a seal against the disc regardless of flow direction.

When the valve is shut, the disc slightly deflects the seat. This slight deflection "energizes" the seat. While energized, the sealing surface of the seat is constantly pushing against the edge of the disc.

When pressure is on the insert side, pressure is applied under the seat lip. This further amplifies the sealing force between the disc and the seat.

When pressure is on the non-insert side, the disc moves into the seat. Due to the spherical profile of the disc, the more the disc moves into the seat, the tighter the shut-off. Excessive movement of the seat is limited by the flexible lip which contacts the bottom of the groove in the insert ring.

Seat Tightness

ANSI/FCI 70-2 establishes a series of six leakage classes for control valves and defines the test procedure. Class VI allows the least leakage. Wafer-Sphere High Performance Butterfly Valves are bubble-tight, MSS-SP61, which would exceed Class VI requirements.

Fire-Tite Seats

The Fire-Tite seat was developed for applications where effective shut-off during a fire is a concern. The primary sealing element is PTFE with a back-up metal seat ring. In the event that the PTFE is destroyed, the secondary metal seat provides effective shut-off. The Fire-Tite seat is also ideal for critical or severe service applications. Wafer Sphere butterfly valves with Fire-Tite seats have been tested and approved to API 607 Edition 4 and to BS6755 part 2.

METSO ACTION UNION

SPECIAL SERVICES

Emission-Pak® Live-Loaded Packing

When enhanced emissions control is needed to comply with evolving emissions standards, Emission-Pak live-loaded packing is available. The Emission-Pak live-loaded packing assembly includes PTFE V-ring packing live-loaded with disc spring washers to maintain a constant packing force without overcompression. It is available with new valves or as a retrofit kit for existing valves. Additional options, available with or without the Emission-Pak live-

loaded packing, include double packing or double packing with monitoring port to facilitate testing of the primary seal and allow detection of a potential leak problem. Refer to the How to Order section at the end of this bulletin for specific ordering instructions. The **operating torque** of valves with Emission-Pak live-loaded packing will increase. (Refer to the torque equation in the Valve Torque Data section).

Emission-pak Live-loaded Packing

Emission-pak Live-loaded Packing With Double Packing

Emission-pak Live-loaded Packing With Double Packing And Monitoring Port

Steam Service.

Wafer-Sphere butterfly valves are well-suited for a wide range of steam applications. These range from PTFE-seated valves capable of handling lower pressure to valves with Xtreme seats. Ratings of Wafer-Sphere valves in this bulletin for on-off steam service are as follows: Valves may be derated based on shaft material selection.

Valve Type	Seat Material	Maximum Pressure Differential	
		psi	bar
815W, 815L	Xtreme	200*	14*
830W, 830L	Xtreme	450	31

* Max. rating of carbon steel body per ASME/ANSI B16.34 at corresponding saturated steam temperature.

Cryogenic Service

Using Wafer-Sphere with unique polymeric and polymeric/metal composite seats, cryogenic Wafer-Sphere valves are rated to give tight, reliable shutoff on service extending from -420°F (-251°C) to ambient condition at pressures up to 1440 psi (99 bar). Cryogenic seats for valve sizes 3" – 12" (DN 80 – 300) are composite. Seats for sizes 14" – 48" (DN 350 – 1200) are Kel-F® material. See Bulletin W130-1.

Chlorine Service

Wafer-Sphere valves reliably control the flow of both liquid and gaseous chlorine. The patented seat design insures positive, leaktight shutoff of this lethal substance. A range of key materials permits selection of the Wafer-Sphere valve best suited for the moisture content of the chlorine that is to be handled. Valves for chlorine service are specially cleaned to preclude possible reaction of the chlorine to foreign substances. For further information see Bulletin W150-2.

Oxygen Service

Wafer-Sphere valves are available specially prepared for oxygen service, capable of filling a wide range of applications that include both on-off operation and proportional control. A rigid procedure is followed in preparing components,

assembling, testing, and packaging these valves to assure cleanliness and to avoid the inherent danger of oxygen's reaction with grease, oil, or other foreign matter. Bulletin W150-3 contains additional details.

NACE Service

ANSI Class 150 and 300 Wafer-Sphere valves are available to comply with the NACE MR0103 standard. These valves are well suited for oil and gas industry applications requiring sulfide stress cracking resistant metallic materials.

Abrasive Service

For applications involving slurries or gas-borne solid particles, Wafer-Sphere valves are available with the disc hard-coated with tungsten titanium carbide (TTC). Service life of the valve is increased significantly with the assurance of extended sealing capability. This hard coating is also available on application on other valve components that may be subject to wear in other unusual process conditions.

Vacuum Service

Standard Wafer-Sphere valves are rated for tight shut-off of vacuum to 2×10^{-3} torr. Special high vacuum Wafer-Sphere valves can be provided for vacuums to 1×10^{-5} torr. Additionally, high vacuum valves can be certified to have a leakage rate not to exceed 1×10^{-2} cc/sec. of helium at 1×10^{-5} torr vacuum. Refer to Bulletin W150-4 for details.

High-Cycle Option

Testing in the Jamesbury R&D laboratories indicates that a combination of components, including Xtreme(X) seat, filled super PTFE shaft seals, 316 SS/Woven PTFE shaft bearings, PEEK®-filled PTFE thrust bearings and excluder rings, yields significantly longer life than a standard configuration valve. Actual cycle performance is subject to media, pressure, and temperature conditions. Applications such as oxygen, nitrogen, hydrogen, water, and other clean media are ideally suited for this option. **Warning:** Avoid any media containing acids or chemicals such as chlorine, bromine, sulfur dioxide, or steam, or temperatures that exceed 325°F (163°C).

SEMI-RTS AND CLASS 150 AND 300 WSH AND FAWN 100 WAFER-SPHERE HIGH PERFORMANCE BUTTERFLY VALVES

OPERATING HANDLES AND ACTUATORS

As an option, handles are available for smaller sizes of the Wafer-Sphere high-performance butterfly valve. We recommend that manual-gear, pneumatic, or electric

actuators be used at differential pressures higher than the values listed below.

Series 815											
Valve Size		Valve Type	Maximum Differential Pressure				Handle Length		Handle Weight		Handle Code
			T, M, or U Seats		Fire-Tite Seat						
Inches	DN		psi	bar	psi	bar	Inches	mm	lb.	kg	
2 1/2	65	815W/815L	285	19.7	285	19.7	11	279	3	1.3	WSH-36*
3	80	815W/815L	285	19.7	285	19.7	11	279	3	1.3	WSH-36*
4	100	815W/815L	285	19.7	285	19.7	11	279	3	1.3	WSH-36*
5	125	815W/815L	150	10.3	---	---	11	279	3	1.3	WSH-36*
6	150	815W/815L	150	10.3	---	---	11	279	3	1.3	WSH-38*
8	200	815W/815L	150	10.3	---	---	22	559	15	6.8	WSH-23
10	250	815W/815L	50	3.4	---	---	22	559	15	6.8	WSH-24
12	300	815W/815L	50	3.4	---	---	22	559	15	6.8	WSH-25

Series 830											
Valve Size		Valve Type	Maximum Differential Pressure				Handle Length		Handle Weight		Handle Code
			T, M, or U Seats		Fire-Tite Seat						
Inches	DN		psi	bar	psi	bar	inches	mm	lb.	kg	
3	80	830W/830L	300	20.7	300	20.7	11	279	3	1.3	WSH-36*
4	100	830W/830L	300	20.7	300	20.7	11	279	3	1.3	WSH-36*
6	150	830W/830L	150	10.3	—	—	22	559	15	6.8	WSH-23
8	200	830W/830L	150	10.3	—	—	22	559	15	6.8	WSH-24
10	250	830W/830L	50	3.4	—	—	22	559	15	6.8	WSH-25

Materials of Construction for Handle Kits			
Part Number**	Part Name	Handle Code	
		WSH-36 WSH-38	WSH-23 WSH-24 WSH-25
H1	Handle Subassembly	Stainless steel	Malleable iron
H2	Ratchet	Stainless steel	Carbon steel
H3	Cap Screw	Stainless steel	Carbon steel
H4	Lock Washer	—	Carbon steel
H5	Hex Nut	—	Carbon steel
H6	Cap Screw	Stainless steel	Carbon steel
H7	Lock Washer	Stainless steel	Carbon steel

* Equipped with a lockout as standard ** Refer to drawing on pages 11 and 12.

VALVE TORQUE DATA

VALVE TORQUE DATA

The torque required to open or close the Series 815 and Series 830 can easily be calculated using the equation on the following page. However, for your convenience, the following tables can be used as a quick guide for actuator selection. If the valve's torque is not listed in the tables,

use the equation on next page to calculate the torque. Refer to other bulletins for pneumatic and electric actuators. Select an actuator that provides the same or greater torque output than the valve's torque. **If in doubt, select the next larger actuator.**

Valve Size		Torque – Series 815 Shaft Downstream; T, M, U, & X Seats					
		Shut-off Differential Pressure					
Inches	DN	FT-LBS @ 100 psi	N-m @ 6.9 bar	FT-LBS @ 200 psi	N-m @ 13.8 bar	FT-LBS @ 285 psi	N-m @ 19.7 bar
2-1/2	65	21	29	23	31	24	33
3	80	25	34	27	37	29	39
4	100	35	47	39	53	43	58
5	125	48	65	56	76	63	86
6	150	72	97	83	113	93	126
8	200	121	164	142	193	160	217
10	250	163	222	202	274	234	318
12	300	214	290	287	390	350	475
14	350	362	491	505	684	626	849
16	400	463	628	646	876	802	1087
18	450	602	816	844	1144	1050	1423
20	500	810	1098	1140	1546	1421	1926
24	600	1234	1673	1758	2384	2200	2983
30	750	2170	2942	2940	3986	3595	4873
36	900	3530	4786	4860	6589	5990	8121
42	1050	5780	7837	8060	10928	10000	13558
48	1200	9170	12433	12840	17409	15960	21638
54	1350	12950	17558	17900	24269	22110	29977
60	1500	19020	25790	26040	35310	32000	43397

Valve Size		Torque – Series F815 Shaft Downstream or Upstream; All Fire-Tite Seats					
		Shut-off Differential Pressure					
Inches	DN	FT-LBS @ 100 psi	N-m @ 6.9 bar	FT-LBS @ 200 psi	N-m @ 13.8 bar	FT-LBS @ 285 psi	N-m @ 19.7 bar
2-1/2	65	42	57	45	61	47	64
3	80	53	72	57	77	59	81
4	100	67	91	74	100	80	108
5	125	97	132	114	155	128	174
6	150	131	178	152	206	170	230
8	200	218	296	256	347	288	391
10	250	333	452	406	550	468	635
12	300	508	689	636	862	745	1010
14	350	604	819	758	1028	889	1205
16	400	710	963	920	1247	1099	1489
18	450	970	1315	1370	1857	1710	2318
20	500	1390	1885	1980	2685	2482	3364
24	600	2050	2779	2700	3661	3353	4410
30	750	2920	3959	3940	5342	4807	6517
36	900	3530	4786	4960	6725	6176	8373
42	1050	5620	7620	7440	10087	8987	12185
48	1200	8800	11931	12100	16405	14905	20208

Valve Size		Torque – Series 830 Shaft Downstream; T, M, U, & X Seats											
		Shut-off Differential Pressure											
Inches	DN	FT-LBS @ 300 psi	N-m @ 20.7 bar	FT-LBS @ 400 psi	N-m @ 27.6 bar	FT-LBS @ 500 psi	N-m @ 34.5 bar	FT-LBS @ 600 psi	N-m @ 41.4 bar	FT-LBS @ 700 psi	N-m @ 48.3 bar	FT-LBS @ 740 psi	N-m @ 51 bar
3	80	31	42	34	46	38	51	41	55	44	60	45	62
4	100	52	70	58	79	65	88	72	97	78	106	81	110
6	150	119	161	138	188	158	214	178	241	197	267	205	278
8	200	231	313	271	368	312	422	352	477	392	532	408	554
10	250	354	480	422	572	490	664	557	756	625	848	652	885
12	300	492	667	582	790	673	913	764	1035	854	1158	890	1207
14	350	824	1117	1012	1372	1200	1627	1388	1882	1576	2137	1651	2239
16	400	989	1340	1212	1643	1435	1946	1658	2248	1881	2550	1970	2671
18	450	1279	1734	1562	2118	1845	2502	2128	2885	2411	3269	2524	3422
20	500	1707	2314	2096	2842	2485	3369	2874	3897	3263	4424	3419	4635
24	600	2309	3131	2832	3840	3355	4549	3878	5258	4401	5967	4610	6251
30	750	4210	5708	5080	6888	5950	8067	6820	9247	7690	10426	8038	10898
36	900	7220	9789	8760	11877	10300	13965	11840	16053	13380	18141	13996	18976

2. For valves with Live-Loaded PTFE shaft packing, use (Ts x 1.06). For valves with Live-Loaded Graphite shaft packing, use (Ts x 1.26).

VALVE TORQUE DATA (CONTINUED)

Valve Size		Torque – Series F830											
		Shaft Upstream or Downstream; All Fire-Tite Seats											
		Shut-off Differential Pressure											
Inches	DN	FT•LBS @ 300 psi	N•m @ 20.7 bar	FT•LBS @ 400 psi	N•m @ 27.6 bar	FT•LBS @ 500 psi	N•m @ 34.5 bar	FT•LBS @ 600 psi	N•m @ 41.4 bar	FT•LBS @ 700 psi	N•m @ 48.3 bar	FT•LBS @ 740 psi	N•m @ 51 bar
3	80	57	77	58	79	60	81	61	83	63	85	63	86
4	100	86	117	94	127	102	138	110	149	118	160	121	164
6	150	189	256	212	287	235	319	258	350	281	381	290	394
8	200	313	424	354	480	395	536	436	591	477	647	493	669
10	250	464	629	522	708	580	786	638	865	696	944	719	975
12	300	825	1119	960	1302	1095	1485	1230	1668	1365	1851	1419	1924
14	350	922	1250	1076	1459	1230	1668	1384	1877	1538	2085	1600	2169
16	400	1170	1586	1390	1885	1610	2183	1830	2481	2050	2779	2138	2899
18	450	1980	2685	2440	3308	2900	3932	3360	4556	3820	5179	4004	5429
20	500	2800	3796	3460	4691	4120	5586	4780	6481	5440	7376	5704	7734
24	600	4400	5966	5400	7321	6400	8677	7400	10033	8400	11389	8800	11931

TORQUE EQUATION

Use the following equation to calculate the torque required to open and close the Series 815 and Series 830 valves.

Torque required (FT•LBS) = (Kt multiplied by the shut-off differential pressure in psi) + Ts

EXAMPLE: 6" (DN 150) 815W-11-36HBMT at 230 psi (15.9 bar) differential pressure, installed shaft downstream = (0.116 X 230) + 60 = 87 FT•LBS.

To convert FT•LBS to N•m, multiply by 1.356.

Valve Size		Class 150					Class 300				
		Series 815 T, M, U, & X Seats			Series 815 Fire-Tite		Series 830 T, M, U, & X Seats			Series 830 Fire-Tite	
		Kt Shaft Upstream	Kt Shaft Downstream	Ts	Kt Shaft Upstream or Downstream	Ts	Kt Shaft Upstream	Kt Shaft Downstream	Ts	Kt Shaft Upstream or Downstream	Ts
Inches	DN										
2-1/2	65	0.017	0.014	20	0.024	40	—	—	—	—	—
3	80	0.021	0.021	23	0.033	50	0.034	0.033	21	0.015	52
4	100	0.046	0.046	30	0.07	60	0.068	0.066	32	0.08	62
5	125	0.105	0.081	40	0.13	65	—	—	—	—	—
6	150	0.156	0.116	60	0.21	110	0.203	0.196	60	0.23	120
8	200	0.301	0.211	100	0.38	180	0.423	0.403	110	0.41	190
10	250	0.584	0.384	125	0.73	260	0.689	0.674	150	0.58	290
12	300	0.847	0.737	140	1.28	380	1.106	0.906	220	1.35	420
14	350	2.034	1.424	220	1.54	450	2.28	1.88	260	1.54	460
16	400	2.88	1.83	280	2.1	500	3.21	2.23	320	2.2	510
18	450	3.65	2.42	360	4.0	570	3.94	2.83	430	4.6	600
20	500	4.72	3.30	480	5.9	800	5.01	3.89	540	6.6	820
24	600	7.34	5.24	710	6.5	1400	6.88	5.23	740	10	1400
30	750	11.2	7.7	1400	10.2	1900	9.4	8.7	1600	—	—
36	900	20.4	13.3	2200	14.3	2100	16.1	15.4	2600	—	—
42	1050	29.9	22.8	3500	18.2	3800	—	—	—	—	—
48	1200	43.7	36.7	5500	33	5500	—	—	—	—	—
54	1350	59.5	49.5	8000	—	—	—	—	—	—	—
60	1500	80.7	70.2	12000	—	—	—	—	—	—	—

Note: The Ts value for a valve with Emission Pak Live-Loaded Packing will increase. For valves with Live-Loaded PTFE shaft packing, use (Ts x 1.06). For valves with Live-Loaded Graphite shaft packing, use (Ts x 1.26).

TEST COMBUSTOR

FEATURED PRODUCT - SERIES RKW PROGRAMMABLE

DIN-RAIL MOUNTABLE

1500W, 600W and 300W RKW Models

The Programmable-Series RKW are industrial-grade single-output power supplies in the 300, 600 and 1500 watt sizes. They provide d-c outputs from 3.3 volts to 48 volts from a-c mains 85-265V a-c with power factor correction (PFC). They are fully enclosed, fan-cooled power supplies. All models feature overvoltage and overcurrent protection and remote error sensing and feature a remote on-off control, remote voltage trimming and master-slave paralleling with a current balance function. The RKW conform to EN60950 following the provisions of the Low Voltage Directive 73/23/EEC and 93/68/EEC for the CE mark. Conducted EMI is suppressed to FCC Class B, VCCI Class B, EN55011-B and EN55022-B. The 300 and 600 watt models meet the radiated noise limits of FCC Class B and EN55022 Class B. The RKW 1500 watt models meet the Class A limits for both conducted and radiated EMI, but can be upgraded to Class B with a noise filter, PN 245-0031. Consult factory for details.

CE RKW are CE marked per the Low Voltage Directive (LVD), EN60950.

FEATURES

- Output indicator, green LED.
- Remote on-off logic control.
- Remote error sensing.
- Parallel operation for redundancy or to increase current.
- Current share circuitry to equalize current.
- Remote voltage programming by resistance.
- Remote voltage programming by voltage.
- Master-slave operation.
- Power fail logic signal.
- Thermal protection.
- Overvoltage protection.
- Overcurrent protection.
- Power factor corrected, wide-range a-c input.
- DIN-Rail mountable. For information, consult factory.

RKW Programmable modules can be individually installed or may be combined into a custom power assembly for multi-output requirements. Please see pages 131-135 for details on Kepco's Power Assembly Program.

KEPCO, INC. • 131-38 Sanford Avenue • Flushing, NY 11352 USA • Tel: (718) 461-7000 • Fax: (718) 767-1102
Email: hq@kepcopower.com • www.kepcopower.com

RKW PROGRAMMABLE MODEL TABLE

MODEL	OUTPUT	ADJUSTMENT RANGE	OVP SETTING (1)	OUTPUT CURRENT	CURRENT LIMIT	SHORT CIRCUIT CURRENT	SWITCHING RIPPLE	NOISE	EFFICIENCY (%) TYPICAL	
	Volts		Volts	Amps -10 to +50°C	Amps(2)	Amps	mV p-p	mV p-p(3)	100V a-c	200V a-c
300 WATT MODELS										
RKW 3.3-70K	3.3	1.8-3.6	3.96-4.62	70	73.5-91	90	80	120	68	72
RKW 5-60K	5	3.5-6.0	6.0-7.0	60	63.0-78.0	82	80	120	74	78
RKW 12-27K	12	7.2-14.4	14.4-16.8	27	28.4-35.1	35	120	150	76	80
RKW 15-22K	15	10.5-18.0	18.0-21.0	22	23.1-28.6	29	120	150	77	81
RKW 24-14K	24	16.8-28.8	28.8-33.6	14	14.7-18.2	20	150	200	80	84
RKW 28-12K	28	19.6-33.6	33.6-38.4	12	12.6-15.6	17	150	200	80	84
RKW 48-7K	48	33.6-52.8	50.5-58.0	7	7.4-9.1	11	200	300	81	85
600 WATT MODELS										
RKW 3.3-150K	3.3	1.8-3.6	3.96-4.62	150	156-186	180	80	120	74	78
RKW 5-120K	5	3.5-6.0	6.0-7.0	120	126-156	160	80	120	76	81
RKW 12-53K	12	7.2-14.4	14.4-16.8	53	55.6-68.9	65	150	200	80	84
RKW 15-43K	15	10.5-18.0	18.0-21.0	43	45.1-55.9	55	150	200	81	85
RKW 24-27K	24	16.8-28.8	28.8-33.6	27	28.3-35.1	35	200	300	82	86
RKW 28-23K	28	19.6-33.6	33.6-38.4	23	24.1-29.8	29	200	300	82	86
RKW 48-13K	48	33.6-52.8	52.8-60.0	13	13.7-16.9	19	300	400	84	87
1500 WATT MODELS										
RKW 3.3-375K	3.3	1.8-3.6	3.96-4.62	375	390-430	430	100	200	73	77
RKW 5-300K	5	3.5-6.0	6.0-7.0	300	315-350	350	100	200	77	82
RKW 12-125K	12	7.2-14.4	14.4-16.8	125	130-140	152	150	200	80	84
RKW 15-100K	15	10.5-18.0	18.0-21.0	100	105-115	135	150	200	82	86
RKW 24-65K	24	16.8-28.8	28.8-33.6	65	68-72	80	200	300	82	86
RKW 28-55K	28	19.6-33.6	33.6-38.4	55	57.7-63.2	70	200	300	82	86
RKW 48-32K	48	33.6-52.8	52.8-60.0	32	33.6-36.8	45	300	400	84	88

- (1) An overvoltage shuts down the output. Recover by resetting the RC terminals. The overvoltage setting tracks the REF voltage.
 (2) The current limit is rectangular. If overcurrent persists for more than 30 seconds, the output shuts down. Reset by resetting the RC terminals.
 (3) Bandwidth 100MHz. Ripple and noise will be approximately 1.5 times these values in the operating temperature range -10-0 °C.
 The ripple and noise values tabulated are valid when the output is derated as shown in figure 1 from 50-65 °C.

PROGRAMMABLE POWER 300-1500 WATTS

The new Kepco RKW Programmable power supplies are more than high-efficiency switch-mode boxes. Beyond their wide-range a-c (or d-c) input, beyond their power factor correction (PFC) to reduce harmonic corruption of the a-c mains, beyond the current-share capacity that allows multi-unit paralleling, the RKW are **fully programmable** by either external voltage (0-5V) or by resistance.

The output will track the programming signal with remarkable fidelity as the traces to the right show. Of course, the RKW have large output capacitors so the time constant will depend upon load – and at very light loads or no load, the discharge response will be slow.

Note particularly the linearity of the RKW power supply's response to square and triangular programming inputs. A 0-5V signal programs the output from 0 to maximum output. A 0-5.5V programming signal will control the RKW to 10% over the rated nominal output.

Output voltage from
0V goes to 52.8V (CH2)
Rising Time = 8.50 ms

Output voltage from
52.8V goes to 0V (CH2)
Falling Time = 9.92 ms

RKW PROGRAMMABLE GENERAL SPECIFICATIONS

SPECIFICATION		RATING/DESCRIPTION	CONDITION
Temperature	Operating	-10 to +50°C	See rating curves, figure 1
	Start up	-20 to +10°C	
	Storage	-30 to +75°C	
Humidity	Operating	10 to 95% RH	Wet bulb temperature <35°C No condensation
	Storage	10 to 95% RH	
Vibration	5-10Hz	10mm amplitude	Sweep time 10 min. 1 hr each axis, not operating
	10-200Hz	2g	
Shock	Acceleration	30g 1/2 sine pulse duration 11 ±5 msec	3 shocks each axis, not operating
Withstand Voltage	Input-Output	a-c 3.0KV 1 min.	Cutout current ⁽¹⁾
	Input-Ground	a-c 2.0KV 1 min.	Cutout current ⁽¹⁾
	Output-Ground	a-c 500V 1 min.	Cutout current ⁽¹⁾
Insulation Resistance	Input-Output	>100MΩ	500V d-c ⁽²⁾
	Input-Ground	>100MΩ	500V d-c ⁽²⁾
	Output-Ground	>100MΩ	500V d-c ⁽²⁾
Safety Standards		UL1950	Certified by UL
		CSA C22.2 No. 950-95	
		EN 60950	Certified by TÜV

(1) Cutout current, 300 and 600W models = 100mA, 1500W models = 300mA.

(2) Normal temperature (15-35°C) and humidity (10%-85% RH).

RKW FUNCTIONS

DESCRIPTION	300W	600W	1500W
Overvoltage	yes	yes	yes
Overcurrent	yes	yes	yes
Thermal Protection	yes	yes	yes
PFC	yes	yes	yes
Remote On-Off	yes	yes	yes
External Voltage Adjust	yes	yes	yes
Remote Sense	yes	yes	yes
Parallel Operation	yes	yes	yes
Master-Slave Operation	yes	yes	yes
Series Operation	yes	yes	yes
Current Balance	yes	yes	yes
Operation Indicator	yes	yes	yes
Power Fail Alarm	yes	yes	yes
Fan	yes	yes	yes (two)

FIGURE 1
Output Power vs. Ambient Temperature
300, 600, 1500W Models

KEPCO, INC. • 131-38 Sanford Avenue • Flushing, NY 11352 USA • Tel: (718) 461-7000 • Fax: (718) 767-1102
Email: hq@kepcopower.com

Model RKW 12-27K
300 Watts

Model RKW 48-13K
600 Watts

Model RKW 12-125K
1500 Watts

RKW PROGRAMMABLE COMMON INPUT CHARACTERISTICS

SPECIFICATIONS	RATING/DESCRIPTION	CONDITION
Input Voltage Range	85-265V a-c 110-370V d-c ⁽²⁾	0-100% load, -10 to +50°C
Input Frequency Range	47-66Hz	0-100% load, -10 to +50°C
EMI Conducted Noise ⁽¹⁾	FCC Class B, VCCI-Class B EN55011-B, EN55022-B	300-600W models. 1500W models require noise filter: PN 245-0031
Radiated Noise ⁽¹⁾	FCC Class B, VCCI-Class B EN55011-B, EN55022-B	
Immunity To Electrostatic Discharge (ESD)	EN61000-4-2 Level 4	Normal operation
Radiated Susceptibility	EN61000-4-3 Level 3	Normal operation
Electrical Fast Transient	EN61000-4-4 Level 3	Normal operation
Surge Withstand	EN61000-4-5 Level 4	No damage
Conducted Susceptibility	EN61000-4-6 Level 3	Normal operation
Power Freq Mag Field	EN61000-4-8 Level 4	Normal operation
Voltage Dips, Short Interruptions and Voltage Variations	EN61000-4-11	Normal operation
Input Harmonics	EN61000-3-2	

(1) The 300 and 600W RKW meet radiated and conducted FCC Class B and EN55022 Class B limits. The RKW 1500W models meet radiated and conducted FCC Class A and EN55022 Class A. The radiated and conducted emissions of the 1500W models are reduced to the Class B level by the use of a noise filter, PN 245-0031. Consult factory.
(2) Safety agency approval applies only to a-c input operation.

RKW PROGRAMMABLE MODEL-SPECIFIC INPUT CHARACTERISTICS

SPECIFICATION	CONDITION	300W	600W	1500W
Input Current	100-120V a-c	4.4	8.4	22
Amps	200-240V a-c	2.2	4.2	11
(5V-48V models)				
Input Current	100-120V a-c	3.6	7.2	18
Amps	200-240V a-c	1.8	3.6	9
(3.3V models)				
Surge Current	120V a-c	20	30	20
Amps, typ ⁽¹⁾	240V a-c	40	60	40
Fuse Value		10	15	30
Amps				
Switching Frequency		200KHz	140KHz	140KHz ⁽²⁾
Leakage Current	120V a-c	0.24	0.45	0.5
typ (mA)	240V a-c	0.31	0.6	1.1
Leakage Current	120V a-c	0.3	0.75	0.8
max (mA)	240V a-c	0.38	0.75	1.6
Power Factor	120V a-c	0.99	0.99	0.99
	240V a-c	0.99	0.95	0.95

(1) First surge only, not including the current flow into the EMI filter.

(2) Model RKW 3-375K: 100KHz.

KEPCO, INC. • 131-38 Sanford Avenue • Flushing, NY 11352 USA • Tel: (718) 461-7000 • Fax: (718) 767-1102
Email: hq@kepcopower.com • www.kepcopower.com

RKW PROGRAMMABLE COMMON OUTPUT CHARACTERISTICS

SPECIFICATIONS		RATING DESCRIPTION	CONDITION
Source Effect	typ	0.1% (1)	85-132 or 170-265V a-c
	max	0.2% (1)	
Load Effect	typ	See model specific output ratings	0-100% load
Temperature Effect	typ	0.5%	-10°C to +65°C
	max	1.0%	
Combined Effect	typ	±0.9% (2)	Source, load and temperature
	max	±1.8% (2)	
Time Effect (drift)	typ	0.2%	0.5-8 hours
	max	0.5%	
Transient Recovery Characteristic	Excursion	±4% maximum	50-100% load transient time >50µsec
	Recovery	1millisecond max	
Start Up Time	100V a-c	See model specific output ratings	
Hold Up Time	100V a-c	See model specific output ratings	
Remote Error Sensing	3.3V models	0.15V	Voltage compensation per line
	5V models	0.25V	
	12-48V models	0.4V	

(1) 3.3V models: 600 and 1500W: 0.15% typ, 0.3% max; 300W: 5mV typ, 10mV max.
 (2) 3.3V models: 600 and 1500W: ±1.1% typ, ±2.2% max.

RKW PROGRAMMABLE MODEL-SPECIFIC OUTPUT CHARACTERISTICS

SPECIFICATION	CONDITION	300W	600W	1500W
Load Effect	typ	0.2%	0.3%	0.3%
	max	0.4% (2)	0.6% (1)	0.6% (1)
Start Up Time typ msec	100V a-c	280	280	280
	240V a-c	150	100	180
Start Up Time max msec	100V a-c	350	350	500
	240V a-c	210	150	400
Hold Up Time typ msec	100V a-c	30	30	35
	240V a-c	40	40	40
Hold Up Time min msec	100V a-c	20	20	20
	240V a-c	20	20	20

(1) 3.3V models: 0.45% typ, 0.9% max.

(2) 3.3V models: 10mV typ, 20mV max.

RKW PROGRAMMABLE MECHANICAL SPECIFICATIONS

SPECIFICATION		300W	600W	1500W
Dimensions English	Height	3.62"	3.62"	3.62"
	Width	3.15"	4.72"	7.48"
	Length	6.89"	7.87"	11.81"
Dimensions Metric	Height	92mm	92mm	92mm
	Width	80mm	120mm	190mm
	Length	175mm	200mm	300mm
Weight	English	3.96 lb.	6.6 lb.	13.2 lb.
	Metric	1.8Kg	3.0Kg	6.0Kg
Cooling		1 fan		2 fans
Mounting		3 surface (see figure 2)		

FIGURE 2
Mounting Directions
300, 600, 1500W Models

The fan should be situated at intervals of 30mm min. from other equipment in a well ventilated area.

OUTLINE DIMENSIONAL DRAWINGS

Fractional dimensions in light face type are in inches. **dimensions in bold face type are in millimeters.**

**RKW
300W
Models**

FRONT VIEW

SIDE VIEW

TOP VIEW

REAR VIEW

RKW 600W Models

FRONT VIEW

SIDE VIEW

TOP VIEW

REAR VIEW

RKW 1500W Models

FRONT VIEW

SIDE VIEW

TOP VIEW

REAR VIEW

KEPCO, INC. • 131-38 Sanford Avenue • Flushing, NY 11352 USA • Tel: (718) 461-7000 • Fax: (718) 767-1102
Email: hq@kepcopower.com

FUEL SKID

M-03 Series

M-23 Integral Gas Engine Powered System

The M-23 model is a direct drive system designed to be close coupled with a Honda engine (Model GX160K1LX) 5.5 HP with 2:1 gearbox.

M-03 with brass pump head
(close coupled) for 56C frame motors

D-03 (shaft-driven)

M-03 with polypropylene pump head
(close coupled) for 56C frame motors

Hydra-Cell
SIMPLY BUILT TO LAST

M-03 Series

M-03-X	3.0	11.3	1750
M-03-E	2.2	8.3	1750
M-03-S	1.8	6.8	1750
M-03-B	1.1	4.2	1750
M-03-G	0.5	1.9	1750

Maximum Inlet Pressure:
250 psi (17.3 bar)

Pressure Variable To:

Metallic Heads:

M-03-X: 1000 psi (69 bar)

M-03-E: 1200 psi (83 bar)

M-03-S: 1200 psi (83 bar)

M-03-B: 1200 psi (83 bar)

M-03-G: 1200 psi (83 bar)

Non-Metallic Heads:

All Models: 250 psi (17.3 bar)

*** Note**

Performance and specification ratings apply to M-03, D-03 and M-23 configurations unless specifically noted otherwise.

M-03 Series

Maximum Capacity*			
	rpm	gpm	l/min
M-03-X	1750	3.0	11.3
M-03-E	1750	2.2	8.3
M-03-S	1750	1.6	6.0
M-03-B	1750	1.1	4.2
M-03-G	1750	0.5	1.9
Delivery @ max Rated Pressure*			
	revs/gal	revs/liter	
M-03-X	584	155	
M-03-E	746	211	
M-03-S	972	258	
M-03-B	1591	417	
M-03-G	3900	921	
Max Inlet Pressure			
250 psi (17.3 bar)			
Pressure Variable to			
Metallic Heads: M-03-X: 1600 psi (109 bar)			
M-03-S, E, B, G: 1200 psi (83 bar)			
Non-Metallic Heads: All models: 250 psi (17.3 bar)			
Max Temperature			
250°F (refer to engineering section, page 94 for temperatures above 180°F)			
Inlet Port			
1/2 inch NPT			
Discharge Port			
3/8 inch NPT			
Shaft Diameter			
M-03: 5/8 inch			
D-03: 7/8 inch			
M-23: 20 mm hollow shaft			
Shaft Rotation			
Bi-directional			
Bearings			
Ball bearings			
Oil Capacity			
1 US quart (0.95 liters), see page B3 for oil selection and specification.			
Weight			
Metallic Heads: 78 lbs (35.4 kg)			
Non-Metallic Heads: 19 lbs (8.6 kg)			

Calculating Required Horsepower

6 x rpm

63,000

+

gpm x psi

1,460

=

electric motor HP

* Note

Performance and specification ratings apply to M-03, D-03 and M-23 configurations unless specifically noted otherwise.

For installation guidelines and other pump selection design considerations, refer to pages 92-95.

Net Positive Suction Head (NPSHr)

Dry Lift

M-03 Series

M-03 Models with Metallic Pumping Head

Brass
316 Stainless Steel
Nickel Alloy (C Series)

M-03 Models with Non-metallic Pump Head

Kynar[®]
Polypropylene

United States
(612) 332-5681 Fax (612) 332-6937

Instant Information: www.hydra-cell.com
Document Fax Back System: (510) 745-0440

United Kingdom
+44 (0) 1252 781234 Fax +44 (0) 1252 731235

M-03 Series

D-03 Models with Metallic Pumping Head

Brass
316 Stainless Steel
Nickel Alloy (C Series)

— Note

*M-03 Pump/Motor Adapter
flange ordered separately
(see accessories, page 38.)*

D-03 Models with Non-metallic Pump Head

Kynar[®]
Polypropylene

— Note

*M-03 Pump/Motor Adapter
flange ordered separately
(see accessories, page 38.)*

M-03 Series

M-23 Models with Metallic Pumping Head

Brass
316 Stainless Steel
Nickel Alloy (C Series)

M-23 Models with Non-metallic Pump Head

Kynar®
Polypropylene

United States
(612) 332-5681 Fax (612) 332-6937

Instant Information: www.hydra-cell.com
Document Fax Back System: (510) 745-0440

United Kingdom
+44 (0) 1252 781234 Fax +44 (0) 1252 781235

M-03 Series

All M-03, 11-03 and M-24 configurations of Hydra-Cell pumps are manufactured in a variety of heavy-duty materials to meet specific pumping needs. Refer to the design section for more information on appropriate material selection and chemical compatibility. Other customized materials are available by special order. Contact factory application engineering department for further information.

Pumping Head

316 Stainless Steel
Brass
Kynar®
Nickel Alloy (Hastelloy®/Monel
C-276/Inconel)
Polypropylene

Valves

1/4 PSI Stainless Steel
316 Stainless Steel
Ceramic
Hastelloy® C

Diaphragms & O-rings

Buna-N-XS
EPDM
Neoprene
Teflon®
Viton®-XT

Valve Springs

316 Stainless Steel
Fluorinert®
Hastelloy® C

Valve Seats

1/4 PSI Stainless Steel
316 Stainless Steel
Ceramic
Hastelloy® C

Valve Spring Retainers

Celcon®
Kynar
Nylon
Polypropylene

M-03 Series

Options, Accessories and Custom Designs

- Valves, page 78
- Hydra-Oil, page 88
- Couplers, page 87
- Hose Connectors, page 87
- Tool Kits, page 90

Pump/Motor Adapter

Part Number: A04-032-1000

Must be ordered separately for M-03 models for use with 56C, 143TC and 145TC frame motors.

M-03 Series

A complete M-03 Series Model Number contains 12 digits including 11 customer-specified design options; for example M03XABTHHECA.

1	2	3	4	A	6	7	8	9	10	11	12
1 2 3 Configuration											
M03 Direct drive											
D03 Shaft driven											
M23 for use w/ 5.5 HP Honda Engine (GX160K1LX)											
4 Hydraulic End Cam											
X Max 3.0 gpm (11.3 lpm) @ 1750 rpm											
E Max 2.2 gpm (8.3 lpm) @ 1750 rpm											
S Max 2.8 gpm (6.8 lpm) @ 1750 rpm											
B Max 1.1 gpm (4.2 lpm) @ 1750 rpm											
G Max 0.5 gpm (1.9 lpm) @ 1750 rpm											
6 Pumping Head Material											
B Brass											
M Kynar [®]											
P Polypropylene											
S 316 Stainless Steel											
T Nickel Alloy (Hastelloy Remelt, CMW12D)											
7 Diaphragm & O-ring Material											
E EPDM (requires order code 3-20 wt EPDM compatible oil)											
G Viton [®] X1											
J Teflon [®] (available with X and E cams only; cannot be used with non-metallic heads)											
P Neoprene											
T Buna N-XS											
8 Valve Seat Material											
C Ceramic											
H 17-4 PH Stainless Steel											
S 316 Stainless Steel											
T Hastelloy [®] C											
9 Valve Material											
C Ceramic											
H 17-4 PH Stainless Steel											
S 316 Stainless Steel											
T Hastelloy [®] C											
			10 Valve Springs								
			E Elgiloy [®]								
			S 316 Stainless Steel								
			T Hastelloy [®] C								
			11 Valve Spring Retainers								
			C Celcon								
			M Kynar [®]								
			P Polypropylene								
			Y Nylon								
			12 Hydra-Oil								
			A 10W30 standard duty oil								
			G 5W30 cold-temperature severe duty synthetic oil								
			J 20 wt EPDM compatible oil								
			K 20-wt food-contact oil								

F/G-20 Series

F/G-22 with Pump/Motor Adapter for coupling to NEMA C-Face and IEC B5 Flange motors

F/G-20 hollow shaft for close coupling with NEMA C-Face and IEC B5 Flange motors

F/G-21 shaft-driven

Hydra-Cell
SIMPLY BUILT TO LAST

F/G-20 Series

F/G-20-X	0.96	3.63	1750
F/G-20-E	0.73	2.76	1750
F/G-20-S	0.55	2.08	1750
F/G-20-B	0.33	1.25	1750
F/G-20-G	0.20	0.76	1750

Maximum Inlet Pressure:

100 psi (7 bar)

Maximum Pressure:

Metallic Pump Heads:

F/G-20:	1000 psi (70 bar)
F/G-21:	1500 psi (100 bar)
F/G-22:	1500 psi (100 bar)

Non-Metallic Pump Heads:

All Models:	250 psi (17 bar)
-------------	------------------

* Note

Performance and specification ratings apply to all configurations unless specifically noted otherwise.

Calculating Required Horsepower (kW) **

$$\frac{2 \times \text{rpm}}{63,000} + \frac{\text{gpm} \times \text{psi}}{1,460} = \text{electric motor HP}$$

$$\frac{2 \times \text{rpm}}{84,428} + \frac{\text{lpm} \times \text{bar}}{511} = \text{electric motor kW}$$

**rpm equals pump shaft rpm. HP/kW is required application power. Use caution when sizing motors with variable speed drives.

United States
(612) 332-5681 Fax (612) 332-6937

Instant Information:
www.hydra-cell.com

United Kingdom
+44 (0) 1252 816847 Fax +44 (0) 1252 629242

F/G-20 Series

Max Pressure*			
Metallic Heads:	F/G-20: 1000 psi (70 bar); F/G-21 & F/G-22: 1500 psi (100 bar)		
Non-Metallic Heads:	All Models: 250 psi (17 bar)		
Capacity @ Max Pressure*			
	rpm	gpm	l/min
F/G-20-X	1750	0.96	3.64
F/G-20-E	1750	0.73	2.76
F/G-20-S	1750	0.55	2.06
F/G-20-B	1750	0.31	1.25
F/G-20-G	1750	0.20	0.76
Delivery @ Max Pressure*			
	revs/gal	revs/liter	
F/G-20-X	1823	500	
F/G-20-E	2337	653	
F/G-20-S	3182	906	
F/G-20-B	5303	1400	
F/G-20-G	8750	2300	
Max Inlet Pressure 100 psi (7 bar)			
Max Temperature			
Metallic Heads:	250°F (121°C) – Consult factory for correct component selection for temperatures above 160°F (71°C)		
Non-Metallic Heads:	140°F (60°C)		
Inlet Port F-20/21/22: 1/2 inch NPT G-20/21/22: 1/2 inch BSP1			
Discharge Port F-20/21/22: 3/8 inch NPT G-20/21/22: 3/8 inch BSP1			
Shaft Diameter F-20: 5/8 inch hollow shaft for NEMA 56C C-Face motor (with feet) F-21: 5/8 inch shaft driven* F-22: 5/8 inch* G-20: 19 mm for IEC 80 B5 Flange motor (with feet) G-21: 19 mm shaft driven* G-22: 19 mm shaft driven* *Refer to Pump/Motor Adapter section			
Shaft Rotation Bi-directional			
Bearings Ball bearings			
Oil Capacity 1.8 US quart (0.12 liters); see Accessories Section for oil selection and specification.			
Weight			
Metallic Heads:	12 lbs (5.5 kg)		
Non-Metallic Heads:	9.95 (4.1 kg)		

Refer to installation guidelines and design considerations section for additional information.

Net Positive Suction Head (NPSHr)

Dry Lift

* Note

Performance and specification ratings apply to all configurations unless specifically noted otherwise.

F/G-20 Series

F/G-20 Models with Metallic Pumping Head

Brass
316 Stainless Steel
Hastelloy[®] C

F/G-20 Models with Non-metallic Pump Head

Kynar[®]
Polypropylene

United States
(612) 332-5681 Fax (612) 332-6937

Instant Information:
www.hydra-cell.com

United Kingdom
+44 (0) 1252 816847 Fax +44 (0) 1252 629242

F/G-20 Series

F/G-21 Models with Metallic Pumping Head

Brass
316 Stainless Steel
Hastelloy[®] C

— Note

*F/G-21 Pump/Motor Adapter
flange ordered separately
(see page 32)*

F/G-21 Models with Non-metallic Pump Head

Kynar[®]
Polypropylene

— Note

*F/G-21 Pump/Motor Adapter
flange ordered separately
(see page 32)*

F/G-20 Series

F/G-22 Models with Metallic Pumping Head

Brass
316 Stainless Steel
Hastelloy[®] C

— Note
F/G-21 Pump/Motor Adapter
flange ordered separately
(see page 32)

F/G-22 Models with Non-metallic Pump Head

Kynar[®]
Polypropylene

— Note
F/G-21 Pump/Motor Adapter
flange ordered separately
(see page 32)

United States
(612) 332-5681 Fax (612) 332-6937

Instant Information:
www.hydracell.com

United Kingdom
+44 (0) 1252 816847 Fax +44 (0) 1252 629242

F/G-20 Series *Automatic Transfer*

Hydra-Cell pumps are manufactured in a variety of heavy-duty materials to meet specific pumping needs. Refer to the design section for more information on appropriate material selection and chemical compatibility. Other customized materials are available by special order. Contact factory application engineering department for further information.

Pumping Head

316 Stainless Steel
Brass
Kynar[®]
Hastelloy[®] C
Polypropylene

Valves

17-7 PH Stainless Steel
Ceramic
Hastelloy[®] C
Nitronic 50
Tungsten Carbide

Diaphragms & O-rings

Buna-N-XS
EPDM
Neoprene
Teflon[®]
Viton[®] XL

Valve Springs

Elgiloy[®]
Hastelloy[®] C

Valve Seats

17-4 PH Stainless Steel
316 Stainless Steel
Ceramic
Hastelloy[®] C
Tungsten Carbide

Valve Spring Retainers

Celcon[®]
Kynar[®]
Nylon
Polypropylene
17-7 PH Stainless Steel
Hastelloy[®] C

F/G-20 Series *Automatic Transfer*

Options, Accessories and Custom Designs

See the Accessories Section for complete information on these other products.

- Valves
- Couplings
- Hose Connectors
- Hydra-Oil
- Oil Cooler and Filtering System
- Oil Reservoir
- Tool Kits
- Pump/Motor Adapters

Pump/Motor Adapter

(Ordered separately)

Part Number: A04-005-1200

For F-21/22 for use with NEMA 56C, 143/145TC C-Face motors

Part Number: A04-006-1200

For G-21/22 for use with IEC 80-90 B5 Flange motors

See the Accessories Section for dimensions.

F/G-20 Series

A complete F/G-20 Series Model Number contains 12 digits including 9 customer-specified design options: for example F20XABGSNEPG

1 2 3 4 5 6 7 8 9 10 11 12

Digit	Order Code	Description
1-3 Pump Configuration		
	F20	Close-coupled to NEMA 56C (NPT ports)
	F21	Shaft-driven (NPT ports)
	F22	For use with pump/motor adapter (NPT ports)
	G20	Close-coupled to IEC 80 (BSPT ports)
	G21	Shaft-driven (BSPT ports)
	G22	For use with pump/motor adapter (BSPT ports)
4 Hydraulic End Cam		
	X	Max 0.96 gpm (3.79 lpm) @ 1750 rpm
	E	Max 0.73 gpm (2.76 lpm) @ 1750 rpm
	S	Max 0.55 gpm (2.08 lpm) @ 1750 rpm
	B*	Max 0.33 gpm (1.25 lpm) @ 1750 rpm
	G*	Max 0.20 gpm (0.76 lpm) @ 1750 rpm
5 Pump Head Version		
	A	Version A Pump Head (NPT ports)
	D	Version D Pump Head (BSPT ports)
6 Pump Head Material		
	B	Brass
	M	Kynar*
	P	Polypropylene
	S	316 Stainless Steel
	T	Hastelloy* C
7 Diaphragm & O-ring Material		
	E	EPDM (requires EPDM-compatible oil - Digit 12 oil code J)
	G	Viton* -XT
	J*	Teflon* (available with X and E cams only; cannot be used with non-metallic heads)
	P	Neoprene
	T	Buna-N-XS
8 Valve Seat Material		
	C	Ceramic
	D	Tungsten Carbide
	H	17-4 PH Stainless Steel
	S	316 Stainless Steel
	T	Hastelloy* C
9 Valve Material		
	C	Ceramic
	D	Tungsten Carbide
	H	17-7 PH Stainless Steel
	N	Nitronic 50
	T	Hastelloy* C

Digit	Order Code	Description
10 Valve Springs		
	E	Elgiloy*
	T	Hastelloy* C
11 Valve Spring Retainers		
	C	Celcon
	H	17-7 PH Stainless Steel
	M	Kynar*
	P	Polypropylene
	T	Hastelloy* C
	Y	Nylon
12 Hydra-Oil		
	G	SW30 standard & cold-temp severe duty oil
	J	20-wt EPDM-compatible oil
	K	20-wt food-contact oil

Replacement Hydraulic End Assembly

Complete F/G-20 Hydraulic End Assemblies are available as replacement items. The Hydraulic End contains all drive end components from the drive shaft up to and including the diaphragms. All Hydraulic Ends are factory tested and shipped with oil. To order a Replacement Hydraulic End, specify the desired Cam (Digit 4), the Diaphragm and O-ring Material (Digit 7), and the Hydra-Oil (Digit 12).

Part Number*

F20	4	XX	7	XXXX	12
G20	4	XX	7	XXXX	12
F21	4	XX	7	XXXX	12
G21	4	XX	7	XXXX	12
F22	4	XX	7	XXXX	12
G22	4	XX	7	XXXX	12

* Order Code Digits 4, 7 and 12 must be filled in when ordering.

* May require pressurized inlet.

United States
(612) 332 5681 Fax (612) 332 6937

Instant Information:
www.hydra-cell.com

United Kingdom
+44 (0) 1252 816847 Fax +44 (0) 1252 629242

C62 Series

Materials of Construction

Attention to detail. Wanner Engineering doesn't stop with a great design. We will custom fit your valve with the materials best suited for your specific application.

Bodies/Tops Material

- Brass
- Nickel Alloy (Hastelloy B2/B7, CMW12D)
- 316 Stainless Steel

O-Rings/Diaphragms

- PTFE/PTFE
- Viton®/PTFE

Valve Seats

- Hastelloy® C
- 17-4 Stainless Steel
- 316 Stainless Steel

Plungers

- Hastelloy® C
- 17-4 Stainless Steel
- 316 Stainless Steel

The Hydra-Cell C62 Valve design is simple: a tapered plunger with an attached diaphragm. When excess pressure overcomes the adjustable spring pressure on the plunger, the plunger lifts off the valve seat, allowing fluid to bypass and reduce system pressure. When a Hydra-Cell Valve is mounted in the discharge line, its modified flow-through design reduces wear on the plunger and seat.

For service, simply remove the top of the valve and replace the worn internal components. Hydra-Cell Valves can be serviced in place without removing any fittings or plumbing.

- Various materials available: stainless or brass bodies, PTFE diaphragm, etc.
- Made in America
- Heavy-duty industrial construction
- Accurate, repeatable
- Flow-through design
- Minimal pressure surge
- Smooth, chatter-free bypass
- No external springs or moving parts
- Use with any positive displacement pump
- Immediate response
- Adjustable, easy to service

Dimensions

Capacity	Maximum: 14 gpm (53 l/min) Minimum: 1 gpm (3.8 l/min)
Pressure Range	Configuration A: 50-500 psi (3.5-34.5 bar) Configuration B: 500-2500 psi (34.5-172 bar)
Max Temperature	200°F
Inlet and Outlet Ports	3/4" NPT (BSPT)
Weight	4 lbs. (1.8 kg)

C62 Series

A complete C62 Series Model Number contains 11 digits of customer-specified design options; for example C62ABBSVSSEF.

1	2	3	4	5	6	7	8	9	10	11
---	---	---	---	---	---	---	---	---	----	----

Digit	Order Code	Description
1-3	C62	Valve Configuration 1-14 gpm (3-53 l/min)
4	A D	Inlet/Outlet Ports NPT Threaded Ports BSPT Threaded Ports
5	A B	Pressure Range 75-600 psi (5.3-34.5 bar) 500-2500 psi (34.5-172 bar)
6	B H S	Body/Top Material Brass Nickel Alloy (Hastelloy [®] C, Inconel, CMW120) 316 Stainless Steel
7	J V	O-rings/Diaphragm Teflon/Teflon Viton [®] /Teflon
8	H R S	Valve Seats Hastelloy [®] C 316 Stainless Steel 17-4 HT Stainless Steel
9	H R S	Plungers Hastelloy [®] C 316 Stainless Steel 17-4 HT Stainless Steel
10	E	Seat Size For C62 Models
11	F	Port Size For C62 Models (3/4")

STATIC MIXERS

A Technical Introduction

Sizes:
3/8" - 2"
diameter

FMX7200 Series

OMEGA® FMX7200 Series mixers are designed for efficient turbulent-flow mixing at low pressure drop. Ideal for admixing water/wastewater treatment chemicals, polymer dilution, and other low-viscosity applications. Mixing elements consist of a series of polypropylene baffles, and are mounted in a PVC housing with FNPT ends. CPVC and clear PVC housings available.

Sizes:
1/8" - 2"
diameter

FMX8400 Series

OMEGA® FMX8400 Series mixers offer efficient mixing of low or high viscosity fluids at low pressure drop. Also ideal for two-phase (gas-liquid) mixing and blending of gases. Elements consist of a series of left and right helices fabricated from 316SS. 304SS housing is corrosion-resistant, designed for high pressure and high temperature service. MNPT ends ensure easy installation.

Sizes:
1/2" - 3"
diameter

FMX9800 Series Sanitary Mixers

OMEGA® FMX9800 Series mixers are ideal for food and beverage processing, manufacturing pharmaceuticals and cosmetics, and other sanitary in-line applications. Features 3-A, 316LSS tube housing and removable 316LSS elements polished to a mirror finish. Tri-clamp flange ends permit easy removal, cleaning and reinstallation.

Sizes:
2" - 18"
diameter

FMX9200/ FMX9400 Series Process Mixers

OMEGA® PVC and CPVC mixers, and OMEGA all stainless and carbon steel mixers, are designed for higher flow rates and installations involving 2" to 18" diameter piping systems. Many standard models provide complete turbulent flow mixing at low pressure drop. Housing ends are 150# flanges. Special configurations to your specifications available.

STATIC MIXERS

A Technical Introduction

Selection Guide

For each application, the designer must first determine the number of mixing sections required to achieve a complete mix. The guidelines below are based upon the Reynolds Number of your system. Also included are tables with some general application guidelines.

Next, the designer should select a diameter and/or a construction that will give the desired mixing performance without exceeding your system's maximum allowable pressure drop (see item 3 below).

1. Calculate the Reynolds Number. Use the diameter given in the charts. If both inside and outside diameters are supplied, use the inside diameter

$$RE = \frac{3157 \times Q \times S}{D \times MU}$$

2. Select a model based on the Reynolds Number.

FMX7000 Series Mixers:

Reynolds No.	No. of Elements
800-1000	14
>1000	7

Typical Application	No. of Elements
Ozone Absorption	7
pH Control	7
Gas/Gas Blending	7
Dilution of Chemicals	7
Polyelectrolyte Dilution	14

FMX8000 Mixers:

Reynolds No.	No. of Elements
<10	24-32
10-500	16-24
500-2000	8-16
>2000	4-8

Typical Application	No. of Elements
1-1 Epoxies	24
Urethanes/Elastomers	32
Urethane Foam	16
In-line Aeration	8
Admixing of Additives	8

3. Determine the Pressure Drop

Laminar Flow:
Reynolds Number < 500

$$DP = Q \times MU \times L$$

Turbulent Flow:
Reynolds Number > 500

$$DP = Q^2 \times S \times T$$

NOTE: If the pressure drop across the mixer exceeds its maximum rating, a modular mixer is required. For example, if a 24-element FMX8300 mixer is required and the pressure drop exceeds the 250 psi rating, we recommend coupling two 12-element mixers in series.

Symbols

RE = Reynolds Number—Dimensionless

Q = Flowrate in Gallons per Minute

S = Specific Gravity—Dimensionless

MU = Viscosity in Centipoise

D = Diameter in Inches

DP = Pressure Drop in psi

L = Laminar Factor—See Mixer Tables

T = Turbulent Factor—See Mixer Tables

L

ALL STAINLESS STEEL STATIC MIXERS

With Optional Teflon® Coated Elements

FMX8400 Series pipe mixers feature 304SS piping (schedule 40 nominal) with 316SS elements. This series is available with Teflon® coating or non-coated stainless elements. Teflon® coating does not impart greater chemical resistance than stainless steel. The coating simply enhances the cleanability of the mixing elements. For routine maintenance, the elements can be pushed out and cleaned.

The leading and trailing edges of the mixers are "Knife Edged" to flush clean with less solvent, having no flat leading edges to accumulate material.

The FMX8400 and FMX9400 Series are an effective motionless mixer. When combined with metering pumps, these mixers replace expensive treatment tanks and dynamic mixers. Consider these advantages: Zero Maintenance, Low Cost, Easy Installation and Low Energy Consumption.

Typical applications include both laminar or turbulent blending, liquid/gas contacting and enhanced heat transfer. The mixing process is modular, the more difficult the application, the greater number of elements required.

Teflon® is a registered trademark of DuPont.

FMX8400 Pressure Limitations

Pipe Size	psig @ 24°C (75°F)
¾"	8750
1"	8500
1½"	7250
2"	7250
2½"	6000
3"	4500
1½"	3000
2"	2500

To Order (Specify Model Number)

Model No.	Price	Pipe Size	Housing I.D. (Inch)	No. of Elements	Length	Weight (lbs)	Flow Range (usgpm)	Pressure Drop Range (psi)
FMX9401	\$864	2" Sch40	2.05	3	10.7"	15	5-100	0.02-8
FMX9402	1000	2" Sch40	2.05	6	18.5"	19	5-100	0.04-2
FMX9403	1752	3" Sch40	3.07	3	15.8"	33	25-250	0.07-7
FMX9404	2576	3" Sch40	3.07	6	28"	42	25-250	0.14-13
FMX9405	2368	4" Sch40	4.03	3	20"	54	30-300	0.04-9
FMX9406	3112	4" Sch40	4.03	6	38"	68	30-300	0.08-17
FMX9407	2832	6" Sch40	6.06	3	29"	95	80-1000	0.05-6
FMX9408	4192	6" Sch40	6.06	6	56"	140	80-1000	0.10-12

Flanged Models

MOST POPULAR MODELS HIGHLIGHTED!

To Order (Specify Model Number)

Model No. 316SS Elements	Price	Model No. F.P. Coated Elements	Price	I.D.	No. of Elements	Ends MNPT	Length	Factors	
								L	T
FMX8441S	\$106	FMX8441T	\$134	28"	6	¾"	2.7"	.0588	6.1
FMX8442S	141	FMX8442T	170	28"	12	¾"	5.4"	.1176	12.2
FMX8451S	114	FMX8451T	144	37"	6	¾"	3.7"	.0237	1.9
FMX8452S	153	FMX8452T	185	37"	12	¾"	7.0"	.0474	3.8
FMX8461S	122	FMX8461T	156	51"	6	¾"	5.0"	.0092	.55
FMX8462S	163	FMX8462T	200	51"	12	¾"	9.5"	.0184	1.1
FMX8481S	143	FMX8481T	175	64"	6	¾"	5.7"	.0049	.22
FMX8482S	192	FMX8482T	229	64"	12	¾"	11.0"	.0098	.44
FMX8411S	156	FMX8411T	199	.80"	6	¾"	7.7"	.0023	.04
FMX8412S	209	FMX8412T	274	.80"	12	¾"	14.7"	.0046	.08
FMX8413S	198	FMX8413T	254	1.06"	6	1"	9.5"	.001	.024
FMX8414S	264	FMX8414T	328	1.06"	12	1"	18.5"	.002	.048
FMX8415S	281	FMX8415T	368	1.61"	6	1½"	14.0"	.0002	.004
FMX8416S	392	FMX8416T	451	1.61"	12	1½"	27.2"	.0004	.008
FMX8421S	341	FMX8421T	425	2.07"	6	2"	17.5"	.0001	.0013
FMX8422S	462	FMX8422T	643	2.07"	12	2"	34.5"	.0002	.0026

DATA ACQUISITION SYSTEM

A GREATER MEASURE OF CONFIDENCE

KEITHLEY

Integra Series Model 2700 Multimeter/ Data Acquisition System

www.keithley.com

A complete solution for PC-based multi-point measurement and control

Get a DMM, a switch mainframe, and a data acquisition control system for the price of a PC plug-in board

The **Model 2700 Multimeter Data Acquisition System** combines the functionality and high channel count of a switch mainframe with the accuracy, convenience, and traceability of a true 6 1/2-digit (22-bit) DMM. It packs all these capabilities into a compact half-rack unit at a price that's comparable to a high performance data acquisition board. Keithley's growing family of Integra Series plug-in modules gives the Model 2700 the industry's lowest per-channel installed cost in a high performance data acquisition and control package. Mix or match any two modules to get up to 80 differential channels of multiplexed measurement and control. That means significantly more channels in less space than competing solutions.

An astonishing range of functions and built-in signal conditioning

Each channel of the Model 2700 can be configured separately for any of 14 measurement functions and provides built-in signal conditioning. The Model 2700's high noise isolation up to 100kV allows it to measure virtually any electrical or physical parameter with high accuracy:

DC volts	DC current
Temperature measurements with thermocouples, RTDs, or thermistors	AC volts
2-wire Ω	Frequency
4-wire Ω	Period
Continuity	AC current
	Event counter/totizer
	Digital I/O

Perform system level control functions

Optional plug-in modules allow the Model 2700 to manage a variety of system control tasks:

- Actuate indicator lights and/or relays to provide alarm limit status, and directly interface with mechanical systems through open-collector digital I/O
- Control power to the DUT, switch in or change loads, and perform general signal routing through isolated switching
- Bias the DUT or perform analog control through dual $\pm 12V$ analog output ports
- Route DC, AC, or RF signals from the DUT to other test equipment in the rack

Wide testing flexibility

This economical, easy-to-configure solution is widely used in applications like temperature logging, precision measurement and control, and mixed signal data acquisition for product development, ATE, component testing, and process monitoring. The plug-in approach eliminates the triggering, timing, and processing issues that often complicate building systems from separate instruments and switches. The tight switching-and-measurement integration also helps reduce test time significantly. That means higher throughput and a better return on equipment investment.

Powerful software options

The Model 2700 is compatible with a variety of software options to match a variety of test programming needs. For example, the free TestPoint runtime offers basic datalogging capabilities. This start-up utility can be modified with the powerful TestPoint application development package. Optional ExcelJNX-IA software makes it easy to acquire data directly into an Excel spreadsheet. Free IVI (VISA-based) drivers simplify developing fully custom programs in Visual Basic, C/C++, LabVIEW, LabWindows/CVI, or TestPoint.

Keithley's patented measurement engine provides true 6 1/2-digit (22-bit) performance at higher resolution rates.

Typical 16-bit converters only deliver 5 digits (16-bit) performance under similar conditions.

Engineers trust Keithley to provide best-in-class measurement performance. In many cases, our products provide up to 10X better performance at equivalent reading rates or up to 10X greater speed at equivalent measurement performance. Our patented AD converter and high performance signal conditioning circuitry make this possible.

High ease of use meets high measurement accuracy

If there's a power failure, the battery-backed set-up memory and non-volatile RAM data storage means scans can automatically be resumed right where they stopped when power returns

Front panel input jacks simplify manual probing, troubleshooting, and calibration. Includes 1000V protection in case of accidental overload

On-board statistical analysis is available at the push of a button, including channel average and ratio, mX+b scaling, min, max, average, and standard deviation

Non-volatile memory stores up to 55,000 time-stamped readings

Its familiar DMM-like front panel scheme makes the Model 2700 easy to use on the bench or in the rack. Select or change functions with the press of a button

GPIO and RS-232 communications are standard

Built-in open collector digital I/O lines provide for control, external triggering, and HILLO alarm limit outputs

Screw terminals use oversize connectors for easier, mistake-free wiring

Rugged 50-pin D-sub connectors ensure dependability and quick setup/teardown in production test racks

A variety of measurement and control modules makes it simple to mix, match, and change input signals or control lines as needed. Install up to two modules at a time to create a "mini-AIE" system with up to 80 channels

Built-in relay cycle counters on each module for ease of maintenance

Versatile plug-in options for any application

We're continuing to expand our line of Integra plug-in switch/control modules:

- 7700** 20-channel differential multiplexer with automatic CJC and screw terminals for general purpose or thermocouple measurements
- NEW! 7701** 32-channel differential multiplexer with D-sub connectors, IDC ribbon cable compatible
- 7702** 40-channel differential multiplexer with screw terminals
- 7703** 32-channel high speed differential multiplexer with reed relays and D-sub connectors
- 7705** 40-channel switch/control module, SPST independent switch with D-sub connectors (Form C configurable)
- 7706** All-in-one I/O module, 20-channel differential multiplexer, 2 analog outputs, 16 digital outputs and event counter/timer/trigger with screw terminals
- NEW! 7707** 32 open-collector digital I/O and 16-channel differential multiplexer with D-sub connectors, IDC ribbon cable compatible
- NEW! 7708** 40-channel differential multiplexer with automatic CJC and screw terminals for general purpose or thermocouple measurements
- NEW! 7709** 64x8 matrix switch module, with D-sub connectors, IDC ribbon cable compatible
- NEW! 7711** 2GHz RF switch module with dual 18+4 configuration
- NEW! 7712** 3.5GHz RF switch module with dual 18+4 configuration

Additional hardware accessories:

- KPC1-488** IEEE-488 GPIB interface for PCI bus
- 7707-2** 2-meter double shielded premium GPIB IEEE-488 cable
- 7705-MTC-2** 2-meter male to female 50-pin D-sub cable for 7703, 7705, 7707, and 7709
- 7707-MTC-2** 2-meter male to female 25-pin D-sub cable for 7707 and 7709
- 7788** 50-pin D-shell connector kit (2 each)
- 7789** 50-pin/25-pin D-shell connector kit (1 each)
- 7790** 50-pin male, 50-pin female and 25-pin male IDC D-shell kit (1 each)

Visit www.kithley.com for more information on modules and accessories

Ideal for production testing

Use the Model 2700 for high throughput production testing of multiple points on a DUT and/or testing multiple DUTs in batch mode. D-sub and SMA rear panel connectors make it fast and easy to disconnect the Model 2700 from the test fixture. Free instrument drivers designed for use in a variety of popular Application Development Environments simplify creating custom systems for production test.

Versatile enough for environmental stress, burn-in, and QA testing

The Model 2700 is ideal for both short- and long-term monitoring and characterization tasks. It's immune to power failures, resuming scanning where it left off when power is restored—all set-up information is battery backed and data is stored in non-volatile RAM. Input channels can handle virtually any input while its digital output lines can trigger external alarms or perform other controls independent of a PC.

Perfect for research and product development

A DMM-like front panel, half-rack footprint, 80 channel capacity, outstanding measurement performance, and low cost make the Model 2700 ideal for R&D applications. The free TestPoint™ runtime start-up software included with the Model 2700 and the economical ExcelINX-IA add-in utility provide basic data logging capabilities, so it's easy to get new applications "Up & Running" quickly and inexpensively.

Powerful, easy-to-use software options

TestPoint™ is our basic start-up software. This free TestPoint runtime offers basic data logging capabilities that can get a system up and running almost immediately. With just a few clicks of the mouse, this software can confirm that the system's hardware, wiring, communications, and software drivers are installed and operating correctly. It can also be used to configure instrument functions and perform simple data acquisition tasks. Data from multiple channels can be saved to disk and up to eight channels of data can be graphed automatically. If the application demands greater functionality, this runtime can be modified with the TestPoint package.

TestPoint Application Development Package. If the free start-up software doesn't provide a feature the job demands, there's no problem—just use the economical TestPoint application development package to modify it. TestPoint's object-oriented, drag-and-drop technology offers the flexibility needed to build basic systems quickly, without in-depth programming. Expanding TestPoint applications is easy, too, with optional Internet, database, and statistical process control toolkits.

ExcelINX-1A. This powerful and economical add-in utility for Microsoft® Excel makes it simple to acquire data from the Model 2700 directly into Excel, then employ Excel's graphics, charting, and analysis capabilities to turn that data into useful information. No programming is required to use ExcelINX—a few mouse clicks are all it takes to configure channels, set parameters, triggers, and scan lists.

IVI/VISA-based instrument drivers. Experienced programmers who prefer to build fully custom systems from scratch can take advantage of our instrument driver, which is designed for use with Application Development Environments such as Visual Basic®, C/C++, LabVIEW®, LabWindows™/CVI, and TestPoint. This IVI-style driver (VISA-based) supports all of the instrument's functionality, and comes with numerous programming examples to help programmers get started quickly.

Three new system bundles make it easy to get applications off to a quick, economical start:

- The **2700/7700** value pack provides a basic 20-channel system.
- The **2700-DAQ-40** includes the Models 2700 and 7708 plus ExcelINX-1A for a 40-channel system.
- The **2700-DAQ-80** provides one Model 2700, two Model 7708 modules, and ExcelINX-1A for an 80-channel system.

Condensed specifications*

DC VOLTAGE

±0.5% protection on ranges, Auto Accuracy (1 year) only, 1 year range, 120000 max counts

Range	Resolution	Accuracy (1 year) (rdg. + range)	Accuracy (1 year) (rdg. + range)	Input Resistance
1000000V	1000V	0.0025% + 0.0035%	0.0030% + 0.0035%	10MΩ or >100MΩ
1000000V	100V	0.0025% + 0.0035%	0.0030% + 0.0035%	10MΩ or >100MΩ
1000000V	10V	0.0025% + 0.0035%	0.0030% + 0.0035%	10MΩ or >100MΩ
1000000V	100μV	0.0035% + 0.0035%	0.0040% + 0.0035%	10MΩ
1000000V	10μV	0.0035% + 0.0035%	0.0040% + 0.0035%	10MΩ

THERMOCOUPLE

Conversion to IHS-90, Automatic, External, or Stimulated (J, K, Open, E, C, types)

Type	Range	Accuracy (1 year) with stimulated (C, J, K)	Accuracy (1 year) with automatic (C, J, K)
J	2000 to +1000°C	±0.2°C for all ranges	±1.5°C
K	2000 to +1372°C	±0.2°C for all ranges	±1.5°C
N	2000 to +1400°C	±0.2°C for all ranges	±1.5°C
T	2000 to +600°C	±0.2°C for all ranges	±1.5°C
E	2000 to +1000°C	±0.2°C for all ranges	±1.5°C
R	0 to +1308°C	±0.6°C for all ranges	±1.5°C
S	0 to +1708°C	±0.6°C for all ranges	±1.5°C
B	2500 to +1820°C	±0.6°C for all ranges	±1.5°C

RESISTANCE

2-wire, 4-wire, Offset Compensation self-cable, 100kV, ±50% protection on source, sense inputs

Range	Resolution	Accuracy (1 year) (rdg. + range)	Accuracy (1 year) (rdg. + range)	Test Current
1000000Ω	100kΩ	0.0060% + 0.0060%	0.0100% + 0.0060%	100A
1000000Ω	100Ω	0.0060% + 0.0060%	0.0100% + 0.0060%	100A
1000000Ω	10mΩ	0.0060% + 0.0060%	0.0100% + 0.0060%	100A
1000000Ω	100μΩ	0.0060% + 0.0060%	0.0100% + 0.0060%	100A
1000000Ω	10μΩ	0.0060% + 0.0060%	0.0100% + 0.0060%	100A
1000000Ω	10nΩ	0.0200% + 0.0040%	0.0400% + 0.0040%	0.75A
1000000Ω	0.001	0.2000% + 0.0030%	0.4000% + 0.0030%	0.75A

RTD

D100, F100, PT500, PT5000, or user type, plus probe error

Range	Resolution	Accuracy (1 year)
2000 to +1000°C	0.001°C	±0.60°C

THERMISTOR

10kΩ, 5kΩ, and 10kΩ, plus sensor error

Range	Resolution	Accuracy (1 year)
2000 to +1000°C	0.001°C	±0.35°C

DC CURRENT

28-V, 4-wire inputs, built-in shunt resistors

Range	Resolution	Accuracy (1 year) (rdg. + range)	Accuracy (1 year) (rdg. + range)	Input Resistance
2000000mA	100A	0.05% + 0.004%	0.05% + 0.004%	<10V
2000000mA	1000A	0.05% + 0.004%	0.05% + 0.004%	<10V
2000000mA	1A	0.05% + 0.004%	0.05% + 0.004%	<10V
2000000mA	100μA	0.11% + 0.004%	0.12% + 0.004%	<10V

AC VOLTAGE

True RMS, 5:1 max Crest Factor

Range	Resolution	Frequency Range	Accuracy (1 year) (rdg. + range)
0.000V to 750V	0.1μV to 1mV	0.1Hz - 10Hz	0.45% + 0.05%
		10Hz - 20kHz	0.60% + 0.05%
		20kHz - 50kHz	0.72% + 0.05%
		50kHz - 100kHz	0.8% + 0.05%
		100kHz - 800kHz	1.0% + 0.5%

FREQUENCY and PERIOD

Selectable Gate Times of 100ns, 100μs, 10ms

Range	Frequency Range	Period Range	Accuracy (1 year) (rdg. + range)
100mV to 750V	0.1Hz to 500kHz	0.000001 to 100s	0.01% + 0.0035% (100ns to 10ms) 0.01% + 0.0035% (10μs to 10ms) 0.01% + 0.0035% (10ns to 10ms)

AC CURRENT

True RMS, 5:1 Crest Factor

Range	Resolution	Frequency Range	Accuracy (1 year) (rdg. + range)
1A	10A	0.1Hz - 50kHz	0.45% + 0.05%
5A	100A	0.1Hz - 50kHz	0.45% + 0.05%

DC READING RATES

Function	Digits	Readings/sec	NPLC
10V, 100V	6.5	5	10
20V, 100V	6.5	50	1
	5.5	250	0.1
	4.5	2000	0.01
4W Ohms, RTD	6.5	2.5	10
Thermistor	6.5	25	1
Thermocouple	5.5	125	0.1
	4.5	250	0.01

DC READING SPEED VS. NOISE REJECTION

NPLC	Digits	Filter	SMRR	CMRR	FMS Noise (10V range)
10	6.5	50	110dB	140dB	<1.2μV
1	6.5	0dB	90dB	140dB	<1.0μV
0.1	5.5	0dB	-	80dB	<1.2μV
0.01	4.5	0dB	-	80dB	<1.5μV

SCANNING RATE, INTO AND OUT OF MEMORY TO GPIB

	Channels/s
***03 scanning DCV	180/s
***04 scanning DCV with limits or timestamp on	150/s
***05 scanning DCV alternating 2W	60/s
***02 scanning DCV	60/s
***01, ***06, and ***08 scanning temperature (1°C)	50/s

SYSTEM FEATURES

Scanning Channels	Up to 80 differential
Trigger Source	External digital input, front panel keypad, channel monitor, interval timer, GPIB/RS-232, Trigger Link, remote date
Scan Count	1 to 55700 or continuous
Scan Interval	0 to 99 hours, Insex step size
Channel Delay	0 to 999999999 per channel, Insex step size
Configuration	Per channel for measurement setups, math, and limits
Power Fail Recovery	Resume scanning sequence, configuration and stored data are preserved
Power up Memory	4 user configurations with labels
Real Time Clock	Included, use to timestamp readings
Data Storage	Non-volatile 55000 reading buffer with timestamp, continuous fill, query while filling, min, max, avg, std dev
Alarm Limits	2 HI and 2 LO limits per channel, selectable polarity
Digital Inputs	2 TTL level - external trigger plus interlock
Digital Outputs	4 TTL level - selectable polarity, HI/LO limit, configurable
Master Alarm	4 TTL level output toggles when any HI/LO limit is exceeded
Front Panel Lock	Software enabled
Communication	IEEE488.2, RS-232
Per Channel Math	6E+/-0.5
Multi-channel Math	Ratio, Average
Resolution	6-digit with 20% over range, 28-bit readings available over IEEE488
Software	TestPoint-based start-up applications, LabVIEW, TestPoint, LabWindows/CVI, Visual Basic, C/C++ - driver

GENERAL INFORMATION

Power Supply	100V - 120V - 220V, 20W, ±10%
Line Frequency	45Hz to 66Hz, 50Hz to 400Hz
Operating Environment	0°C to 50°C
Size	80mm H x 215mm W x 376mm D
Warranty	3 years on instrument, 1 year on Measurement & Control Modules
Safety	UL, IEC, IEC 1919-1, CSA
EMC	CE mark, FCC Class A

* Visit www.galvan.com for detailed specifications

Specifications subject to change without notice

High channel count measurement and control solutions

While the **Model 2700** offers the capacity needed to handle applications with up to 80 channels, many applications require hundreds of switch control channels. For these cases, the five-slot, 200s-channel **Model 2750** Multimeter Switch System is often the perfect size. Built on the same measurement platform, the Model 2700 and Model 2750 share many of the same capabilities and programming commands. The Model 2750 also offers low-ohms measurement capabilities with $1\mu\Omega$ sensitivity. All the switch control modules and software work in both mainframes. This high compatibility also makes it easy to migrate applications from the Model 2700 to the Model 2750 as new test needs emerge or the number of test points grows.

Register for a free online interactive demo

Keithley's engineering experts offer free online demonstrations of the Model 2700 hardware and software. All it takes to participate is an Internet connection and a telephone to watch the demo and communicate with the instructor. Call us or contact us via our website to register for a session.

Request more technical information on the Model 2700

Detailed information on the Model 2700 is free for the asking, including a technical data book, which includes detailed specifications and application examples that can help you choose the most appropriate modules and accessories. A brochure on software for the Model 2700 and 2750 is also available. Request your copies by calling 1-888-KEITHLEY (534-8453) or contacting us at www.keithley.com.

Service you can depend on

When you need help, contact us at www.keithley.com or call us at **1-888-KEITHLEY (534-8453)**. Whatever your application is, Keithley's application engineers are ready to help you meet its challenges, before and after the sale. You can rely on us to suggest the most effective system configurations and to provide prompt, reliable applications support once your system is set up.

The next time you're faced with a challenging application, give us a call. We'll offer you a cost-effective solution that will help you improve your product quality, throughput, and yield.

FREE reference handbooks

To request your free copy of the first edition of Keithley's *Data Acquisition and Control Handbook* or the fourth edition of our *Switching Handbook*, contact us at **1-888-KEITHLEY (534-8453)** or on the web at www.keithley.com.

Specifications are subject to change without notice.

All Keithley trademarks and trade names are the property of Keithley Instruments, Inc. All other trademarks and trade names are the property of their respective companies.

KEITHLEY

Keithley Instruments, Inc.

Sales Offices:

BELGIUM:
CHINA:
FINLAND:
FRANCE:
GERMANY:
GREAT BRITAIN:
INDIA:
ITALY:
KOREA:
NETHERLANDS:
SWEDEN:
SWITZERLAND:
TAIWAN:

28775 Aurora Road • Cleveland, Ohio 44139 • 440-248-0400 • Fax: 440-248-6168
1-888-KEITHLEY (534-8453) • www.keithley.com

Bergenseweg 709 • B-1600 Sint-Pieters-Leeuw • 02-363 00 40 • Fax: 02-363 00 64
 Yuan Chen Xin Building, Room 705 • 12 Yunxin Road, Dewai, Madien • Beijing 100029 • 8610-6202-2886 • Fax: 8610-6202-2892
 Tienjantie 2 • 02130 Espoo • Phone: 09-54 75 08 10 • Fax: 09-25 10 51 00
 3, allée des Garages • 91127 Palaiseau Cedex • 01-64 53 20 20 • Fax: 01-60 11 77 26
 Landsberger Strasse 65 • 82110 Gerning • 089 84 93 07 40 • Fax: 089 84 93 07 34
 Unit 2 Commerce Park, Brunel Road • Theale • Berkshire RG7 4AB • 0118 929 7500 • Fax: 0118 929 7519
 Flat 2H, WILCOBRISA • 14, Rest House Crescent • Bangalore 560 001 • 91-80-509-1320 21 • Fax: 91-80-509-1322
 Viale San Gennaro, 38 • 20146 Milano • 02-48 39 16 01 • Fax: 02-48 30 22 74
 2FL., URI Building • 2-14 Yangjae-Dong • Seocho-Gu, Seoul 137-130 • 82-2-574-7778 • Fax: 82-2-574-7838
 Postbus 559 • 4200 AN Grommchem • 0183-635333 • Fax: 0183-630821
 c/o Regus Business Centre • Frosmundaväls Alle 15, 4tr • 109 70 Solna • 08-509 04 679 • Fax: 08-655 26 10
 Kriesbachstrasse 4 • 8600 Dübendorf • 01-821 94 44 • Fax: 01-820 30 81
 1FL., 85 Po Ai Street • Hsinchu, Taiwan, R.O.C. • 886-3-572-9077 • Fax: 886-3-572-9031

© Copyright 2002 Keithley Instruments, Inc.
 Printed in the U.S.A.

No. 2167
 000225KOP

ECONOMICAL CORROSION RESISTANT PRESSURE TRANSDUCER WITH VOLTAGE OUTPUT

3 m (12") Cable Included
Optional .9 m (36") and
3 m (120") cables
available

PX181
All Models
\$195

CABLE AND
CONNECTOR
INCLUDED

PX181 Series 0-15 to 0-500 psi Ranges

- ✓ Stainless Steel Pressure Port for High Durability
- ✓ Assured 0.3% Accuracy
- ✓ Corrosion Resistant Housing Permits Mounting In Any Environment
- ✓ Operating Temperature Range -55 to 105°C
- ✓ Extremely Compact, Weighs Only 50 Grams

OMEGA's PX181 Series pressure transducers combine state-of-the-art semiconductor technology and durability resulting in a high accuracy general purpose pressure sensor. The 1 to 5 volt output assures compatibility with most process controllers and computer interface equipment. Applications include engine monitoring and testing, HVAC, compressors, etc. The silicon sensor is bonded on a glass pedestal to isolate it from induced stresses, provide wide media compatibility, and the stainless steel pressure port permits use with corrosive substances. These rugged, compact transducers exhibit 0.3% accuracy and excellent interchangeability.

Not Recommended
For Freon Applications.

MADE IN
USA

SPECIFICATIONS

Excitation: 12 to 25 Vdc
Output: 1 to 5 Vdc (20 mA max)
Accuracy: $\pm 0.3\%$ BFSL includes linearity, repeatability, and hysteresis
Zero Balance: $\pm 1\%$ span
Operable Temperature Range: -40 to 105°C (-40 to 221°F)
Compensated Temperature Range: -5 to 55°C (23 to 131°F)
Thermal Zero Effect: $\pm 0.5\%$ span
Thermal Span Effect: $\pm 0.5\%$ span
Proof Pressure: lessor of 2 x full scale or 750 psi max
Burst Pressure: lessor of 3 x full scale or 750 psi max
Gages: Laser trimmed semiconductor
Wetted Parts: Stainless steel, glass, silicon, Fluorosilicon
Pressure Port: 1/8-27 NPT stainless steel fitting
Stability: $\pm 1\%$ full scale output/year
Shock: 500 g
Vibration: 10 g, 10 to 2000 Hz
Response Time: < 5 ms
Electrical Connection: 12 in, 20 AWG, 3 conductor shielded wire with self sealing connector
Weight: 50 grams (1.8 oz)

MOST POPULAR MODELS HIGHLIGHTED

To Order (Specify Model Number)			
RANGE (psi)	MODEL NO.	PRICE	COMPATIBLE METERS
0 to 15 psig	PX181-015G5V	\$195	DP41-E, DP25-E, DP24-E
0 to 30 psig	PX181-030G5V	195	DP41-E, DP25-E, DP24-E
0 to 60 psig	PX181-060G 5V	195	DP41-E, DP25-E, DP24-E
0 to 100 psig	PX181-100G5V	195	DP41-E, DP25-E, DP24-E
0 to 200 psig	PX181-200G5V	195	DP41-E, DP25-E, DP24-E
0 to 300 psig	PX181-300G5V	195	DP41-E, DP25-E, DP24-E
0 to 500 psig	PX181-500G5V	195	DP41-E, DP25-E, DP24-E

Ordering Example: PX181-100G5V has a range of 100 psig. \$195.

LOW COST METAL CASE TRANSDUCERS FOR LOW PRESSURE AND VACUUMS

MADE IN
USA
Aluminum
Case Models

New!
Stainless
Steel
Models

PX240 Series 5 to 250 psig

- SILICON DIAGRAM**
- ✓ Aluminum or Stainless Steel Case
 - ✓ Buna-N Seals
 - ✓ 8.0 Vdc Excitation
 - ✓ 12 Inch Lead Wires
 - ✓ -40 to +85°C
 - ✓ 1 to 6 Vdc Output
 - ✓ Temperature Compensated

VOLTAGE OUTPUT
PRESSURE TRANSDUCERS
B

Shown approximately actual size

Supplied with
12" leads

PX242
\$149
Ranges ≥60psi

SPECIFICATIONS

Excitation: 8 Vdc regulated (16 V max.)

"A" Series: 30 Vdc Max

Output: 1 to 6 Vdc into 800 Ω min

Linearity: ±1.5% FS BFS

±0.5% FS for 60 to 100 psig

"A" Series: ±0.25% Lin & Hys Combined

Hysteresis & Repeatability: ±0.25% FS

"A" Series: ±0.1% Repeatability

Zero Balance: 1.0 Vdc ±0.05

PX243 3.5 Vdc ±0.05

Compensated Temperature Range:

-18 to 63°C (0 to 145°F)

"A" Series: -27 to 63°C (-18 to 145°F)

Operable Overpressure: 2 x FS

Response Time: 1 ms

Gage Type: Solid State Piezo-Resistive

Body Material: PX241/242/243:

Die-Cast Aluminum Epoxy Finish

PX241A/242A/243A: Stainless Steel

Diaphragm Material: 0.10" Silicon

Sensor Chip with Buna-N "O" Ring

Media Compatibility: Limited only to

those non-caustic media which will not

attack die-cast aluminum, silica

borosilicate glass, or Buna-n seal.

Pressure Port: 1/8-27 NPT male

Metric threads available, consult sales

MOST POPULAR MODELS HIGHLIGHTED

To Order (Specify Model Number)

RANGE (psi)	MODEL NO.	PRICE	COMPATIBLE METERS
Painted Aluminum Housing			
-15 to 0 psig	PX241-15NG5V	159	DP3002-E, DP2000E5, DP25-E
0 to 15 psig	PX242-015G5V	159	DP3002-E, DP2000E5, DP25-E
0 to 60 psig	PX242-060G5V	149	DP3002-E, DP2000E4, DP25-E
0 to 100 psig	PX242-100G5V	149	DP3002-E, DP2000E4, DP25-E
0 to 150 psig	PX242-150G5V	149	DP3002-E, DP2000E5, DP25-E
0 to 250 psig	PX242-250G5V	149	DP3002-E, DP2000E5, DP25-E
±5.0 psig	PX243-05BG5V	159	DP3002-E, DP2000E4, DP25-E
±15 psig	PX243-15BG5V	159	DP3002-E, DP2000E4, DP25-E
Stainless Steel Housing			
-15 to 0 psig	PX241A-15NG5V	159	DP3002-E, DP2000E5, DP25-E
0 to 5 psig	PX242A-005G5V	159	DP3002-E, DP2000E5, DP25-E
0 to 15 psig	PX242A-015G5V	159	DP3002-E, DP2000E5, DP25-E
0 to 30 psig	PX242A-030G5V	159	DP3002-E, DP2000E5, DP25-E
0 to 60 psig	PX242A-060G5V	149	DP3002-E, DP2000E4, DP25-E
0 to 100 psig	PX242A-100G5V	149	DP3002-E, DP2000E4, DP25-E
0 to 150 psig	PX242A-150G5V	149	DP3002-E, DP2000E5, DP25-E
0 to 250 psig	PX242A-250G5V	149	DP3002-E, DP2000E5, DP25-E
±2.5 psig	PX243A-2.5BG5V	159	DP3002-E, DP2000E4, DP25-E
±5.0 psig	PX243A-05BG5V	159	DP3002-E, DP2000E4, DP25-E
±15 psig	PX243A-15BG5V	159	DP3002-E, DP2000E4, DP25-E

Ordering Example: PX242A-015G5V, a stainless steel model with a 0 to 15 psig range. \$159.

B-64

EXCITATION FOR MASS FLOW CONTROLLERS AND METERS

SCREW TERMINAL STYLE
For Easy Field Termination Without Soldering

- ✓ 4-40 Screw Terminations and Mounting Inserts
- ✓ Floating Output
- ✓ Efficient
- ✓ Rugged
- ✓ Lightweight (15 oz)

From
\$165
Model
PST-5

Shown actual size

ENCAPSULATED POWER SUPPLIES

provide a versatile excitation source for transducers and bridges. The barrier strip-type case is designed to be mounted to a bulkhead or chassis using four 4-40 screws. Screw terminals are provided for connection using either crimp lugs or stripped wires. These regulated power supplies are designed to be a modular solution to your excitation needs. The stable output allows drift-free performance even if the input power source is noisy or unstable. Long-term measurements can then be meaningfully compared with confidence. Short circuit protection prevents failure due to excessive current drain, and the conservative design assures long-term reliability.

Dimensions in Inches (mm)

MOST POPULAR MODELS HIGHLIGHTED

To Order (Specify Model Number)							
Output			PRICE	Output			Price
V	mA	Model No.		V	mA	Model No.	
5	500	PST-5	\$165	15	300	PST-A15	\$245
8	300	PST-8	165	15	500	PST-B15	295
10	240	PST-10	165	18	270	PST-18	199
15	200	PST-15	165	28	150	PST-28	199

Ordering Example: PST-B15, encapsulated power supply with 15 V, 500 mA output, \$295.

PITOT TUBE
FLOW ELEMENTS

PRODUCT SPECIFICATION

Description

KLflo's annular primary flow tubes are designed to meet customer specifications. Their construction offers an alternative to the standard differential pressure metering devices presently available on the market, yet consistently offering the highest cost/performance advantages. They are very easy to install, operate, and maintain. KLflo offers one of the most complete line of models and sizes to choose from. Take the LUB, for instance, it can be installed without any costly shutdown while providing the industry with the shortest form of not tap in existence.

The sensors have a flow turndown from 4:1 to 7:1, sense bidirectionally, and are maintenance-free thanks to their simple configuration.

Applications

These primary flow elements are designed to measure clean fluids in full pipes under well developed, symmetrical velocity profiles. Their versatility proves itself in usages that range from:

Water
Steam
Air
Gases

Piping Requirements

KLflo annuaries may be installed at any angle from horizontal to vertical. With reference to ASME Fluid Meters, 6th Edition, the key to measuring volumetric flow (or differential pressure) is the maintaining of pipes full with sufficient upstream piping so as to secure a well developed symmetrical velocity profile.

General Specifications

Accuracy

The multiport self averaging pitot tubes can produce accurate measurements of:

$\pm 1\%$ of rate accuracy

$\pm 0.1\%$ of repeatability

Pressure Loss

The permanent pressure loss of a KLflo annular pitot tube is amongst the lowest of the differential producing primary elements. Typically it produces an unrecoverable head loss of 2 to 14%. This head loss is the accountable energy loss or the pressure drop across your pump or fan that has to be overcome due to the primary element's flow stream obstruction.

Materials of Construction

The flow tubes may be fabricated from any known weldable material, ie.

-Stainless Steel
-Monel
-Hastelloy C

Typical Water Flow Chart

INSTALLATION INSTRUCTIONS FOR PITOT TUBES

Location

The correct mounting location and position of KLflo sensors depend on the pipeline. The figures below depict the recommended straight run requirements of uniform diameter for both upstream and downstream locations relative to the sensor (as per AGA/ASME Standards and the National Research Council of Canada). This will ensure that the flow measurements are made in a fully developed symmetrical flow profile. Accuracy of measurement can otherwise be affected. (For more precise flow measurements, longer lengths are recommended).

RECOMMENDED MIN. STRAIGHT PIPE RUNS FOR UPSTREAM

KLflo Meter multiport pitot tubes are bi-directional. This allows them to be installed in either flow direction. However, insure that the instrument head is parallel to the pipe run in horizontal installations, and perpendicular to the pipe run in vertical installations (see back).

For a $\frac{3}{8}$ " probe dia.:	1. drill a hole $\frac{1}{2}$ " on one side of the pipe
	2. Weld the supplied pipe fitting concentric to the hole.
	3. Thread in the supplied compression fitting and pass the multiport probe through both the compression fitting and the pipe fitting pushing it in all the way. Now tighten the compression fitting as per standard manufacturers recommended practice.
$\frac{1}{2}$ " probe dia.:	1. drill a hole $\frac{5}{8}$ " on one side of the pipe.
	2. Repeat steps 2 & 3 as in <u>$\frac{3}{8}$" probe diameter</u> .
1" probe dia.:	1. drill a hole 1 $\frac{1}{8}$ " on one side of the pipe.
	2. Repeat steps 2 & 3 as in <u>$\frac{3}{8}$" probe diameter</u> .
2 $\frac{1}{2}$ " probe dia.:	1. drill a 2 $\frac{1}{4}$ " hole on one side of the pipe.
	2. Repeat steps 2 & 3 as in <u>$\frac{3}{8}$" probe diameter</u> .

In the event that the probes require a double support option please use the same drills as previously mentioned drilling a second hole in the opposite wall (180° apart). Ensure that the Probe is flush with the outside pipe wall, then tighten the hex nut of the packing gland as per the manufacturers recommended practice. You are now ready to take your flow measurements.

INSTALLATION INSTRUCTIONS FOR PITOT TUBES

Sensor Orientation

The flowmeters may be mounted on either horizontal or vertical pipelines. In the instance of horizontal flow involving liquids or steam, it is recommended that the primary units are installed below the centerline and above the centerline for gases. Instrument valve positioning plays the dominant role in vertical lines. See diagram. (Note: Other orientations are possible with additional considerations)

TOLERANCE	NOT	U. I. A.	DATE	APPD.	SCALE	SHEET	SHEET
			12-8-97		1/1	MS 356	A3
						REGISTER	
						METER & REGISTER	
						500	
						1 OF 1	
						MS 356	
						A3	

OMP OPTION 2" = 120 RATE & TOTAL DISPLAY

OMP - Positive Displacement Flowmeters

Features

- Flow Ranges From .53 to 26 GPH Through 4 to 132 GPH
- Handles Viscosities to 1,000,000 cPs
- Pressure Ratings to 8,000 PSIG Available
- Low Head Loss Oval Gear Design

The KOBOLD series OMP combines high accuracy, repeatability and low cost with a variety of material combinations allowing it to solve just about any flow metering problem. The OMP series positive displacement flowmeters use an oval gear design to accurately meter the flow of viscous liquids. The oval gear design provides highly precise measurements with a lower pressure drop relative to other types of gear type meters. The OMP low flow series are available with ryton bodies for lower pressure applications and stainless steel bodies for pressures up to 8000 PSIG. The standard gear design can measure fluids with viscosities up to 1000 centipoise with special gear designs available for high viscosities. A pulse output is provided for input to a variety of display, batch control or distributed control systems.

Specifications

Available Flow Ranges:

- OMP-1: 0.53 to 26 GPH
OMP-2: 4 to 132 GPH

Maximum Pressure

- Ryton Body: 75 PSIG
SS Body: 150 PSIG standard, 800 or 8000 PSIG optional

Max. Differential Pressure:

14.5 PSI

Wetted Components

- Body: Ryton or 316 stainless steel
- Gears:
- OMP-1: 316 stainless steel and teflon
 - OMP-2: 316 stainless steel and carbon
 - Optional: Ryton gears with hastelloy C shafts (Ryton body only)

OMP-1 & OMP-2 Low Flow Series

Shafts		Optional (OMP-2 only):	
Standard:	316 stainless steel		to 1,000,000 centipoise with reduced measuring range
Optional:	Ryton gears with hastelloy C shafts (Ryton body only)		
O-ring:			
	Viton standard, EPDM or teflon optional	Accuracy:	1% of reading
Maximum Operating Temp.		Repeatability:	0.03% of reading
Ryton Body:	175 F	Normal K-Factor	
SS Body:	250 F	OMP-1:	3785 pulses/gallon
		OMP-2:	1514 pulses/gallon
Minimum Viscosity: 5 centipoise (lower viscosities possible with reduced measuring range)		Output Type:	NPN Open Collector, 5-24 VDC Power
Maximum Viscosity		Optional Output:	4-20 mA integral transmitter (SS versions only)
Standard:	1000 centipoise	Elec. Protection:	NEMA 3R/IP54
		Filtration Requirements:	200 mesh

Maximum Flowrate Limit vs. Viscosity for Optional High Viscosity Gears, OMP-2 Series

Viscosity	Max. Flow	Viscosity	Max. Flow
<2,500 cPs	132 GPH	<25,000 cPs	52 GPH
<3,000 cPs	118 GPH	<40,000 cPs	39 GPH
<4,000 cPs	105 GPH	<95,000 cPs	13 GPH
<5,000 cPs	92 GPH	<450,000 cPs	6.6 GPH
<8,000 cPs	79 GPH	<1,000,000 cPs	6.6 GPH
<12,000 cPs	66 GPH		

OMP - Positive Displacement Flowmeters

OMP-1 and OMP-2 Ordering Information

OMP = Positive Displacement Flowmeter	
Flow Range	
1	= 0.53 to 26 GPH
2	= 4 to 132 GPH
Body Material	
R	= Rytan Body
L	= Stainless Steel Body 150 PSIG Max. Pressure
I	= Stainless Steel Body 800 PSIG Max. Pressure
H	= Stainless Steel Body, 8,000 PSIG Max. Pressure
Fitting	
N2	= 1/4" NPT
O-Ring Material	
V	= Viton (standard)
J	= EPDM
T	= Teflon
Options	
A5	= 2-wire 4-20 mA module in place of pulse output (SS Meters Only)
C	= Rytan Gears with Hastelloy C Shafts (Rytan Body Only)
P	= High Viscosity Gears for Viscosity > 1000 Centipoise (for OMP-2 only)

OMP - 2 - I - N2 - V - P Example

S4

Dimensions

Standard Version

High Pressure Version

See us at the trade show with all your questions

Product Data Sheet

PS-00363

June 2002

Micro Motion® R-Series Mass and Volume Flowmeter for General Purpose Applications

Now available with MVD™ Technology

MVD™ technology **CE** www.micromotion.com

Micro Motion® R-Series Flowmeters

Welcome to a new era in measurement technology! Now you can afford to replace your old volumetric technology with the new Micro Motion R-Series flowmeters. Micro Motion R-Series meters are competitive in both price and accuracy specifications with positive displacement, differential pressure, magnetic, and vortex flowmeters, yet they have many advantages that the other technologies do not.

Like all our flowmeters, Micro Motion R-Series meters offer highly accurate flow measurement for virtually any process fluid—be it clean or not.

The same meter can provide direct mass and volume flow for liquids, gases, and slurries without having to be recalibrated. Their immunity to flow profile means that you can install Micro Motion R-Series meters anywhere in your process without having to worry about expensive straight runs or flow straightening devices. This translates to real savings in installation and engineering costs.

For general purpose flow measurement applications, Micro Motion R-Series meters provide an ideal alternative to other flowmetering technologies. Micro Motion meters have no moving parts—saving you money over the course of their lifetime by helping you make the best use of your time, people, and material.

Micro Motion R-Series meters feature integral sensors and transmitters, making them easy to install. With the new MVD™ Technology, you can also remotely mount your transmitter up to 1000 feet, using standard 4-wire cable. You get the flexibility you need to mount the sensor anywhere in your process piping while saving installation costs.

R-Series meters are available to support several digital communication protocols, including HART®, MODBUS®, FOUNDATION™ Fieldbus, and Profibus-PA. Other features include a variety of standard process connections, milliampere and pulse outputs, a standard display, and a built-in totalizer resettable from the display.

Micro Motion R-Series meters are designed to perform in harsh operating environments, and carry hazardous area approvals for the U.S.A., Canada, Europe, Japan, and other areas around the world.

Micro Motion is well known for increasing plant efficiency, product quality, and profitability. Now, Micro Motion R-Series meters offer all this and more.

Easy to use

Easy to start up, no moving parts, no need for periodic recalibration, non-intrusive, no regular maintenance requirements.

Reliable and rugged

Nothing to wear out or break down – more than 400,000 Micro Motion meters are installed and working in processes just like yours. The accumulated knowledge of Micro Motion is built into each flowmeter.

Easy to install

No special mounting, no straight run requirements and no flow conditioning elements.

Direct mass or volume measurement

With direct mass measurement, Micro Motion R-Series flowmeters are immune to variations in pressure, temperature or process fluids. The same meter can measure liquids, gases, or slurries.

Greater accuracy

Accuracy to 0.5% on liquids and 0.75% on gases means better product quality and less waste.

Hygienic options

An improved surface finish option of 32 Ra (0.8 μm), which is both 3-A authorized and EHEDG approved, is available in all sizes. All Micro Motion R-Series meters can be installed to be self-draining, with or without this option.

Micro Motion R-Series flowmeters support PlantWeb® field-based architecture, a scalable way to use open and interoperable devices and systems to build process solutions of the future.

Performance specifications

Flow specifications		Mass		Volume		
Nominal flow range ⁽¹⁾		lb/min	kg/h	gal/min	l/h	
standard sensors	R025S	0 to 50	0 to 1360	0 to 6	0 to 1360	
	R050S	0 to 150	0 to 4080	0 to 18	0 to 4080	
	R100S	0 to 600	0 to 16,325	0 to 72	0 to 16,325	
	R200S	0 to 1600	0 to 43,550	0 to 192	0 to 43,550	
hygienic option	R025F	0 to 38	0 to 1034	0 to 4.5	0 to 1034	
	R050F	0 to 90	0 to 2450	0 to 11	0 to 2450	
	R100F	0 to 410	0 to 11,160	0 to 49	0 to 11,160	
	R200F	0 to 1175	0 to 31,980	0 to 141	0 to 31,980	
Maximum flow rate ⁽²⁾		lb/min	kg/h	gal/min	l/h	
standard sensors	R025S	100	2720	12	2720	
	R050S	300	8160	36	8160	
	R100S	1200	32,650	144	32,650	
	R200S	3200	87,100	384	87,100	
hygienic option	R025F	76	2068	9	2068	
	R050F	180	4900	22	4900	
	R100F	820	22,320	98	22,320	
	R200F	2350	63,960	282	63,960	
Accuracy ⁽³⁾		Series 1000 transmitter, and FOUNDATION™ Fieldbus and Profibus-PA				
		±0.5% of rate ⁽⁴⁾				
		IFT9703 transmitter				
		±0.5% of rate ± [(zero stability/flow rate) x 100]% of rate				
Repeatability ⁽³⁾		Series 1000 transmitter, and FOUNDATION™ Fieldbus and Profibus-PA				
		±0.25% of rate ⁽⁴⁾				
		IFT9703 transmitter				
		±0.25% of rate ± [½(zero stability/flow rate) x 100]% of rate				
Zero stability		lb/min	kg/h	gal/min	l/h	
		R025	0.01	0.27	0.0018	0.41
		R050	0.03	0.82	0.0054	1.22
		R100	0.12	3.27	0.0216	4.90
		R200	0.32	8.71	0.0576	13.07

⁽¹⁾Micro Motion has adopted the terminology "nominal flow range." The upper limit of this range is the flow rate at which water at reference conditions causes approximately 15 psi (1 bar) of pressure drop for Micro Motion R-Series flowmeters.

⁽²⁾The maximum flow rate for volume measurement is based on a process-fluid density of 1 g/cc. For fluids with density other than 1 g/cc, the maximum volume flow rate equals the maximum mass flow rate divided by the fluid's density.

⁽³⁾Flow accuracy includes the combined effects of repeatability, linearity, and hysteresis. All specifications for liquids are based on reference conditions of water at 68 to 77°F (20 to 25°C) and 15 to 30 psig (1 to 2 bar), unless otherwise noted.

⁽⁴⁾When flow rate is less than (zero stability/0.005), accuracy equals ±[(zero stability/flow rate) x 100]% of rate and repeatability equals ±[½(zero stability/flow rate x 100)]% of rate.

Functional specifications

Temperature limits

Process fluid	Sensors with core processor on extended mount	–400 to 300°F (–240 to 150°C)
	All other models	–40 to 257°F (–40 to 125°C)
Ambient temperature	Storage ⁽¹⁾	–40 to 185°F (–40 to 85°C) with IFT9703 transmitter, no display –4 to 158°F (–20 to 70°C) with IFT9703 transmitter and display –40 to 158°F (–40 to 70°C) with Series 1000 transmitter
	Operation ⁽²⁾	–22 to 131°F (–30 to 55°C) with IFT9703 transmitter, no display 32 to 131°F (0 to 55°C) with IFT9703 transmitter and display –40 to 140°F (–40 to 60°C) with Series 1000 transmitter
Process fluid vs. ambient temperature		At their upper limits, process fluid temperature and ambient temperature restrict each other. For ATEX-compliant sensors, the minimum process fluid and ambient temperature is –40°C. The ATEX "T" rating and hazardous area classification depend on the maximum process fluid and ambient temperature. See page 9.

Pressure ratings

Flow tube rating⁽³⁾	All models	1450 psi	100 bar
PED approved	Sensors comply to council directive 97/23/EC of 29 May 1997 on Pressure Equipment.		
Housing rating	All models	<i>Housing is not rated for pressure containment.</i>	

Hygienic standards

	For hygienic applications, Micro Motion R-Series sensors with hygienic fittings feature a 32 Ra (0.8 µm) tube surface finish.		
3-A	Micro Motion R-Series sensors with hygienic fittings meet 3-A Sanitary Standards for Milk and Dairy Products.		
EHEDG	Micro Motion R-Series sensors with hygienic fittings are approved by the European Hygienic Equipment Design Group. Sensors comply with the hygienic criteria of Machinery Directive 98/37/EC, annex 1 (additional essential health and safety requirements for certain categories of machinery), section 2.1 (agri-foodstuffs machinery). Test results show that Micro Motion R-Series sensors can be cleaned in place as least as well as the reference pipe.		

⁽¹⁾For Series 1000 transmitters, display responsiveness can decrease and display may become difficult to read below –4°F (–20°C). Above 131°F (55°C), some darkening of display may occur.

⁽²⁾Over entire temperature range, according to ASME B31.3.

*continued***Dimensions — with integrally mounted Series 1000 transmitter**

Model	Dimensions ⁽¹⁾						
		C	D	E	F	G	H
R025	inches	5/8	5 1/8	9 3/4	2 13/16	4 11/16	6 1/16
	(mm)	(15)	(130)	(247)	(72)	(119)	(154)
R050	inches	5/8	6 3/4	11 7/8	2 15/16	4 11/16	6 1/16
	(mm)	(15)	(171)	(301)	(74)	(119)	(154)
R100	inches	7/8	9 1/8	14 7/8	4 1/8	4 15/16	6 15/16
	(mm)	(22)	(232)	(378)	(104)	(126)	(160)
R200	inches	1 3/4	12 9/16	17 7/8	5 5/8	5 13/16	7 3/16
	(mm)	(44)	(319)	(454)	(144)	(148)	(182)

⁽¹⁾For dimensions A and B, see process fittings table, pages 14 and 15.

Physical specifications

Fittings for standard R-Series meters

R025S fitting options⁽¹⁾	Fitting code	Dim. A, face-to-face inches (mm)	Dim. B, outside diam. inches (mm)
1/2" ANSI 150 lb weld neck raised face flange	113	16 (406)	3 1/2 (89)
1/2" ANSI 300 lb weld neck raised face flange	114	16 3/8 (416)	3 3/4 (95)
1/2" ANSI 600 lb weld neck raised face flange	115	16 7/8 (429)	3 3/4 (95)
1/2" NPT female CAJON size 8 VCO fitting	319	14 (356)	not applicable
1/2" sanitary fitting (Tri-Clamp compatible)	121	14 (356)	1 (25)
15 mm DIN PN40 weld neck, DIN 2635, type C face	116	15 1/4 (387)	3 3/4 (95)
15 mm DIN PN100/160 weld neck, DIN 2637, type E face	120	15 13/16 (401)	4 1/8 (105)
15 mm DIN 11851 hygienic coupling	222	13 15/16 (353)	Rd 34 x 1/8
15 mm JIS 10K/20K weld neck raised face flange	122	15 7/16 (393)	3 3/4 (95)
15 mm JIS 40K weld neck raised face flange	221	16 1/2 (420)	4 1/2 (115)
R050S fitting options⁽¹⁾			
1/2" ANSI 150 lb weld neck raised face flange	113	18 1/8 (460)	3 1/2 (89)
1/2" ANSI 300 lb weld neck raised face flange	114	18 1/2 (469)	3 3/4 (95)
1/2" ANSI 600 lb weld neck raised face flange	115	19 (482)	3 3/4 (95)
3/4" NPT female CAJON size 12 VCO fitting	239	16 3/8 (415)	not applicable
3/4" sanitary fitting (Tri-Clamp compatible)	322	15 7/8 (403)	1 (25)
15 mm DIN PN40 weld neck, DIN 2635, type C face	116	17 3/8 (441)	3 3/4 (95)
15 mm DIN PN100/160 weld neck, DIN 2637, type E face	120	17 7/8 (455)	4 1/8 (105)
25 mm DIN PN40 weld neck, DIN 2635, type C face	131	17 1/2 (444)	4 1/2 (115)
15 mm DIN 11851 hygienic coupling	222	16 (407)	Rd 34 x 1/8
15 mm JIS 10K/20K weld neck raised face flange	122	17 9/16 (446)	3 3/4 (95)
15 mm JIS 40K weld neck raised face flange	221	18 5/8 (473)	4 1/2 (115)
R100S fitting options⁽¹⁾			
1" ANSI 150 lb weld neck raised face flange	126	22 11/16 (576)	4 1/4 (108)
1" ANSI 300 lb weld neck raised face flange	129	23 3/16 (588)	4 7/8 (124)
1" ANSI 600 lb weld neck raised face flange	130	23 11/16 (601)	4 7/8 (124)
1" sanitary fitting (Tri-Clamp compatible)	138	21 1/4 (540)	2 (50)
25 mm DIN PN40 weld neck, DIN 2635, type C face	131	21 7/16 (544)	4 1/2 (115)
25 mm DIN PN100/160 weld neck, DIN 2637, type E face	137	22 13/16 (580)	5 1/2 (140)
25 mm DIN 11851 hygienic coupling	230	20 9/16 (522)	Rd 52 x 1/6
25 mm JIS 10K/20K weld neck raised face flange	139	21 11/16 (550)	4 15/16 (125)
25 mm JIS 40K weld neck raised face flange	229	22 15/16 (582)	5 1/8 (130)

⁽¹⁾Fittings listed here are standard options. Other types of fittings are available. Contact your local Micro Motion representative

APPENDIX E:
CUSTOM PART DRAWINGS

L40 / L48 NOZZLE ADAPTOR

XAAD NOZZLE ADAPTOR

HASTELLOY CONE

L40 / L48 nozzle

L40 / L48 nozzle adaptor for
placement in Test Combustor

Original XAAD nozzle

Adapted nozzle portion to fit into
Test Combustor

NOZZLE ADAPTOR FOR L40 AND L48 NOZZLES (PRESSURE ATOMIZING NOZZLE)

ADAPTED NOZZLE FOR XAAD (AIR ATOMIZING NOZZLE)

HASTELLOY CONE REDUCER FROM TEST COMBUSTOR CASING TO EXHAUST PIPES

RING CONNECTION

Drawing not to scale
All dimensions in inches

CONE SECTION FROM HASTELLOY SHEET

Drawing not to scale
All Dimensions in inches

APPENDIX F:
TASK HAZARD ANALYSIS FOR COMBUSTOR TEST RIG

Occupation/Occupational Groups:		TASK HAZARD ANALYSIS for:		Approved by:
Region NCC	Branch / Division ETAD/ERMD	THA for Combustor-Turbine Eng Test Project		Manager's signature
Analyzed by:	Date February, 2003	(see reverse side for definitions)		Employee's signature
BASIC STEPS		HAZARDS (known or foreseeable)		RECOMMENDED CONTROL MEASURES
Evaluating the storage of the combustible liquid, diesel fuel in the VHF and assessing the risk and potential hazards.	<p>A. Under the Fire Code of Canada, diesel fuel is a Class II combustible liquid with a flash point above 37.8C and below 60C, and in TDG, it is Division 3.</p> <p>B. Flammable vapour from open sources may displace oxygen.</p>	<p>1. National Fire Code of Canada 1995 Section 4.1.2.1</p> <p>2. Ensure National Fire Code of Canada guidelines are followed.</p>		
		<p>1. National Fire Code of Canada 1995 Section 4.1.7.2 and NFPA 77</p> <p>2. According to NFPA 77, if the ambient temperature is at or higher than the flash point of the combustible liquid, ignitable vapour will form. Diesel has a flash point of 51.7C which is much higher than the ambient temperature of approximately 25C±5C. No ignitable vapor will form in the containers...closed or open.</p> <p>3. The containers will remain in VHF for storage purposes only. There is no dispensing. No ventilation is required.</p> <p>4. No transfer of fuel is permitted outside FEA.</p>		
	<p>C. Spills or leaks may flow into the drain and into test cell's containment tank. From there, contamination may find its way to the main sewer containment tank.</p>	<p>1. National Fire Code of Canada 1995 Section 4.1.6.1-2.</p> <p>2. No risk to ground or public sewer system shall be present.</p> <p>3. Spillblocker will be placed around barrels to contain fuel spill.</p> <p>4. Snake will be placed around drain to stop the spill flow.</p> <p>5. ERMD VHF's containment tank's pump can be controlled in the event of contamination.</p> <p>6. Main sewer containment tank can be controlled in the event of contamination.</p> <p>7. Waste rags or materials will be placed into metal waste receptacles with a metal cover in the Fuel Exchange Area or disposed of in a manner not to create a fire.</p>		
	D. Static Electricity can form	1. National Fire Code of Canada 1995 Section 4.1.8.2		

	accumulate, spark and ignite flammable vapours.	<p>2. Charge is generated when liquid flows and does not apply for storage of Class II combustibles. Static electricity is addressed in the Fire Code book when pouring a Class I fuel.</p> <p>3. According to NFPA 77, if the ambient temperature is at or higher than the flash point of the combustible liquid, ignitable vapour will form. Diesel has a flash point of 51.7C which is much higher than the ambient temperature of approximately 25C±5C. No ignitable vapours form in the containers. No transfer of fuel is permitted in the test cell.</p>
	E. Contents in the containers must be clearly identified.	<p>1. <i>National Fire Code of Canada 1995 Section 4.2.3.2</i></p> <p>2. Each container is labeled with WHHS label.</p>
	F. Electrical equipment in the test cell is not fire proof.	<p>1. <i>National Fire Code of Canada 1995 Section 4.1.4.1</i></p> <p>2. Fire proof electrical equipment is not required by law for storage of Class II combustible liquid.</p>
	G. A heat source could start a fire.	<p>1. <i>National Fire Code of Canada 1995 Section 4.1.5.3.</i></p> <p>2. Devices producing spark, open flame or heat shall not be permitted in the same area. Determine safe location for diesel fuel with respect to test rig fuel skid.</p>
Carleton University's Analysis		
Air system	I. Hot air leak from bleed connection and pipes	<p>1. Gasket will be placed at bleed connection to minimize potential air leak</p> <p>2. Pressure test with shop air will be done to ensure no air leaks from any joints in the pipes</p> <p>3. The small extension just before the combustor inlet will be tied to an upstream pipe to prevent disconnection (clamping ring does not fit)</p> <p>4. Doors in engine room will be closed</p> <p>5. No one will be in engine room while engine is running</p>
	II. Too much air escapes from engine, causing it to overheat or fail	<p>1. Control system is in place in engine control room to monitor temperature of the Allison engine and also possesses ability to shut down engine remotely</p>
	III. Hot air leak from bleed connection and pipes	<p>1. Gasket will be placed at bleed connection to minimize potential air leak</p> <p>2. Pressure test with shop air will be done to ensure no air leaks from any joints in the pipes</p> <p>3. The small extension just before the combustor inlet will be tied to an upstream pipe to prevent disconnection (clamping ring does not fit)</p> <p>4. Doors in engine room will be closed</p>

		<p>5. No one will be in engine room while engine is running</p>
	IV. Too much air escapes from engine, causing it to overheat or fail	<p>1. Control system is in place in engine control room to monitor temperature of the Allison engine and also possesses ability to shut down engine remotely</p> <p>2. A butterfly valve in the air bleed pipes controls the amount of air being bled from the engine and is operated in the test rig room. To determine limit to butterfly valve opening, operators in the engine control room and the test rig room will be in communication using radios. A stop will be placed on the valve control to prevent opening past the maximum allowed position.</p> <p>3. Doors in engine room will be closed</p> <p>4. No one will be in engine room while engine is running</p>
	V. Weight from bleed connection could damage diffusion duct on engine	<p>1. Piping for the air bleed system is supported by a metal frame that holds it in position so that no weight from the bleed piping is supported by the engine diffusion duct.</p> <p>2. An anchoring mechanism is in place to ensure that the pipe does not slide due to engine vibration.</p> <p>3. Doors in engine room will be closed</p> <p>4. No one will be in engine room while engine is running</p>
Combustor Test Rig	i. Heat radiation from pipes	<p>1. Pipes will be labeled "HOT"</p> <p>2. Protective clothing, such as gloves, will be worn for any operation of valves near the pipes.</p> <p>3. No one will be near the pipes except when butterfly valve operation is required at the beginning or end of a test. Butterfly valve operation will not be permitted while fuel is being delivered to the combustor.</p> <p>4. Operation of the valve controlling air for the air-blast nozzle will be required once per fuel to determine ideal airflow through nozzle. Repeated tests with the same fuel will require the valve to be opened to the desired position before beginning the test. Protective clothing will be worn.</p>
	ii. Heat radiation from combustor casing and surrounding pipes	<p>1. Heat shields will be placed around the combustor and between the combustor and the fuel skid to protect the operator.</p> <p>2. Fuel supply will be shut off before butterfly or air-blast air supply valves are closed.</p> <p>3.</p>

	iii. Hot air leak or fire from combustor	<ol style="list-style-type: none"> 1. All parts are bolted or held in place with a locking ring. Gaskets have been placed at joints. 2. Fuel supply can be easily shut off with a switch. 3. A heat shield will be placed between the combustor and the fuel skid to reduce fire hazard. 4. Wood shelving unit should be replaced with a metal one for long term test rig operation. 5. A fire extinguisher is located in the room near the test rig.
	iv. Excess fuel entering combustion chamber	<ol style="list-style-type: none"> 1. Test procedure will include system start with bleed air before fuel is delivered to the combustor. Fuel supply will be shut off before air supply to ensure that all fuel has the time for combustion. 2. The combustor casing will be drained after each test to ensure that fuel does not build up in the casing
Fuel System	1. Fuel spill / leak	See attachment for fuel handling characteristics
- Bio-Fuel	2. Bio fuel flash point	<ol style="list-style-type: none"> 1. Flash point is 44C. 2. Biofuel is not easily ignitable. Flammable at extremely high temps. Possible to place in test rig room.
	3. Bio-fuel heating to 80C	<ol style="list-style-type: none"> 1. Temperatures above 160C will generate flammable acetone. 2. Temperature will be monitored and de-activated if approaching 160C.
	4. Static Electricity can form, accumulate, spark and ignite flammable vapours.	<ol style="list-style-type: none"> 1. biomass pyrolysis oil is not sensitive to static discharge
- Diesel – see EC section	Diesel Fuel location - see G-2.	
Results:		

TASK HAZARD ANALYSIS - TERMS AND DEFINITIONS

TERM	DEFINITION	EXAMPLE(S)
Job (or occupation)	A position, occupation or profession within an organization. A job usually comprises several tasks.	Hydrometric Technologist Wildlife Biologist
Task	The various components of work that comprise an employee's job. Normally, a task requires a set of distinct steps or actions for completion; each of these steps will have varying degrees of potential for loss.	Flow measurement - cableway Base camp setup Storage of PCBs inspection
Task Hazard Analysis	The systematic examination of the steps of a task to identify and control any potential loss.	See sample THA for Driving and Tower Climbing
Critical Task	A task is considered critical when it has the potential to create major loss to people, equipment, property or environment in the event of an accident or failure of the loss control system.	Flow measurement - wading Buoy deployment Pulp and paper inspection
Loss Control System	<p>The complete system of controls that are used within an organization to prevent or limit loss. For the purposes of safety and health, there are 3 different types of controls:</p> <ol style="list-style-type: none"> 1) administrative controls (e.g., preparation of a fire emergency plan; implementation of safe work procedures; delivery of safety training; establishment of a safety and health committee) 2) engineering controls (e.g., installation of non-slip flooring; purchase of ergonomic office furniture; use of a portable ventilation system in a confined space; substitution of a hazardous product with a non-hazardous product) 3) personal protective equipment (e.g., wearing a hard hat, tyvek coveralls, work boots, gloves, sunscreen; use of a respirator or atmospheric monitoring equipment). 	
Hazard	Any unsafe equipment, acts or conditions in the workplace with a potential to cause an accident or incident (near miss). Examples would include: an unguarded hole in the ground; defective brakes on a forklift; a deteriorated wooden ramp; or a slippery floor.	

**APPENDIX G:
SAMPLE CALCULATIONS AND TEST DATA**

PRESSURE LOSSES IN AIR PIPES

PRESSURE LOSSES IN FUEL PIPES

POWER REQUIREMENTS FOR HEAT EXCHANGER

HIGH PRESSURE BLEED TEST DATA

MathCAD program for determining the pressure drop of air as it travels from Allison engine to test combustor.

Pressure drop for air travelling from Allison engine to test combustor
Conditions: 7 atm, 260 C

Known:

Pipe diameter	$d := 4.26 \text{ in}$	$R := 287 \frac{\text{J}}{\text{kg} \cdot \text{K}}$
Pipe length	$L := 4 \text{ m}$	
Air pressure	$p := 14.7 \cdot 7 \text{ psi}$	$\text{kPa} := 1000 \text{ Pa}$
Air temperature	$T := (260 + 273) \text{ K}$	
Mass flow of air	$\dot{m}_{\text{dot}} := 0.5 \frac{\text{kg}}{\text{s}}$	
Pipe roughness	$\epsilon := .00015 \text{ ft}$	The value of ϵ for commercial steel (White, p. 318, table 6.1)

Calculated:

Density	$\rho := \frac{p}{R \cdot T}$	$\rho = 4.638 \frac{\text{kg}}{\text{m}^3}$
Viscosity	$\mu := 1.80 \cdot 10^{-5} \frac{\text{N} \cdot \text{s}}{\text{m}^2} \left(\frac{T}{293 \text{ K}} \right)^{.7}$	$\mu = 2.736 \cdot 10^{-5} \text{ N} \cdot \frac{\text{s}}{\text{m}^2}$
	$\nu := \frac{\mu}{\rho}$	$\nu = 5.9 \cdot 10^{-6} \frac{\text{m}^2}{\text{s}}$
Pipe Area	$A(d) := \frac{\pi}{4} \cdot d^2$	$A(d) = 9.196 \cdot 10^{-3} \text{ m}^2$
Velocity	$v(d) := \frac{\dot{m}_{\text{dot}}}{\rho \cdot A(d)}$	$v(d) = 11.724 \frac{\text{m}}{\text{s}}$
Minor Losses	$K := .19 \cdot 5 + 3 \cdot .19$	$K = 1.52$

$$\Delta p(T) := \frac{1}{2} \cdot \rho \cdot \left[\frac{\dot{m}}{\rho \cdot \left(\frac{\pi}{4} \cdot d^2 \right)} \right]^2 \cdot \left[\frac{L}{d} \cdot \left[\frac{1}{-1.8 \cdot \log \left[\frac{6.9}{\left[\frac{\dot{m}}{\rho \cdot \left(\frac{\pi}{4} \cdot d^2 \right)} \cdot d \right] \cdot v} + \left[\frac{\left(\frac{\varepsilon}{d} \right)^{1.11}}{3.7} \right]} \right]} \right]^2 + K \right]$$

$$\Delta p(T) = 0.698 \text{ kPa}$$

For the exhaust, the pressure drop would be based on 1 atm, 1000 Deg C

$$T := (1000 + 273) \text{ K}$$

$$T = 1.273 \times 10^3 \text{ K}$$

$$L := 3.6 \text{ m}$$

$$p := 101.3 \text{ kPa}$$

$$\rho := \frac{p}{R \cdot T}$$

$$\rho = 0.277 \frac{\text{kg}}{\text{m}^3}$$

$$\mu := 1.80 \cdot 10^{-5} \frac{\text{N} \cdot \text{s}}{\text{m}^2} \left(\frac{T}{293 \text{ K}} \right)^{-0.7}$$

$$\mu = 5.033 \times 10^{-5} \text{ N} \cdot \frac{\text{s}}{\text{m}^2}$$

$$v := \frac{\mu}{\rho}$$

$$v = 1.815 \times 10^{-4} \frac{\text{m}^2}{\text{s}}$$

$$K := .193$$

$$\Delta p(T) := \frac{1}{2} \cdot \rho \cdot \left[\frac{\dot{m}}{\rho \cdot \left(\frac{\pi}{4} \cdot d^2 \right)} \right]^2 \cdot \left[\frac{L}{d} \cdot \left[\frac{1}{-1.8 \cdot \log \left[\frac{6.9}{\left[\frac{\dot{m}}{\rho \cdot \left(\frac{\pi}{4} \cdot d^2 \right)} \cdot d \right] \cdot v} + \left[\frac{\left(\frac{\varepsilon}{d} \right)^{1.11}}{3.7} \right]} \right]} \right]^2 + K \right]$$

$$\Delta p(T) = 6.469 \text{ kPa}$$

MathCAD program for determining the pressure drop of biofuel as it travels from barrel to fuel nozzle for various pipe diameters.

$$St := 100 \cdot 10^{-6} \frac{\text{m}^2}{\text{s}} \quad cSt := \frac{St}{100}$$

Biofuel flow at room temperature

$$d := .25 \text{ in} \dots .375 \text{ in} \dots 1 \text{ in}$$

$$\dot{m} := 2.4 \cdot 0.0211 \cdot 1.2 \frac{\text{lb}}{\text{s}} \quad v := 50 cSt \quad \rho := 1.2 \cdot 998 \frac{\text{kg}}{\text{m}^3}$$

$$L := 250 \text{ ft}$$

$$\epsilon := .00015 \text{ ft} \quad \text{The value of } \epsilon \text{ for commercial steel (White, p. 318, table 6.1)}$$

$$A(d) := \frac{\pi}{4} \cdot d^2 \quad v(d) := \frac{\dot{m}}{\rho \cdot A(d)}$$

$$\Delta p(d) := \frac{1}{2} \cdot \rho \cdot \left[\frac{\dot{m}}{\rho \cdot \left(\frac{\pi}{4} \cdot d^2 \right)} \right]^2 \cdot \left[\frac{L}{d} \cdot \left(1 + \frac{6.9}{-1.8 \cdot \log \left[\frac{\frac{\dot{m}}{\rho \cdot \left(\frac{\pi}{4} \cdot d^2 \right)} \cdot d}{v} \right]} + \left[\frac{\left(\frac{\epsilon}{d} \right)^{1.11}}{3.7} \right] \right) \right]^2$$

d =		Ap(d) =	
0.25	in	135.272	psi
0.375		24.903	
0.5		7.819	
0.625		3.286	
0.75		1.662	
0.875		0.955	
1		0.604	

Heat Exchanger Power Requirements

Definitions

$$\text{kJ} := 1000\text{J}$$

Flow Rate Required:

$$m_f := 0.027 \frac{\text{kg}}{\text{s}}$$

Temperature Difference

$$T_{\text{H,EX}} := (273 + 80)\text{K}$$

$$T_{\text{ambient}} := (273 + 20)\text{K}$$

$$\Delta T := T_{\text{H,EX}} - T_{\text{ambient}}$$

$$\Delta T = 60\text{K}$$

Heat Capacities of materials and fluids

$$\text{Specific_Heat_Steel} := 0.5 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$\text{Specific_Heat_glycol} := 2.22 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$\text{Heat_Capacity_biofuel} := 3000 \frac{\text{J}}{\text{kg} \cdot \text{K}}$$

Calculation of glycol amount inside barrell.

$$\text{Volume} := 150\text{L}$$

$$\text{Density_glycol} := 1050 \frac{\text{kg}}{\text{m}^3}$$

$$\text{Density_glycol} = 1.05 \times 10^3 \frac{\text{kg}}{\text{m}^3}$$

$$\text{Mass_glycol} := \text{Volume} \cdot \text{Density_glycol}$$

$$\text{Mass_glycol} := 160\text{kg}$$

$$\text{Mass_glycol} = 160\text{kg}$$

Exposed Area of the Barrel

$$\text{Radius} := \frac{0.3}{2} \text{ m}$$

$$\text{Height} := 1 \text{ m}$$

$$\text{Top and Bottom} := 2 \cdot \pi \cdot \text{Radius}^2$$

$$\text{Cylinder} := 2 \cdot \pi \cdot \text{Radius} \cdot \text{Height}$$

$$\text{Total Exposed Area of the Barrel} := \text{Top and Bottom} + \text{Cylinder}$$

$$\text{Total Exposed Area of the Barrel} = 1.084 \text{ m}^2$$

Heat Loss from the Exposed Surface

Based on laminar free convection from a vertical cylinder $h = 1.42 \cdot (dT/L)^{1/4}$
(p.358 Holman)

$$h := 1.42 \frac{\text{W}}{\text{m}^2 \cdot \text{K}} \left(\frac{\Delta T}{\text{Height}} \cdot 1 \frac{\text{m}}{\text{K}} \right)^{1/4}$$

$$h = 3.952 \frac{\text{W}}{\text{K} \cdot \text{m}^2}$$

$$\text{Heat}_{\text{loss}} := h \cdot \text{Total Exposed Area of the Barrel} \cdot \Delta T$$

$$\text{Heat}_{\text{loss}} = 257.008 \text{ W}$$

Energy to Heat Initial Change of Glycol = Qw

$$Q_w := \text{Mass}_{\text{glycol}} \cdot \text{Specific Heat}_{\text{glycol}} \cdot \Delta T$$

$$Q_w = 21312 \text{ kJ}$$

Energy to Heat Steel Tank = Qc

$$Q_c := 7 \text{ kg} \cdot \text{Specific Heat Steel} \cdot \Delta T$$

$$Q_c = 210 \text{ kJ}$$

For 1 Hour of Heating Time

$$\text{Power Required} := \frac{(Q_w + Q_c)}{3600 \text{ s}} + \text{Heat}_{\text{loss}}$$

$$\text{Power Required} = 6.235 \text{ kW}$$

$$\text{Safety_Factor} := 0.25$$

$$\text{Power_Required} := \text{Power_Required} \cdot (\text{Safety_Factor} + 1)$$

$$\text{Power_Required} = 7.794 \text{ kW}$$

$$\underline{\text{Energy to Heat Biofuel (maintain HEX temperature) = Qbf}}$$

$$\text{Qbf} := m_p \text{Heat_Capacity}_{\text{biofuel}} \cdot \Delta T$$

$$\text{Qbf} = 4.86 \text{ kW}$$

$$\text{Power_Required} := \text{Qbf} \cdot (\text{Safety_Factor} + 1)$$

$$\text{Power_Required} = 6.075 \text{ kW}$$

Data Collected with Keithley 2700/2701/2750 Multimeter
Time/Date = 12:16:39/Apr. 28 2004

User Comments: High Pressure Bleed Test

Following is the scan list in scanned order, then data in TAB separated format.

Scan List = 101,106,113,114,115,116,117,118,125,126,127,128,129,132,133,134,102,103,1

	Data =							
Channel	1	6	13	14	15	16	17	25
Time	Air In	Glycol	Diesel	Biofuel	Before	Before	Cross	Diesel
s	Temp	Temp	Temp	Temp	Filter	HEX	Temp	Pressure
	C	C	C	C	C	C	C	V
1	74.4	63.4	18.8	18.5	22.4	25.1	18.6	1.0
2	74.6	63.4	18.8	18.5	22.4	25.1	18.6	1.0
3	74.8	63.4	18.8	18.5	22.4	25.1	18.6	1.0
4	75.1	63.4	18.8	18.5	22.4	25.1	18.7	1.0
5	75.5	63.4	18.8	18.5	22.4	25.1	18.6	1.0
6	75.8	63.4	18.8	18.5	22.4	25.1	18.6	1.0
7	76.0	63.4	18.8	18.5	22.4	25.1	18.6	1.0
8	76.0	63.4	18.8	18.5	22.4	25.1	18.7	1.0
9	76.8	63.4	18.8	18.5	22.4	25.1	18.6	1.0
10	77.8	63.4	18.8	18.5	22.4	25.1	18.6	1.0
11	78.7	63.4	18.8	18.5	22.4	25.1	18.6	1.0
12	79.4	63.4	18.8	18.5	22.4	25.1	18.6	1.0
13	80.3	63.4	18.8	18.5	22.4	25.1	18.6	1.0
14	80.9	63.4	18.7	18.5	22.4	25.1	18.7	1.0
15	81.6	63.4	18.8	18.5	22.4	25.1	18.7	1.0
16	82.4	63.4	18.8	18.5	22.4	25.1	18.7	1.0
17	82.8	63.4	18.8	18.5	22.4	25.1	18.6	1.0
18	83.5	63.4	18.8	18.5	22.4	25.1	18.6	1.0
19	84.2	63.4	18.8	18.5	22.4	25.1	18.7	1.0
20	84.9	63.4	18.8	18.5	22.4	25.1	18.7	1.0
21	85.5	63.4	18.8	18.5	22.4	25.1	18.6	1.0
22	86.1	63.4	18.8	18.5	22.4	25.1	18.7	1.0
23	86.6	63.4	18.8	18.5	22.4	25.1	18.6	1.0
24	87.0	63.4	18.8	18.5	22.4	25.1	18.6	1.0
25	87.9	63.4	18.8	18.5	22.4	25.1	18.6	1.0
26	88.5	63.4	18.8	18.5	22.4	25.1	18.6	1.0
27	89.1	63.4	18.8	18.5	22.4	25.1	18.6	1.0
28	89.6	63.4	18.8	18.5	22.4	25.1	18.7	1.0
29	90.2	63.4	18.8	18.5	22.4	25.2	18.7	1.0
30	90.7	63.4	18.8	18.5	22.4	25.1	18.6	1.0
31	91.1	63.4	18.8	18.5	22.4	25.1	18.6	1.0
32	91.6	63.4	18.8	18.5	22.4	25.1	18.7	1.0
33	92.0	63.4	18.8	18.5	22.4	25.1	18.6	1.0
34	92.0	63.4	18.8	18.5	22.4	25.2	18.6	1.0
35	92.1	63.4	18.8	18.5	22.4	25.1	18.7	1.0
36	92.7	63.4	18.8	18.5	22.4	25.1	18.7	1.0
37	93.2	63.4	18.8	18.5	22.4	25.1	18.7	1.0
38	93.6	63.4	18.8	18.5	22.4	25.1	18.6	1.0
39	93.8	63.4	18.8	18.5	22.4	25.1	18.6	1.0
40	94.1	63.4	18.7	18.5	22.4	25.1	18.7	1.0
41	94.5	63.4	18.8	18.5	22.4	25.1	18.6	1.0
42	94.9	63.4	18.8	18.5	22.4	25.1	18.6	1.0
43	95.5	63.4	18.8	18.5	22.4	25.1	18.7	1.0
44	96.2	63.4	18.8	18.5	22.4	25.1	18.7	1.0
45	96.9	63.4	18.8	18.5	22.4	25.1	18.6	1.0
46	97.5	63.4	18.8	18.5	22.4	25.1	18.6	1.0

26	27	28	29	32			33	
Biofuel Pressure	Before Filter	Before HEX	Cross Pressure	Pitot stag			Pitot static	
V	V	V	V	V	psi	kPa	V	psi
1.0	1.0	1.0	1.0	2.474	29.6	204.4	2.493	29.6
1.0	1.0	1.0	1.0	2.477	29.7	204.8	2.494	29.6
1.0	1.0	1.0	1.0	2.478	29.7	205.0	2.506	29.9
1.0	1.0	1.0	1.0	2.485	29.9	205.9	2.499	29.7
1.0	1.0	1.0	1.0	2.491	30.0	206.7	2.515	30.1
1.0	1.0	1.0	1.0	2.467	29.5	203.3	2.491	29.6
1.0	1.0	1.0	1.0	2.477	29.7	204.7	2.502	29.8
1.0	1.0	1.0	1.0	2.519	30.5	210.6	2.557	30.9
1.0	1.0	1.0	1.0	2.627	32.7	225.4	2.646	32.7
1.0	1.0	1.0	1.0	2.685	33.8	233.4	2.711	34.0
1.0	1.0	1.0	1.0	2.734	34.8	240.2	2.765	35.1
1.0	1.0	1.0	1.0	2.796	36.1	248.7	2.818	36.1
1.0	1.0	1.0	1.0	2.813	36.4	251.1	2.834	36.4
1.0	1.0	1.0	1.0	2.870	37.6	258.9	2.900	37.8
1.0	1.0	1.0	1.0	2.894	38.0	262.2	2.917	38.1
1.0	1.0	1.0	1.0	2.919	38.5	265.8	2.948	38.7
1.0	1.0	1.0	1.0	2.971	39.6	272.9	2.995	39.7
1.0	1.0	1.0	1.0	3.004	40.2	277.4	3.027	40.3
1.0	1.0	1.0	1.0	3.038	40.9	282.1	3.064	41.1
1.0	1.0	1.0	1.0	3.058	41.3	284.8	3.082	41.4
1.0	1.0	1.0	1.0	3.089	41.9	289.1	3.108	41.9
1.0	1.0	1.0	1.0	3.092	42.0	289.5	3.111	42.0
1.0	1.0	1.0	1.0	3.114	42.4	292.6	3.131	42.4
1.0	1.0	1.0	1.0	3.145	43.1	296.9	3.179	43.3
1.0	1.0	1.0	1.0	3.173	43.6	300.8	3.200	43.8
1.0	1.0	1.0	1.0	3.195	44.1	303.8	3.224	44.2
1.0	1.0	1.0	1.0	3.225	44.7	307.9	3.244	44.6
1.0	1.0	1.0	1.0	3.223	44.6	307.6	3.249	44.8
1.0	1.0	1.0	1.0	3.236	44.9	309.4	3.261	45.0
1.0	1.0	1.0	1.0	3.234	44.8	309.1	3.260	45.0
1.0	1.0	1.0	1.0	3.248	45.1	311.1	3.281	45.4
1.0	1.0	1.0	1.0	3.260	45.4	312.8	3.275	45.3
1.0	1.0	1.0	1.0	3.188	43.9	302.8	3.208	43.9
1.0	1.0	1.0	1.0	3.203	44.2	304.9	3.237	44.5
1.0	1.0	1.0	1.0	3.230	44.8	308.7	3.257	44.9
1.0	1.0	1.0	1.0	3.241	45.0	310.2	3.262	45.0
1.0	1.0	1.0	1.0	3.239	44.9	309.8	3.259	45.0
1.0	1.0	1.0	1.0	3.238	44.9	309.7	3.260	45.0
1.0	1.0	1.0	1.0	3.240	44.9	309.9	3.259	44.9
1.0	1.0	1.0	1.0	3.246	45.1	310.8	3.261	45.0
1.0	1.0	1.0	1.0	3.253	45.2	311.8	3.286	45.5
1.0	1.0	1.0	1.0	3.295	46.1	317.6	3.321	46.2
1.0	1.0	1.0	1.0	3.334	46.8	323.0	3.360	47.0
1.0	1.0	1.0	1.0	3.366	47.5	327.4	3.382	47.4
1.0	1.0	1.0	1.0	3.402	48.2	332.4	3.426	48.3
1.0	1.0	1.0	1.0	3.435	48.8	336.8	3.467	49.1

						34			
	Delta P		Density	Air velocity	Mass Flow	Combustor P			
kPa	psi	inH2O	kg/m^3	m/s	kg/s	V	psi	kPa	
204.3	0.0	0.5	2.05	11.12511		1.031	0.9	6.0	
204.4	0.1	1.6	2.05	19.90668		1.031	0.9	6.0	
206.1	-0.2	-4.6	2.05	#NUM!		1.031	0.9	6.0	
205.1	0.1	3.2	2.06	28.00643		1.030	0.9	5.9	
207.4	-0.1	-2.9	2.07	#NUM!		1.031	0.9	5.9	
204.0	-0.1	-2.8	2.03	#NUM!		1.030	0.9	5.9	
205.5	-0.1	-3.1	2.04	#NUM!		1.031	0.9	5.9	
213.1	-0.4	-10.0	2.10	#NUM!		1.032	0.9	6.1	
225.4	0.0	0.1	2.25	5.315077		1.036	1.0	6.6	
234.4	-0.2	-4.2	2.32	#NUM!		1.040	1.0	7.1	
241.8	-0.2	-6.5	2.38	#NUM!		1.041	1.1	7.4	
249.1	-0.1	-1.6	2.46	#NUM!		1.044	1.1	7.7	
251.3	0.0	-1.0	2.48	#NUM!		1.044	1.1	7.8	
260.4	-0.2	-5.8	2.55	#NUM!		1.048	1.2	8.4	
262.8	-0.1	-2.2	2.58	#NUM!		1.048	1.2	8.3	
267.1	-0.2	-5.2	2.61	#NUM!		1.048	1.2	8.3	
273.6	-0.1	-2.7	2.67	#NUM!		1.051	1.3	8.7	
278.0	-0.1	-2.3	2.71	#NUM!		1.053	1.3	9.0	
283.0	-0.1	-3.8	2.75	#NUM!		1.054	1.3	9.1	
285.6	-0.1	-2.9	2.77	#NUM!		1.054	1.3	9.1	
289.1	0.0	0.0	2.81	0		1.055	1.3	9.3	
289.6	0.0	-0.2	2.81	#NUM!		1.056	1.4	9.4	
292.2	0.1	1.4	2.84	15.81123		1.054	1.3	9.2	
298.9	-0.3	-8.2	2.87	#NUM!		1.058	1.4	9.7	
301.8	-0.1	-4.0	2.90	#NUM!		1.059	1.4	9.8	
305.1	-0.2	-5.1	2.93	#NUM!		1.059	1.4	9.8	
307.9	0.0	0.0	2.96	2.363539		1.060	1.4	10.0	
308.6	-0.1	-3.9	2.96	#NUM!		1.061	1.5	10.1	
310.3	-0.1	-3.3	2.97	#NUM!		1.062	1.5	10.2	
310.1	-0.1	-3.9	2.96	#NUM!		1.060	1.5	10.0	
312.9	-0.3	-7.3	2.98	#NUM!		1.061	1.5	10.2	
312.1	0.1	2.7	2.99	21.32727		1.060	1.5	10.0	
302.9	0.0	-0.4	2.89	#NUM!		1.057	1.4	9.6	
306.9	-0.3	-7.8	2.91	#NUM!		1.058	1.4	9.7	
309.6	-0.1	-3.8	2.95	#NUM!		1.060	1.4	9.9	
310.4	0.0	-0.7	2.96	#NUM!		1.058	1.4	9.7	
310.0	0.0	-0.5	2.95	#NUM!		1.059	1.4	9.8	
310.1	-0.1	-1.5	2.94	#NUM!		1.060	1.4	10.0	
309.9	0.0	0.0	2.94	2.370789		1.059	1.4	9.8	
310.2	0.1	2.3	2.95	19.74649		1.058	1.4	9.7	
313.7	-0.3	-7.3	2.96	#NUM!		1.060	1.4	9.9	
318.5	-0.1	-3.6	3.01	#NUM!		1.060	1.4	9.9	
323.8	-0.1	-3.4	3.05	#NUM!		1.063	1.5	10.4	
326.9	0.1	1.9	3.09	17.52496		1.062	1.5	10.3	
333.0	-0.1	-2.5	3.13	#NUM!		1.065	1.5	10.6	
338.6	-0.3	-7.4	3.17	#NUM!		1.066	1.6	10.8	

2	3	4	5	
Exhaust 1	Exhaust 2	Exhaust 3	Exhaust 4	Exhaust Avg
C	C	C	C	C
58.8	59.6	58.3	57.9	58.6
59.1	59.9	58.6	58.2	59.0
59.5	60.3	59.0	58.6	59.3
59.8	60.7	59.4	58.9	59.7
60.2	61.0	59.7	59.2	60.0
60.5	61.4	60.2	59.6	60.4
60.9	61.6	60.5	60.0	60.8
61.3	62.0	61.1	60.5	61.2
61.8	62.6	61.5	61.0	61.7
62.3	63.1	61.9	61.4	62.2
62.7	63.6	62.2	61.7	62.5
63.2	64.2	62.7	62.3	63.1
63.6	64.7	63.2	62.7	63.5
64.2	65.1	63.6	63.2	64.0
64.6	65.7	64.2	63.7	64.6
65.1	66.1	64.6	64.1	65.0
65.7	66.7	65.2	64.7	65.6
66.2	67.2	65.7	65.1	66.0
66.7	67.7	66.2	65.6	66.6
67.2	68.2	66.6	66.1	67.0
67.7	68.8	67.2	66.7	67.6
68.2	69.2	67.7	67.2	68.1
68.6	69.6	68.0	67.6	68.5
69.2	70.2	68.6	68.2	69.0
69.7	70.7	69.0	68.7	69.5
70.3	71.3	69.6	69.3	70.1
70.8	71.8	70.0	69.7	70.6
71.2	72.2	70.5	70.2	71.0
71.8	72.8	71.0	70.7	71.6
72.2	73.2	71.5	71.1	72.0
72.7	73.7	72.0	71.7	72.5
73.1	74.1	72.4	72.1	72.9
73.5	74.5	72.9	72.4	73.3
73.8	74.8	73.2	72.7	73.6
74.2	75.2	73.7	73.2	74.1
74.7	75.8	74.3	73.7	74.6
75.1	76.1	74.6	74.0	75.0
75.4	76.4	74.9	74.3	75.3
75.7	76.7	75.1	74.6	75.5
76.1	77.1	75.4	75.0	75.9
76.5	77.4	75.8	75.4	76.3
76.8	77.8	76.1	75.7	76.6
77.3	78.4	76.7	76.3	77.2
77.8	78.9	77.2	76.7	77.7
78.3	79.5	77.8	77.2	78.2
78.8	79.9	78.2	77.7	78.6