U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

www.nhtsa.gov

DOT HS 812 112F

February 2015

Crashworthiness Research of Prototype Hydrogen Fuel Cell Vehicles: Task Order 7 Project Report

Appendix F

Analysis of the Uncertainity in the Gas Quantity Measurements

DISCLAIMER

This page intentionally left blank.

F1.0 PRESSURE INTEGRITY METHODOLOGY AND ANALYSIS

Some level of uncertainty or error is present in every measurement. The goal of the uncertainty analysis in this report is to quantify the uncertainty in the pressure and temperature measurements and propagate that uncertainty to determine the maximum error in the molar density ratios.

The uncertainty analysis performed in this report follows the general guidelines outlined in the NIST Engineering Statistics Handbook, which adheres to the ISO Guide to the Expression of Uncertainty of Measurement (GUM) [3]. Uncertainty analysis reports for the pressure and temperature sensors used to perform the analysis have been included as Figure F-1 through Figure F-4. The sources of uncertainties considered in the leakage analysis are listed below for each crash test.

1. Temperature
    a. Uncertainty in the solenoid temperature sensor
    b. Uncertainty in the measurement resolution (rounding)
    c. Uncertainty in the test data acquisition system (considered negligible)
2. Pressure
    a. Uncertainty in the pressure transducer
    b. Uncertainty in the test data acquisition system
    c. Uncertainty in the measurement resolution (rounding)
3. Helium Properties
    a. Uncertainty of the NIST Equation of State (0.1%)
    b. Uncertainty resulting from mixing nitrogen with the helium (0.3%) – side crash only

Efforts were made to minimize the propagated error by using calibrated equipment with known uncertainties. Where applicable, the random uncertainties in the measurements were reduced by averaging over several hundred data points. This reduced the standard deviations of the means in many cases to a negligible level.

It should be noted that these uncertainties are highly dependent on the instrumentation used in each test setup, and would change if alternate equipment was used. Good experimental practices help to minimize and characterize the measurement uncertainty. Some of the steps that should be taken are:

- Use calibrated instruments and data acquisition systems with quantified uncertainty.
- Attempts should be made to identify and eliminate (or correct) bias errors while calibrating the instruments and during the experiment itself.
- Data collection rates should be high enough to allow for averages to be taken of the data. This helps reduce the random noise uncertainty on a measurement by reducing the standard deviation of the mean.
- The Guide to the Expression of Uncertainty in Measurement (GUM) should be followed for performing uncertainty analysis.

In instances where enough data was present to perform a statistical analysis (type A uncertainty) the data was plotted as a histogram to verify the distribution type. For these instances a normal distribution was deemed most appropriate based on the histograms. For instruments and equipment which were calibrated by the Battelle metrology laboratory, (type B uncertainty) the coverage factor of k=2 was used with a confidence level of approximately 95%. For handling uncertainties associated with the resolution rounding error, a half uniform (commonly called $\sqrt{12}$ or $2\sqrt{3}$) distribution was used. The uncertainties associated with the temperature and pressure, constitute the measurement errors associated with the instrumentation. The remaining uncertainties result from errors associated with the analysis of the molar densities. These helium uncertainties were handled after the measurement uncertainties were propagated.

Once the uncertainties in the pressure and temperature measurements were established, the bounded molar densities were found by using the Helium equation of state [2]. The upper bound of the molar density arises by taking the nominal pressure P and adding the pressure uncertainty dP, while subtracting the temperature uncertainty dT from the nominal temperature T. While the gases were actually dealt with as real gases, the ideal gas equation shown as equation 1, is adequate to illustrate this concept.

$$\frac{(P+dP)}{R(T-dT)} = \frac{N}{V}\bigg|_{UB} \tag{1}$$

The lower bound molar density is found by subtracting the pressure uncertainty dP from the nominal pressure and adding the temperature uncertainty to the nominal temperature. The lower bound example is illustrated by equation 2 below.

$$\frac{(P-dP)}{R(T+dT)} = \frac{N}{V}\bigg|_{LB} \tag{2}$$

The upper bound and lower bound molar densities are the measurement worst case scenarios. To find the 95% confidence interval of the molar density, each uncertainty for pressure and temperature would need to be propagated through the Helium equation of state to find the uncertainty contribution for each term in the equation. Given the complexity of the equation of state for Helium [2], the worst case uncertainty method described in this appendix is more practical and easier to implement in a regulatory setting.

To account for the uncertainty in the equation of state and the uncertainty resulting from mixing nitrogen with helium in the side crash, the upper and lower bound molar densities were scaled by one plus or minus the helium density uncertainty. Where the helium density uncertainty is 0.1% and 0.4% in the rear and side crash tests respectively.

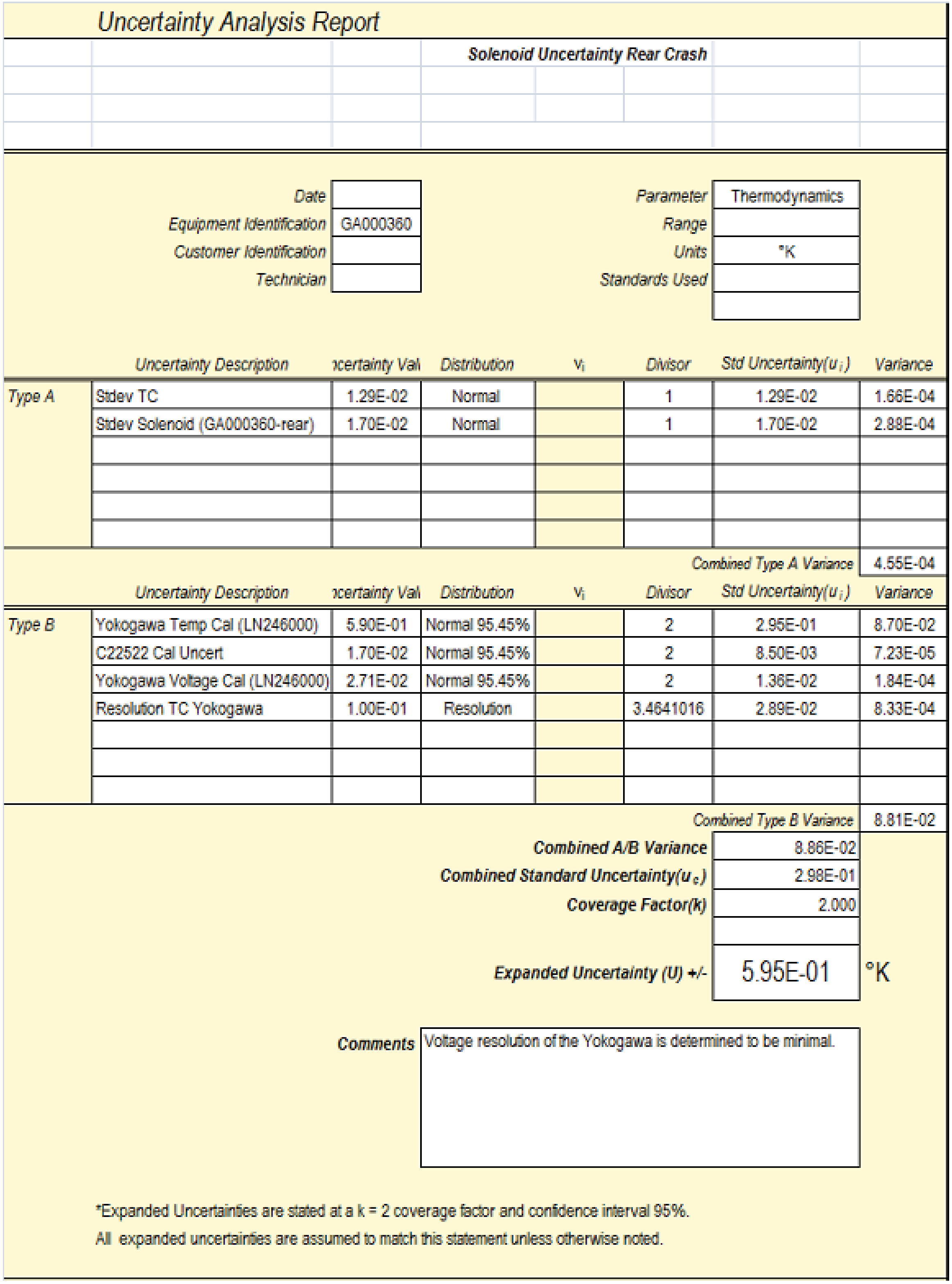
For the Type-3 containers used in this experiment, the volume change in the fuel system, the pressure loss due to a detectable leak is negligible; therefore the fuel system volume can be taken as a constant. This cancels out of the upper bound – lower bound ratio leaving only the ratio of moles of gas. Table F-1 provides the container volume dependency on pressure as provided by the manufacturer. Correspondence with the container's manufacturer indicated that a linear interpolation between the two points would be an accurate assumption [1].

Table F-1. Manufacturer's data on volume expansion with pressure [1].

Container Pressure (psig)	Nominal Volume of 39 L	Nominal Volume of 74 L
0	38.52	73.31
6351	38.903	74.064

F1.1 REFERENCES

1. Correspondence with Neil DeVetten at Dynetek
2. McCarty, D. R., Arp, D. V. A New Wide Range Equation of State for Helium. Advances in Cryogenics Engineering. Vol 35. Plenum Press, New York. 1990.
3. National Institute of Standards and Technology. Engineering Statistics Handbook. Section 2.5-Uncertainty Analysis. http://www.itl.nist.gov/div898/handbook/mpc/section5/mpc5.htm



Uncertainty Analysis Report

Solenoid Uncertainty Rear Crash

Date		*Parameter*	Thermodynamics
Equipment Identification	GA000360	*Range*	
Customer Identification		*Units*	°K
Technician		*Standards Used*	

	Uncertainty Description	certainty Val	*Distribution*	v_i	*Divisor*	*Std Uncertainty(u$_i$)*	*Variance*
Type A	Stdev TC	1.29E-02	Normal		1	1.29E-02	1.66E-04
	Stdev Solenoid (GA000360-rear)	1.70E-02	Normal		1	1.70E-02	2.88E-04
						Combined Type A Variance	4.55E-04

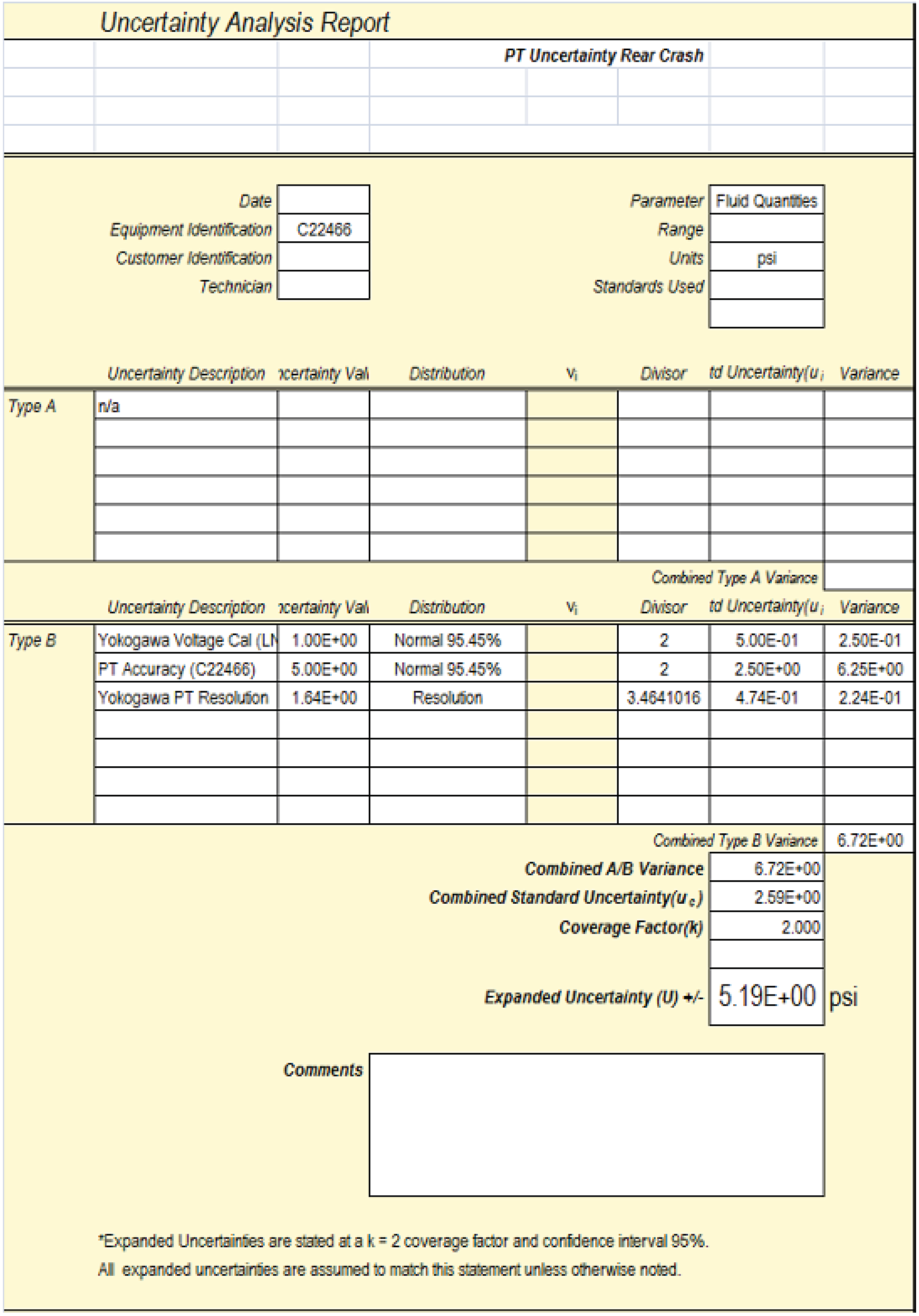
	Uncertainty Description	certainty Val	*Distribution*	v_i	*Divisor*	*Std Uncertainty(u$_i$)*	*Variance*
Type B	Yokogawa Temp Cal (LN246000)	5.90E-01	Normal 95.45%		2	2.95E-01	8.70E-02
	C22522 Cal Uncert	1.70E-02	Normal 95.45%		2	8.50E-03	7.23E-05
	Yokogawa Voltage Cal (LN246000)	2.71E-02	Normal 95.45%		2	1.36E-02	1.84E-04
	Resolution TC Yokogawa	1.00E-01	Resolution		3.4641016	2.89E-02	8.33E-04
						Combined Type B Variance	8.81E-02

Combined A/B Variance	8.86E-02	
Combined Standard Uncertainty(u$_c$)	2.98E-01	
Coverage Factor(k)	2.000	
Expanded Uncertainty (U) +/-	5.95E-01	°K

Comments Voltage resolution of the Yokogawa is determined to be minimal.

*Expanded Uncertainties are stated at a k = 2 coverage factor and confidence interval 95%.
All expanded uncertainties are assumed to match this statement unless otherwise noted.

Figure F-1. Uncertainty Analysis Report for the Rear Crash Temperature Sensor.



Uncertainty Analysis Report

PT Uncertainty Rear Crash

Date		Parameter	Fluid Quantities
Equipment Identification	C22466	Range	
Customer Identification		Units	psi
Technician		Standards Used	

	Uncertainty Description	certainty Val	Distribution	v_i	Divisor	td Uncertainty(u_i	Variance
Type A	n/a						
						Combined Type A Variance	

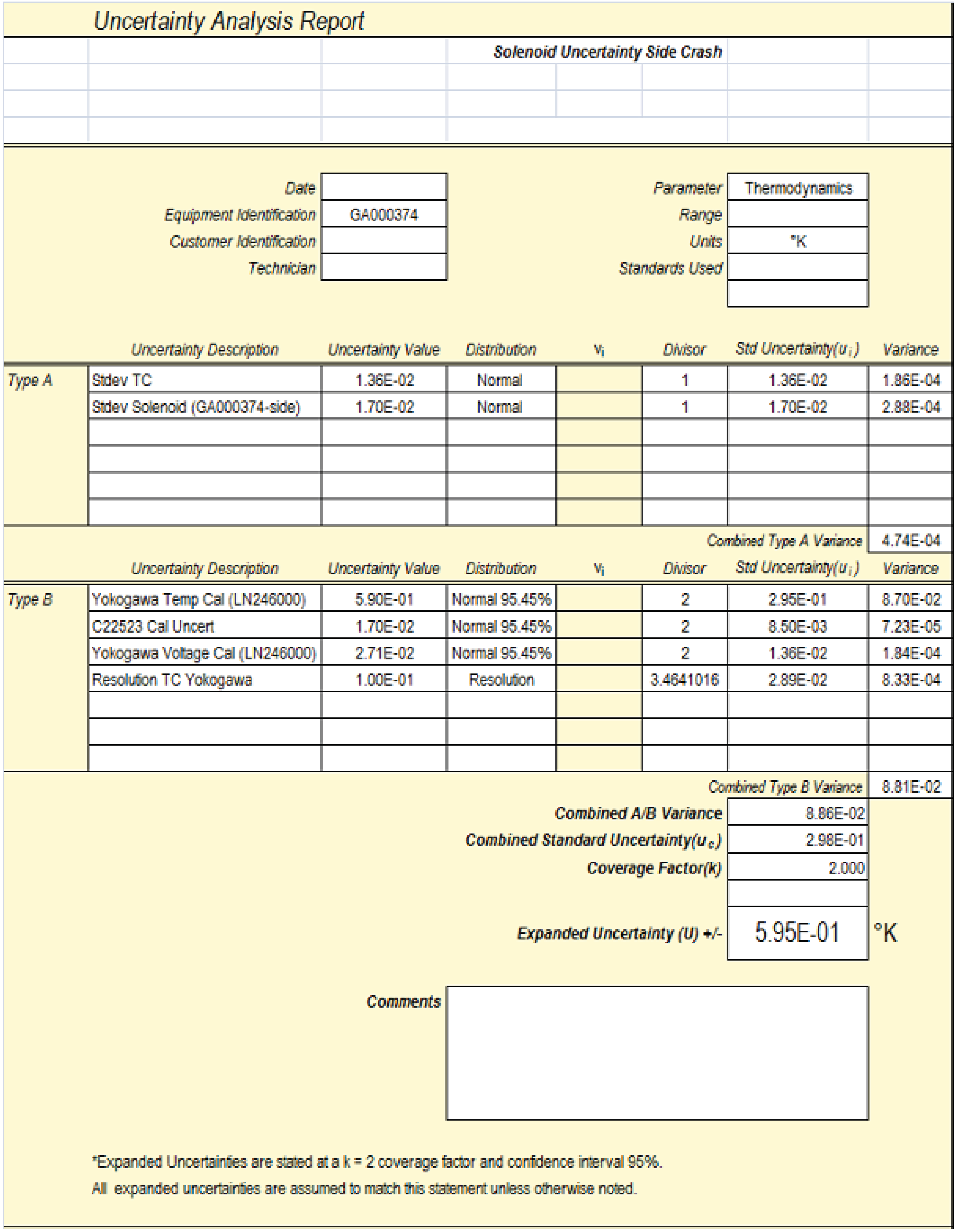
	Uncertainty Description	certainty Val	Distribution	v_i	Divisor	td Uncertainty(u_i	Variance
Type B	Yokogawa Voltage Cal (LN	1.00E+00	Normal 95.45%		2	5.00E-01	2.50E-01
	PT Accuracy (C22466)	5.00E+00	Normal 95.45%		2	2.50E+00	6.25E+00
	Yokogawa PT Resolution	1.64E+00	Resolution		3.4641016	4.74E-01	2.24E-01
						Combined Type B Variance	6.72E+00

Combined A/B Variance	6.72E+00	
Combined Standard Uncertainty(u_c)	2.59E+00	
Coverage Factor(k)	2.000	
Expanded Uncertainty (U) +/-	5.19E+00	psi

Comments

*Expanded Uncertainties are stated at a k = 2 coverage factor and confidence interval 95%.
All expanded uncertainties are assumed to match this statement unless otherwise noted.

Figure F-2. Uncertainty Analysis Report for the Rear Crash Pressure Transducer.



Uncertainty Analysis Report

Solenoid Uncertainty Side Crash

Date		Parameter	Thermodynamics
Equipment Identification	GA000374	Range	
Customer Identification		Units	°K
Technician		Standards Used	

	Uncertainty Description	Uncertainty Value	Distribution	v_i	Divisor	Std Uncertainty(u_i)	Variance
Type A	Stdev TC	1.36E-02	Normal		1	1.36E-02	1.86E-04
	Stdev Solenoid (GA000374-side)	1.70E-02	Normal		1	1.70E-02	2.88E-04
						Combined Type A Variance	4.74E-04

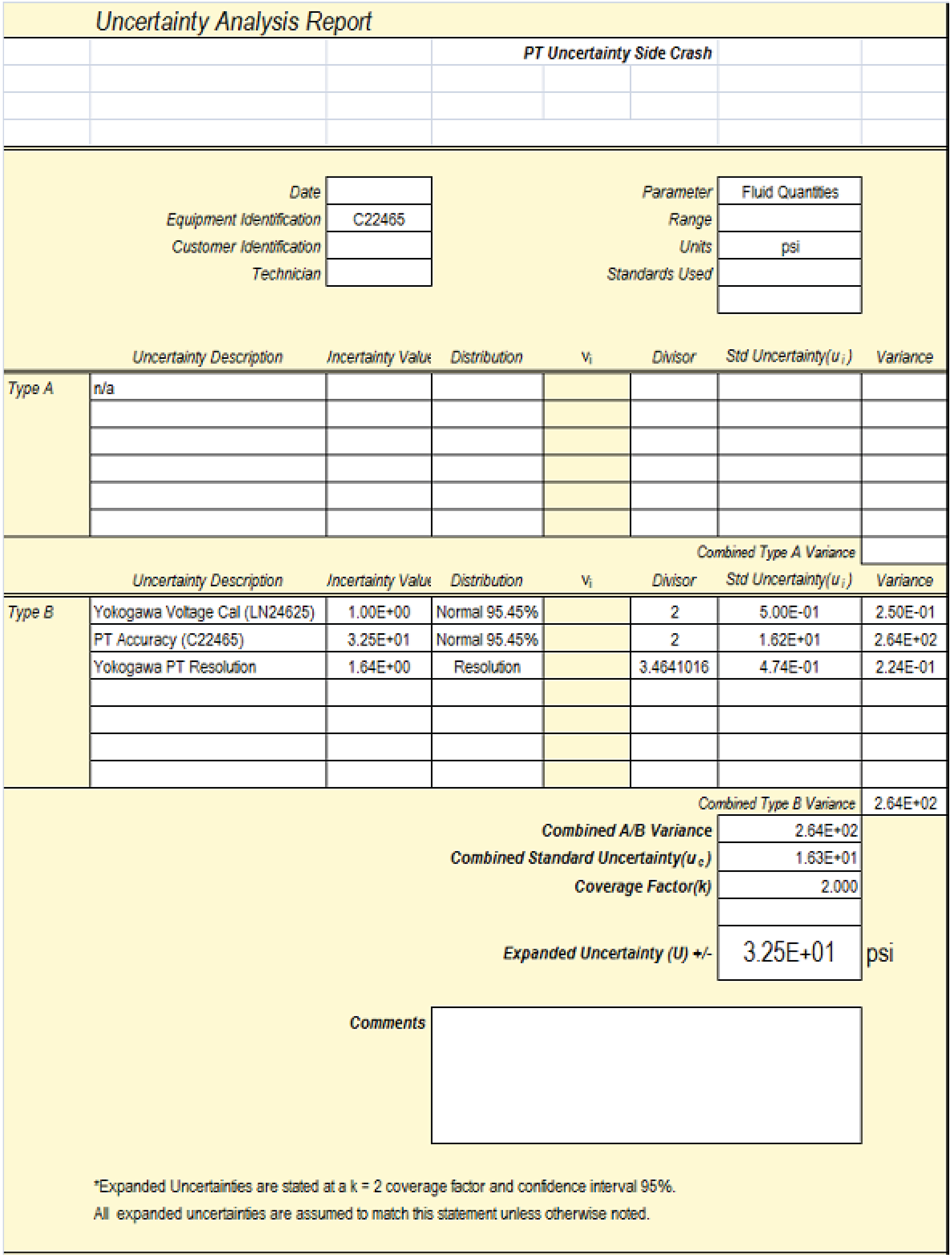
	Uncertainty Description	Uncertainty Value	Distribution	v_i	Divisor	Std Uncertainty(u_i)	Variance
Type B	Yokogawa Temp Cal (LN246000)	5.90E-01	Normal 95.45%		2	2.95E-01	8.70E-02
	C22523 Cal Uncert	1.70E-02	Normal 95.45%		2	8.50E-03	7.23E-05
	Yokogawa Voltage Cal (LN246000)	2.71E-02	Normal 95.45%		2	1.36E-02	1.84E-04
	Resolution TC Yokogawa	1.00E-01	Resolution		3.4641016	2.89E-02	8.33E-04
						Combined Type B Variance	8.81E-02

Combined A/B Variance	8.86E-02
Combined Standard Uncertainty(u_c)	2.98E-01
Coverage Factor(k)	2.000
Expanded Uncertainty (U) +/-	5.95E-01 °K

Comments

*Expanded Uncertainties are stated at a k = 2 coverage factor and confidence interval 95%.
All expanded uncertainties are assumed to match this statement unless otherwise noted.

Figure F-3. Uncertainty Analysis Report for the Side Crash Temperature Sensor.



Uncertainty Analysis Report

PT Uncertainty Side Crash

Date		Parameter	Fluid Quantities
Equipment Identification	C22465	Range	
Customer Identification		Units	psi
Technician		Standards Used	

	Uncertainty Description	ncertainty Valu	Distribution	v_i	Divisor	Std Uncertainty(u_i)	Variance
Type A	n/a						
						Combined Type A Variance	

	Uncertainty Description	ncertainty Valu	Distribution	v_i	Divisor	Std Uncertainty(u_i)	Variance
Type B	Yokogawa Voltage Cal (LN24625)	1.00E+00	Normal 95.45%		2	5.00E-01	2.50E-01
	PT Accuracy (C22465)	3.25E+01	Normal 95.45%		2	1.62E+01	2.64E+02
	Yokogawa PT Resolution	1.64E+00	Resolution		3.4641016	4.74E-01	2.24E-01
						Combined Type B Variance	2.64E+02

Combined A/B Variance	2.64E+02	
Combined Standard Uncertainty(u_c)	1.63E+01	
Coverage Factor(k)	2.000	
Expanded Uncertainty (U) +/-	3.25E+01	psi

Comments

*Expanded Uncertainties are stated at a k = 2 coverage factor and confidence interval 95%.
All expanded uncertainties are assumed to match this statement unless otherwise noted.

Figure F-4. Uncertainty Analysis Report for the Side Crash Pressure Transducer.

DOT HS 812 112F
December 2015

U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

NHTSA
www.nhtsa.gov

10846F-020415-v2