The BERL 300kW Unstaged Natural Gas Flames with a Swirl-Stabilized Burner
Case 1: Hot-Wall Conditions

A Benchmark Problem for Validating Mathematical Combustion Models

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1.0 OVERVIEW

This document provides a model problem for validating multi-dimensional combustion models [1]. The well defined experimental data [2] and model problem of the natural gas flame from 300kW burner tests provide a means to systematically evaluate advanced combustion models. Benchmark problems of this type are needed to develop accurate, practical tools for the natural gas industry.

This model problem and the accompanying experimental data are based on measurements completed in the Burner Engineering Research Laboratory (BERL) at the Sandia National Laboratory, as part of the GRI SCALING 400 Project [2,3]. A 300kW IFRF gas burner was tested in the BERL for both hot and cold wall conditions. Detailed in-flame velocity, temperature, and species measurements were collected. These measurements are provided here with detailed geometry and boundary conditions to provide a well-documented model problem for validation of numerical flow and combustion tools.

Questions on the documented model problem should be directed to:

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This document contains the following information:

Topic	Description	Section
Model Problem Guidelines	Essential and Optional Boundary Specifications; Suggested Variables and Formats for Data Comparison	2.0
Model Geometry	Burner and Furnace Geometry	3.0
Burner Input Conditions	Detailed Burner Boundary Condition Information	4.0
Furnace Conditions	Detailed Furnace Wall Boundary Condition Information	5.0
Properties	Natural Gas Composition and Properties; Flue Gas Properties; Specific Heats	6.0
References	Document References	7.0
Example Results Comparison	Example Data Comparison Format	8.0
Experimental Data Tables	Tabulated Experimental Data	9.0
Experimental Data on Disk	MS Excel (PC & Mac format) Files with Tabulated Data	Attached

This model problem could not have been completed without the high quality experimental data obtained during the SCALING 400 Program. Babcock & Wilcox wishes to thank personnel at the International Flame Research Foundation (IFRF), Sandia National Laboratories, and GRI for their help and cooperation.

2.0 MODEL PROBLEM GUIDELINES

The following set of guidelines has been provided to best apply the documented problem for consistent comparison and evaluation. Any departure from these guidelines should be noted by the analyst.

Problem Formulation:

The problem should be formulated as a 2-D axisymmetric or 3-D cylindrical application, assuming circumferential symmetry of the furnace, and consistent with the following specifications. See the referenced Sections, Figures, and Tables for clarification.

- For 2-D axisymmetric applications, the discrete gas injection holes may be idealized to a slot of equivalent area and position on the centerbody (Section 3.0, Figure 2). The suggested arrangement is a 0.339mm wide slot centered 6.0mm behind the blunt centerbody face.

- There was no flue gas recirculation or fuel staging during the experimental test case. Mass flow through the flue gas burner inlet and the burner staging ports is set to zero (See Section 4.0 and Figures 2 and 4 and Table 5).

- The idealized circular furnace diameter should be set to the radial distance from the furnace centerline to the mid-point of any given spool panel, as shown in the Figure 1 spool cross-section (533.4mm).

- The computational domain should be extended past the furnace hood and into the exhaust duct to the location of the furnace exit probe (See Figure 1).

- Axial positions for all in-flame measurements are referenced from the burner quarl exit (See Figure 2).

Mandatory Specifications:

The application should be completed with the following information fixed as described in this document.

- Combustion air and natural gas mass flow rate and temperatures (Tables 1 and 2)

- Combustion air and natural gas mass velocities. Combustion air velocities should be defined either by mean values or by the profiles provided (Tables 1 and 3). Natural gas radial velocity at the injection ports should be specified as given in Table 2.

- Inlet combustion air and natural gas turbulence parameters. Inlet boundary turbulence values should be specified using the average values provided in Tables 1 and 2.

- Furnace wall temperatures and conditions as defined in Tables 4 and 5.

- Natural gas composition defined by either the actual or simplified breakdown provided in Table 6.

Any variation from these specifications should be clearly noted.

Optional Specifications:

The following items may be defined and varied as desired for the application. The approach/methods chosen should be clearly noted and/or referenced as necessary.

- Gas mixture property correlations, such as the JANAF tables. An optional set of specific heat correlations for the gas mixture with and without dissociation are included.

- Turbulence modeling. A standard, high Reynolds number k-ε two-equation model is assumed. Note/reference near-wall conditions and correlations for turbulent heat transfer coefficient.

- Alternate wall heat transfer boundary conditions. Additional model runs with alternate boundary conditions may be included, in addition to the fixed wall temperature results.

- Combustion modeling.

- Radiation modeling and properties.

- Pollutant modeling.

Results Formatting:

Comparison sets should contain the following information:

(1) Documentation
(2) Comparisons of predictions with provided measurements
(3) Auxiliary figures

Documentation should include a brief description of the numerical model and key sub-models. All variations from essential model specifications, as defined above, should be clearly noted, as well as information pertaining to optional specifications.

Result comparisons should be formatted to conform as closely as possible to the example provided in Section 8.0. Minimum comparisons with data should include:

- Radial profiles of axial and tangential velocity components at each axial traverse
- Radial profiles of temperature at each axial traverse
- Radial profiles of O_2, CO, and CO_2 species concentrations, at each axial traverse
- Profiles of the axial velocity component on the burner/furnace centerline
- Profiles of the gas temperature on the burner/furnace centerline
- Profiles of O_2, CO, and CO_2 species concentrations on the burner/furnace centerline

All species concentrations are given on a dry basis, with the exception of unburnt hydrocarbons (HC), which are reported on a wet basis. Species concentrations should be presented on a percent volume dry basis, with the exception of NO, NO_2, NO_x, total NO_x, H_2, and HC, which should be presented in ppmv. Temperatures should be presented in Kelvin. Velocities should be presented in meters per second.

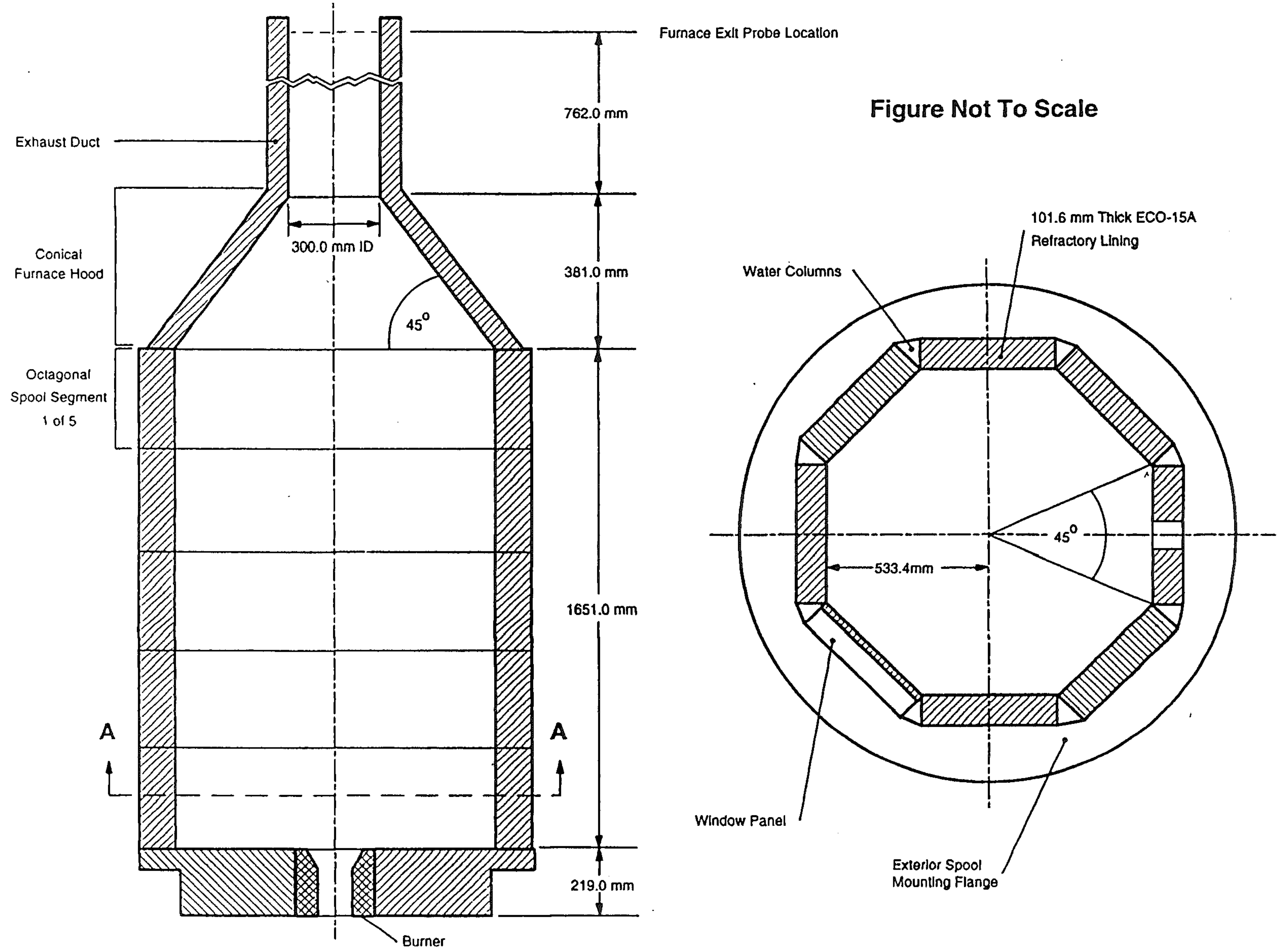
Auxiliary figures should include one figure of the complete numerical domain and grid. Contour plots of gas temperature, velocity field, and key species concentrations should be included for qualitative solution evaluation and comparison.

3.0 MODEL GEOMETRY

The BERL furnace geometry [2,3] is provided in Figure 1. The BERL is a vertically fired furnace consisting of a base plate (in which the burner is installed), five octagonal "spool" sections, and a conical furnace hood with a vertical exhaust duct. The spool sections were constructed using refractory lined panels for the hot-wall measurements. The furnace base, hood and exhaust dust are lined with insulating board.

The geometry of the IFRF gas burner [2] is provided in Figure 2. The 300kW burner used in the measurements is a swirl-stabilized natural gas burner of the type used for all of the SCALING 400 studies. The burner is circumferentially symmetric with a bluff centerbody containing 24 radial gas injection holes. Swirling combustion air is introduced through one annular zone using IFRF swirl blocks. Axial and tangential velocity profiles are obtained downstream of the swirl block exit from the IFRF swirl block calibration procedure [4]. Neither FGR nor fuel staging are included in the model problem measurements.

The burner/furnace configuration is nearly axially symmetric, and lends itself to a simplified representation using an 2-D axisymmetric or 3-D cylindrical combustion model. These are the recommended formats for the application. The furnace expansion ratio is 7.4, based on a quarl exit radius of 72.2 mm and a modeled interior furnace radius of 533.4 mm.



Side View

Spool Cross-section A-A

Figure 1. BERL Furnace Geometry with Refractory Walls

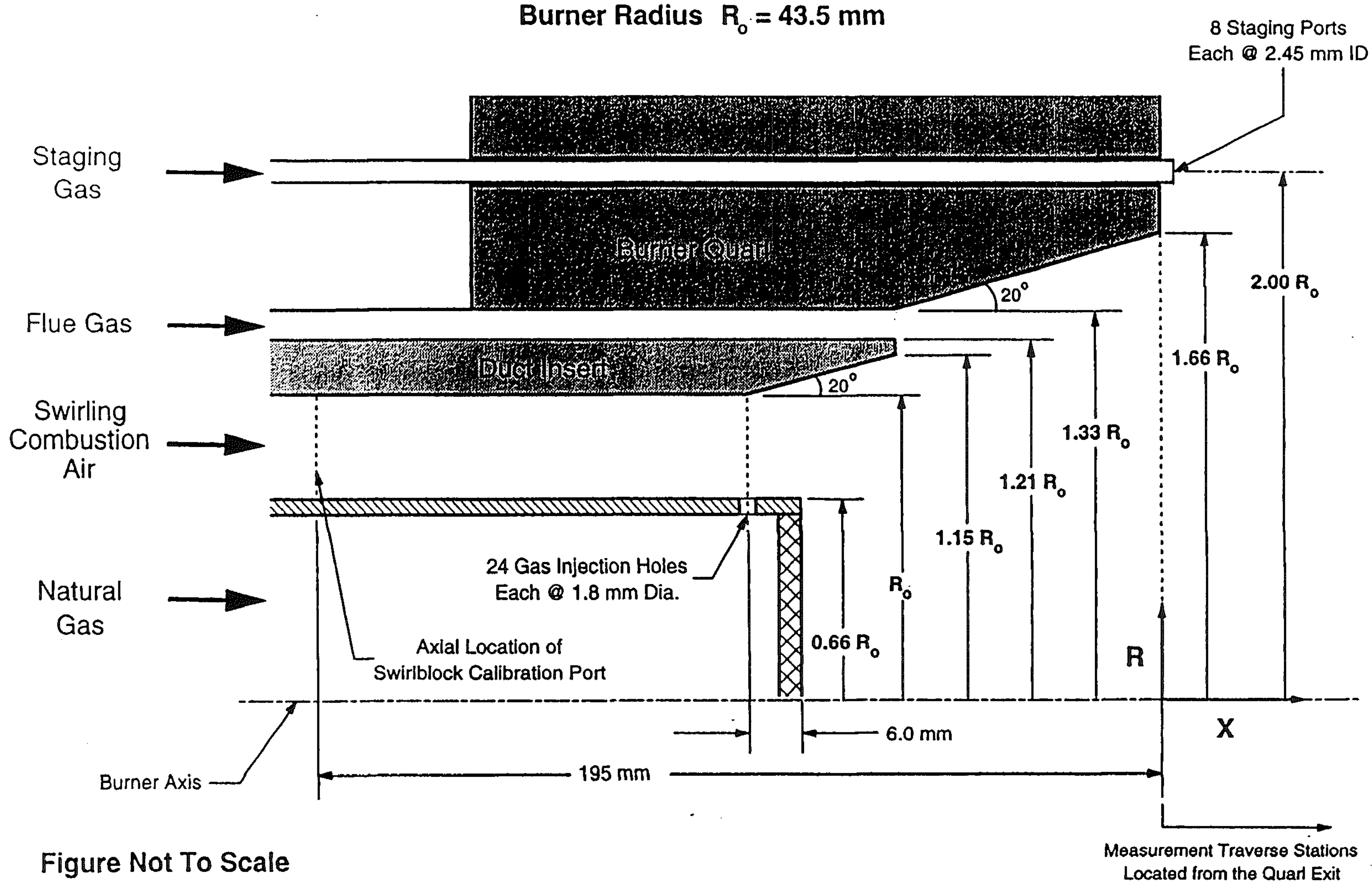


Figure Not To Scale

Figure 2. IFRF 300kW Gas Burner Geometry

4.0 BURNER INLET CONDITIONS

This section contains information for specification of the burner inlet boundary conditions. These inlet locations are shown schematically in Figure 3. Burner combustion air and natural gas conditions are contained in Tables 1 and 2, respectively. Table 3 provides the suggested polynomial fits for the combustion air axial and tangential velocity components at the swirlblock calibration port. These profiles are plotted in Figure 4. Radial velocities at the calibration port may be neglected. Table 5 summarizes specified temperatures for all inlet locations.

The burner tests have been run at a nominal excess air level of 15%, corresponding to a dry oxygen concentration of 3% (by volume) in the flue gas. To set the burner input flowrates:

(1) Set the natural gas mass flow rate, $\dot{m}_{NG}$ to the measured value.

(2) Determine the stoichiometric air requirement, ϕ, as specified in Table 6.

(3) Calculate the combustion air mass flow rate, $\dot{m}_{CA}$

as $$\dot{m}_{CA} = 1.15 \cdot \phi \cdot \dot{m}_{NG}$$

Burner upstream velocity conditions and turbulence information have been determined based on IFRF swirl block calibration procedures [4]. Measurements for mean and RMS values of the fluctuating velocities were completed for swirl settings of 70% and 80% (swirl numbers S_2 of 0.49 and 0.66, respectively) at the calibration port prior to testing. These measurements were used to specify mean velocity profiles and turbulence information at a swirl number S_2 of 0.56. (For the definition of the S_2 swirl number used throughout this document, see eq. (7) in Reference [5].) The turbulent intensities as specified have been calculated as:

$$I_{turb} = \frac{100*(RMS_{ax} + RMS_{tang})}{2*\sqrt{u^2 + w^2}}$$

for the swirling combustion air, and

$$I_{turb} = \frac{100*(RMS_{rad})}{v}$$

for the natural gas jets. For the swirling combustion air, the root-mean-square values and velocities are the radially averaged values obtained from the block swirler calibration.

Table 1

BURNER COMBUSTION AIR INLET CONDITIONS

Conditions at the Combustion Air Inlet (Boundary CA1 in Figure 3):			
Mass Flow Rate (Dry)	=	436.2 kg/hr,	for 290.6 kW and 15% excess air
Inlet Area	=	3.4331×10^{-3} m^2	
Temperature	=	312.15 K	
Oxygen Mass Fraction	=	0.2315	
Nitrogen Mass Fraction	=	0.7685	
Density	=	1.1258 kg/m^3	
Velocity Information:			
Mean Axial Velocity	=	31.35 m/s	See axial velocity profile: Table 3, Figure 3
Swirl Number S_2	=	0.56	
Mean Tangential Velocity	=	20.97 m/s	See tang. velocity profile: Table 3, Figure 3
Turbulent Intensity	=	17%	
Suggested Turbulence Parameters:			
Turbulent Kinetic Energy	=	61.29 J/kg	
Characteristic Length	=	7.6125×10^{-3} m	
Turb. Viscous Dissipation	=	1.479×10^{5} J/kg.s	

Table 2

BURNER NATURAL GAS INLET CONDITIONS

Conditions at the Natural Gas Inlet (Boundary NG1 in Figure 3):

Mass Flow Rate	=	22.7 kg/hr
Inlet Area	=	6.1073×10^{-5} m^2 for 24-1.8mm dia. gas injection holes
Temperature	=	308.15 K
Density	=	0.6544 kg/m^3

Velocity Information:

Mean Radial Velocity	=	157.77 m/s
Turbulent Intensity	=	5%

Suggested Turbulence Parameters:

Turbulent Kinetic Energy	=	94.21 J/kg
Characteristic Length	=	0.9×10^{-3} m
Turb. Viscous Dissipation	=	2.385×10^{6} J/kg.s

Table 3

MODELED AXIAL AND TANGENTIAL VELOCITY PROFILES AT THE COMBUSTION AIR INLET FOR THE UNSTAGED 300-kW FLAMES (SWIRL NUMBER $S_2 = 0.560$)

$v_{axial}(r) = f_{cor}*(c_0 + c_1r + c_2r^2 + ... + c_6r^6)$, for $0.028275 \leq r \leq 0.0435$				
$v_{tang}(r) = f_{cor}*\ (d_0 + d_1r + d_2r^2 + ... + d_6r^6)$, for $0.028275 \leq r \leq 0.0435$				
mass flow correction factor f_{cor} = 1.1178 hot walls				
c_0	-4.8188426870E+04		d_0	-6.8960497786E+04
c_1	7.5296927935E+06		d_1	1.1673343271E+07
c_2	-5.0278973235E+08		d_2	-8.3022991429E+08
c_3	1.8419946151E+10		d_3	3.1709554128E+10
c_4	-3.9029890015E+11		d_4	-6.8471484249E+11
c_5	4.5212286090E+12		d_5	7.9124212930E+12
c_6	-2.2263357665E+13		d_6	-3.8173590138E+13

Boundary Condition ID's:

CA1	- Combustion Air Inlet	W%	- Burner and Furnace Walls
NG1, NG2	- Natural Gas Inlets		
FGR1	- Flue Gas Recirculation Inlet		

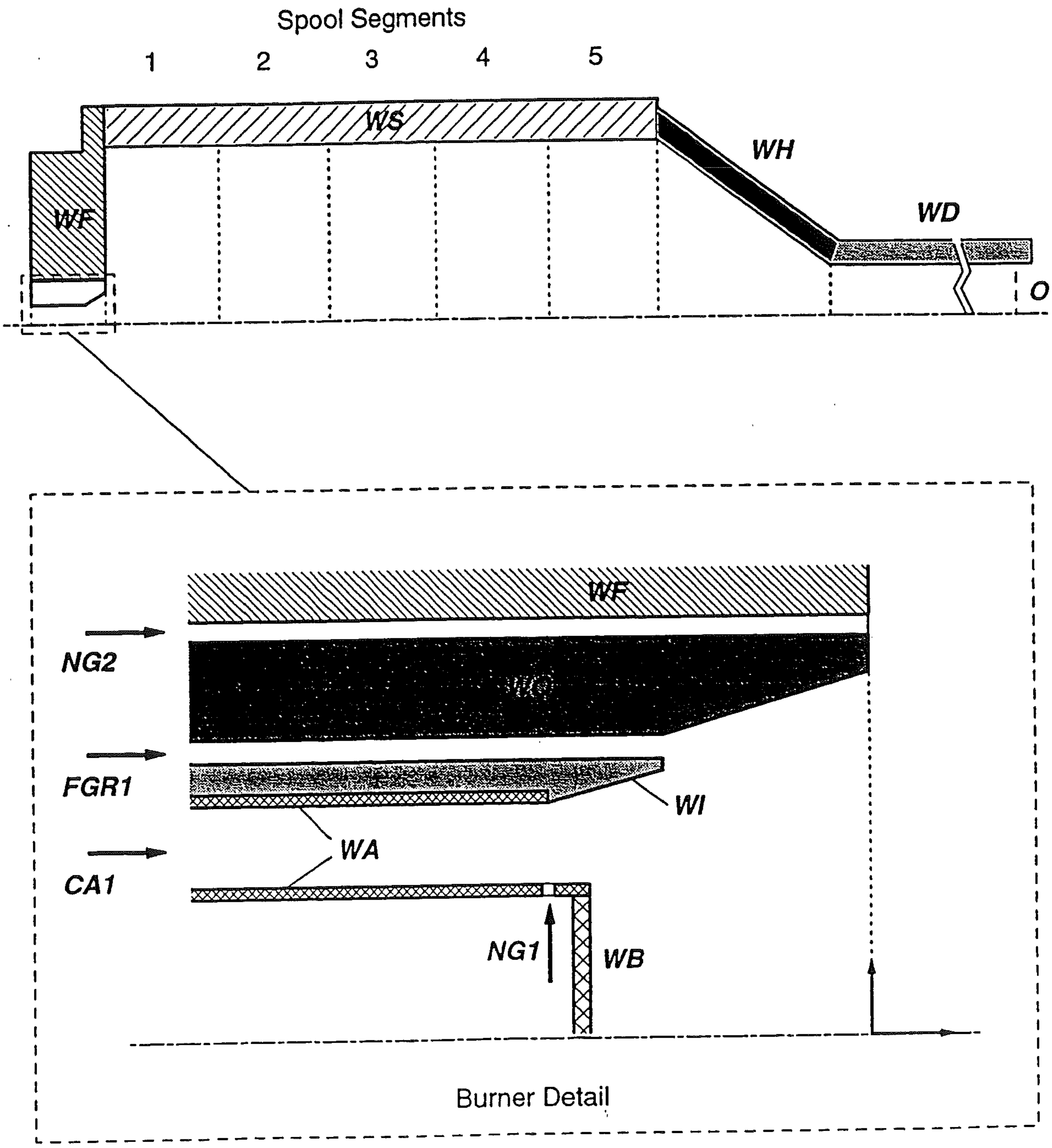


Figure 3. BERL Furnace and IFRF Burner Boundary Condition Schematic

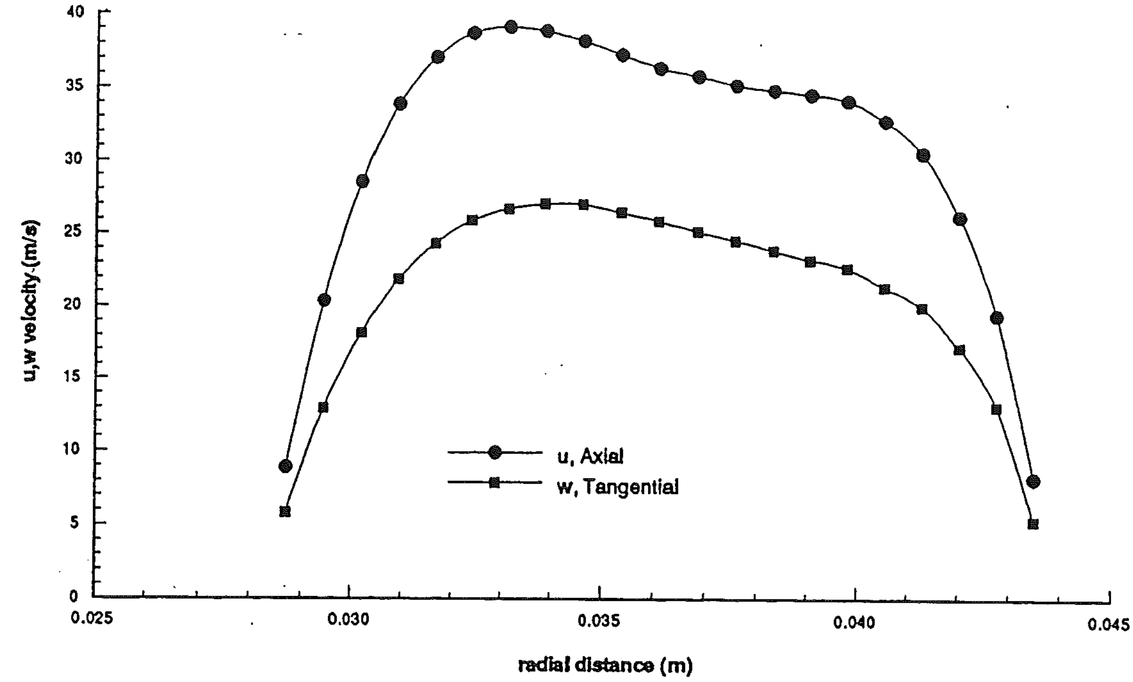


Figure 4. Interpolated Profiles of Mean Axial and Tangential Velocities at the Swirl Block Calibration Port for a Swirl Number of 0.56 (75% Swirl Setting)

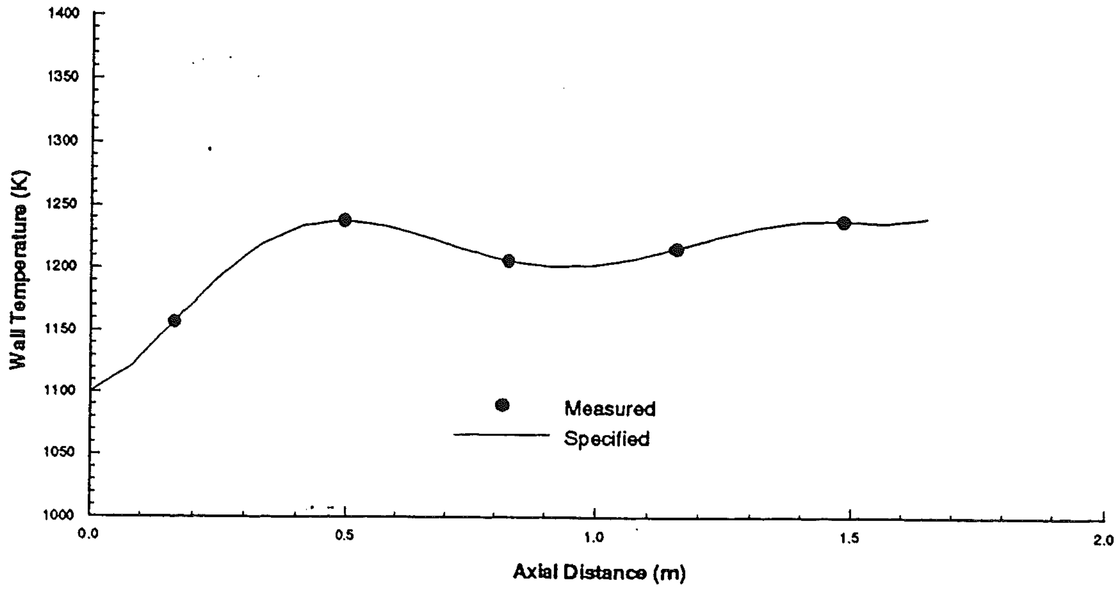


Figure 5. Measured and Specified Furnace Refractory Spool Wall Temperatures

5.0 SURFACE CONDITIONS

This section contains information for specification of burner and furnace wall conditions, including surface temperatures and emissivities. Table 4 provides measured temperatures for each furnace spool sections, and the recommended curve fit. The measured and modeled values are shown in Figure 5. Table 5 provides suggested temperature and emissivity values for all surface boundaries. These boundaries are identified by boundary ID's in Figure 3.

Table 4

MEASURED FURNACE WALL TEMPERATURES
FOR THE UNSTAGED 300-kW BERL FLAMES

Thermocouples in Spool Segment No.	Axial Distance from the Quarl Outlet (m)	(Hot Walls) Wall Temperature (K)
1	0.165	1157
2	0.495	1238
3	0.825	1206
4	1.155	1216
5	1.485	1238
Exhaust Duct	--	1370

$T_{wall}(x) = m_0 + m_1(x + 0.195) + \ldots + m_6(x + 0.195)^6$, in K, for $0 \leq x \leq 1.65$

$m_0 = 1.25700 \times 10^3$	$m_3 = -1.74799 \times 10^4$	$m_5 = -5.83885 \times 10^3$
$m_1 = -2.17770 \times 10^3$	$m_4 = 1.46151 \times 10^4$	$m_6 = 8.98612 \times 10^2$
$m_2 = 9.93349 \times 10^3$		

Table 5

MODELED TEMPERATURES AND EMISSIVITIES
FOR THE UNSTAGED 300-kW BERL FLAMES

Boundary ID	Boundary Description	Temperature (Kelvins)	Emissivity
Surface Boundaries		**Wall Temp.**	
WA	Inlet Duct Walls	312	0.6
WB	Bluff Body Front Wall	1173	0.6
WI	Inlet Duct Insert - Oblique Wall	1173	0.6
WQ	Quarl Wall (Oblique)	1273	0.6
WF	Furnace Bottom Wall	1100	0.5
WS	Furnace Spool Walls	Table 4, Figure 5	0.5
WH	Furnace Hood Wall (Oblique)	1305	0.5
W~~Q~~ D	Exhaust Duct Wall	1370	0.5
Inlet and Outlet Boundaries		**Gas Temp.**	
CA1	Combustion Air Inlet	312*	1.0
NG1	Natural Gas Inlet	308*	1.0
NG2	Staged Natural Gas Inlet	1100	1.0
FGR1	Flue Gas Recirculation Inlet	1173	1.0
O1	Outlet	1386*	1.0

Note: (1) Temperatures in Table 5 are estimated unless otherwise noted.
(2) * indicates measured values.
(3) Emissivities are handbook values.
(4) There is zero massflow set for boundaries NG2 and FGR1.

6.0 PROPERTIES

This section contains property and composition information for the natural gas (Table 6) and property information for the gas mixture (Table 7). An optional set of correlations for the gas mixture specific heat, with and without dissociation, is provided in Table 8 [1]. The analyst may substitute alternative correlations if preferred.

Table 6

MODELED BERL NATURAL GAS COMPOSITION AND PROPERTIES

BERL Natural Gas Composition:

Species	Molecular Weight	Volume Fraction	Mass Fraction	Carbon Portion	Hydrogen Portion
CH_4	16	96.5	93.30	69.98	23.32
C_2H_6	30	1.7	3.08	2.46	0.62
C_3H_8	44	0.1	0.27	0.22	0.05
C_4H_{10} & higher	58	0.1	0.35	0.29	0.06
CO_2	44	0.3	0.80	--	--
N_2	28	1.3	2.20	--	--

Simplified Natural Gas Composition:

Species	Molecular Weight	Mass Fraction	Carbon Portion	Hydrogen Portion
Fuel	16.313	97.00	72.95	24.05
CO_2	44	0.80	--	--
N_2	28	2.20	--	--

Modeled Natural Gas Properties:

Reference Density	= 0.7383 kg/m^3	at 0°C and 1.01325*10^5 Pa (Ideal Gas Law)
Reference Air Density, Dry	= 1.2865 kg/m^3	based on 23.15 weight% O_2 and 76.85 weight % N_2 and at 0°C and 1.01325*10^5 Pa (Ideal Gas Law)
Specific Gravity	= 0.5739	
Lower Calorific Value	= (46.7/0.9700) = 48.14 MJ/kg Fuel	
Carbon Fraction f_C	= (72.95/97.00) = 0.7521 kg C/kg Fuel	
Hydrogen Fraction, f_H	= (24.05/97.00) = 0.2479 kg H/kg Fuel	
Oxygen Requirement, s_1	= (32/12)*f_C + (32/4)*f_H = 3.989 kg O_2/kg Fuel	
Air Requirement (Dry), ϕ	= (0.9700/0.2315)*s_1 = 16.71 kg air/kg NG	

Table 7

GAS MIXTURE PROPERTIES

Gas Mixture Properties:

Density (kg/m^3)	= Ideal gas law
Dynamic Viscosity (Pa.s)	$= 7.6181*10^{-6} + 3.2623*10^{-8}\, T_{gas}$
Thermal Conductivity (W/m.K)	$= 7.6736*10^{-3} + 5.8837*10^{-5}\, T_{gas}$
Mean Specific Heat (J/kg.K)	$= c_{p,\text{flue gas}}\,(0,T_{gas})$
	$= \sum_{species\ i} \omega_i c_{p,i}(0,T_{gas}),$
	i = Fuel, O_2, CO, CO_2, H_2O, N_2 Note: Fuel modeled as CH_4

Gas Mixture Temperature T_{gas} in Kelvins

Species Mass Fraction ω_i in (kg species-i)/(kg gas mixture)

Table 8

MEAN SPECIFIC HEATS

Without Dissociation (Technical Data on Fuel)

N_2	
m_0:	1.02705E+03
m_1:	1.08091E-02
m_2:	4.95459E-05
m_3:	-1.12105E-08

CO	
m_0:	1.04669E+03
m_1:	-7.84203E-02
m_2:	1.79968E-04
m_3:	-7.52653E-08
m_4:	1.01010E-11

CH_4	
m_0:	2.00500E+03
m_1:	-3.40714E-01
m_2:	2.36196E-03
m_3:	-1.17842E-06
m_4:	1.70263E-10

$c_{p,i}(0.T) = m_0 + m_1T + ... + m_6T^6$

With Dissociation (Techn. Data on Fuel & Hoogovens)

CO_2	
m_0:	5.35446E+02
m_1:	6.39334E-01
m_2:	-1.82259E-04
m_3:	-5.95560E-08
m_4:	3.78408E-11

H_2O	
m_0:	1.93780E+03
m_1:	-5.90386E-01
m_2:	1.21452E-03
m_3:	-7.15819E-07
m_4:	1.51916E-10

O_2	
m_0:	8.76317E+02
m_1:	6.14140E-02
m_2:	1.86101E-04
m_3:	-3.00618E-07
m_4:	2.29482E-10
m_5:	-8.53962E-14
m_6:	1.22371E-17

7.0 REFERENCES

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2. Sayre, A., Lallemant, N, Dugué, J., and Weber, R., "Scaling Characteristics of the Aerodynamics and Low NOx Properties of Industrial Natural Gas Burners: The SCALING 400 Study. Part IV: The 300kW BERL Test Results," GRI Contract No. 5090-298-1977, January, 1994, IFRF Doc. No. F40/y/11.

3. "Operation of the Burner Engineering Research Laboratory," Draft Topical Report prepared by Energy and Environmental Research Corporation, GRI Contract No. 5093-260-2513.

4. Dugué, J. and Weber, R., "Design and Calibration of a 300 kW Natural Gas Burner for BERL," IFRF Doc. No. C74/y/5, January 1993.

5. Weber, R. and Dugué, J., "Combustion Accelerated Swirling Flows in High Confinements," Prog. Energy Combust. Sci., 1992, Vol. 18, pp. 349-367.

APPENDIX 2
BOUNDARY CONDITIONS FOR THE SIMULATION OF THE IFRF BURNER

(taken from V K. C. Kaufman, W. A. Fiveland, A. A. Peters, R. Weber, "The BERL 300kW Unstaged Natural Gas Flames with a Swirl-Stabilized Burner. Case 1: Hot-Wall Conditions. A Benchmark Problem for Validating Mathematical Combustion Models", Babcock & Willcox, Research and Development Division, Alliance, OH, November 1994))