CALCULATION OF INSTRUMENT LOOP ERRORS IN SPECIAL SAFETY SYSTEMS OF CANDU REACTORS, A STATISTICAL APPROACH.

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ABSTRACT

Allowances made in Nuclear Safety Analysis for CANDU reactors Special Safety Systems consider expected instrument loop errors. As utilities accumulate more operational experience and more insight on the behaviour of instrumentation in the specific stations environmental conditions, station staff are able to validate allowances used in the Safety Analysis.

This paper describes a statistical method for drift data analysis of the different types of errors attributed to instrumentation and the approach used to determine total instrument loop errors in safety systems at Bruce A & B NGS. While the exercise is still in progress, this paper provides a summary of findings to date, together with recommendations on issues to be considered in the events where a need to reduce errors was identified.

1.0 INTRODUCTION

Verification of trip setpoint tolerances in CANDU reactors is achieved by a combination of Special Safety Systems testing and calibration of the instrumentation frequently enough to ensure that the combination of any drifts resulting from process and environmental conditions and/or deviations from expected values at calibration time do not exceed the allowances allocated for instrument loop errors in the safety analysis. Fig. 1 shows the relationship among the various field and analysis parameters as used in the Ontario Hydro safety analysis (Reference 1).

Thus, an accurate determination of instrument loop errors, including a detailed analysis of the main contributors is necessary to identify actions should changes be required for one or more of the following reasons:

a) Improve the accuracy of the loop error allowances used in the Nuclear Safety Analysis by reflecting the experience gained with the instrumentation at each station.

b) To determine if calibration frequencies, as initially instituted, are consistent with operational experience.

c) To determine whether there is a need to revise calibration or maintenance procedures to reduce operating costs and increase instrumentation availability and production time.

Traditionally, instrument loop errors are calculated using data as specified by instrument suppliers. However, for new equipment there may not be sufficient data to forecast their behaviour with time. Moreover, as instruments age and as they are exposed to field conditions for prolonged periods, their accuracy may deteriorate. Therefore, Bruce A and B Nuclear Generating Stations initiated an analysis of plant instrumentation calibration data using statistical methods to evaluate present status and identify corrective actions, if any, to reduce loop errors.

This paper provides a description of the error calculation program at the Bruce stations. It includes information on the steps taken towards defining the behaviour of field instrumentation over time and as a result of their exposure to "harsh" environmental conditions in the field. It also includes a comparison of errors resulting from the field data analysis against those specified by manufacturers and, where necessary, recommendations aimed at reducing these errors.

2.0 LOOP ERROR DETERMINATION PROCESS

Based on ISA Standard RP67.04 Part II (Reference 2), two alternative approaches for the calculation of instrument errors were considered:

1. Errors calculated using manufacturers' specifications.

2. Errors calculated using field calibration data.

An evaluation of the above two approaches was based on the effort and benefits to the station. Subsequently, a decision was made in favour of using field calibration data for the calculation of instrument loop errors. Section 3.0 describes the main activities carried out in these calculations. The same calculations were repeated using manufacturers' data as means of cross-checking results and to determine the degree to which one should rely on manufacturers' data for similar applications. Table 1 lists advantages and disadvantages of these two methods.

3.0 ACTIVITIES BREAKDOWN FOR LOOP ERROR CALCULATION

Main activities carried out as part of the exercise were:

- **Preparation of an Assumptions and Methodology Document**. (Ref. TP-XX-63700-001). The methodology was prepared based on ISA-RP67.04 Part II (Reference 2).

- **Definition of Instrument Loop Boundaries**. For all trip parameters under study, the devices (including Maintenance and Test Equipment) that play a role in the trip and indication functions were identified (Ref. Figure 2).

- **Data Collection**. Instrument calibration sheets issued since plant inception were retrieved from archives. When necessary, to obtain a statistically valid sample, instrument data from similar systems (i.e., similar instruments working under similar process and environmental conditions) was grouped. Manufacturers' data for the field instrumentation and for all the Maintenance and Test Equipment (M&TE) was compiled . Table 2 is a sample for one subsystem.

- **Data Entry.** All data necessary for the calculation of loop errors was identified, validated and entered into a database. Table 3 is an excerpt from a sample database showing the format and typical data.

- **Spreadsheet Preparation**. All data fields, formulae and logic (e.g., handling of outliers) necessary for error calculation were inputted into a spreadsheet.

- **Error Classification.** Errors were classified as random or systematic (Ref. Section 3.1 below).

- **Error Calculation.** Loop errors were calculated for the indication and the trip function (Ref. Fig. 1) both at the setpoint and at all calibration points.

- **Analysis of Results.** Error values obtained using field data were compared against those obtained using manufacturers' data, major contributors were identified. Section 3.3 discusses the results. Section 5.0 shows some of the recommendations made to decrease errors and improve the calibration process.

3.1 Error Classification

Errors were broken down into basic components as follows:

- Drift (mainly due to process and environmental conditions). For the purpose of this exercise, drift was calculated as the difference between the previous As Left value and the actual As Found value.

- As Left calibration errors. Calculated as the difference between As Left and **expected** calibration values.

- Errors from calibration equipment (Secondary Standards).

- Human Factors errors.

A study of the above error components was made to determine whether they are of the random or systematic type. Table 5 summarizes the findings.

3.2 Error Calculation

The general expression for error calculation (Ref. ISA-RP67.04 Part II, section 6.3.2) is as follows:

$$e_L = \pm\sqrt{\sum_{m=1}^{m=k} e_m^2 + \sum_{m=1}^{m=k} B_{md} + \sum_{m=1}^{m=k} B_{mal}} \qquad \textbf{Eq. 1}$$

When field data is used to calculate instrument loop errors, terms in Eq. 1 are as follows:

e_L	=	Total loop error
k	=	Number of instruments contributing to the loop error.
Bmd	=	Drift bias (systematic) for the instrument. Calculated as the mean drift value of each instrument after excluding outliers.
B_{mal}	=	As Left bias. Calculated as the mean As Left deviation from expected values for each instrument after excluding outliers.
e_m	=	Total random error of each loop instrument Calculated as*:

$$em = \sqrt{D\max^2 + U\max^2 + Eacc^2 + CE^2} \qquad \textbf{Eq. 2}$$

where: D_{max} = Random drift between calibrations for the instrument, calculated as K.σ; where σ is the standard deviation of the drift (As Found - As Left) data population for the instrument after excluding outliers.

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* Each of the loop instruments is calibrated in isolation, therefore no correlation of errors exists between different instruments in a loop.

U_{max} = Random As Left errors for the instrument, calculated as K.σ. where σ is the standard deviation of the As Left uncertainty (As Left - Expected) data population for the instrument after excluding outliers**.

E_{acc} = Random errors associated with environmental conditions resulting from postulated events. These uncertainties are accident scenario dependent and are being included as part of the Nuclear Safety Analysis calculations.

CE = Calibration and Human Factor uncertainties. Consists mainly of the Reference Accuracy of the Measurement and Test Equipment, controlled Standard and scale spacing in analog readouts.

An expression similar to Equation 1 above was used in the calculation of loop errors using manufacturers' data. In this case, errors were treated as random or systematic based on manufacturers' information.

3.3 Analysis of Results

Table 4 summarizes error results. The upper half of the table shows individual device errors as calculated using field and manufacturers' data. These comparisons must be done bearing in mind that the confidence level at which manufacturers' specify their errors is not always known and consequently, a 2σ confidence level was assumed as recommended in ISA-RP67.04 Part II.

For the transmitter and the isolation amplifier, field data calculations result in larger errors than those predicted by the manufacturers. A significant portion of this difference could be attributable to the M&TE (CE) errors which, in both cases, fail to meet the 4:1 accuracy ratio dictated by industry practice. For comparison purposes, CE errors were computed for the field data calculations only since it was assumed that manufacturer specifications already include CE errors.

The lower half of Table 4 shows total loop errors resulting from the computation of individual instrument errors shown in the upper half of the table. Separate loop errors were calculated for the trip and the test functions (functional boundary definition criteria was as illustrated in Figure 1) and within each of these functions, errors were calculated for calibration values at the different setpoints and for all calibration points. The main points of interest are loop errors for the trip function at the low and very low trip setpoints. In both these cases, field data error calculations exceed manufacturer data calculations.

** K is extracted from standardized area tables for a normal distribution. For example, for a 95% confidence level and assuming normally distributed uncertainties (in all cases, populations larger than 100 samples were obtained):

K = 1.645 if, for the parameter under study, the setpoint is approached only from one direction.

K = 2.0 for parameters with increasing and decreasing trip limits approached from different directions.

4.0 FINDINGS

Tables 5&6 show some of the preliminary findings and recommendations resulting from studies performed until now on shutdown system instrumentation loops at the Bruce A & B stations.

5.0 FURTHER WORK

Calibration data analysis is still being conducted for the remaining trip loops at Bruce A & B. In parallel, the following actions are being pursued:

- As error results are calculated, the impact of these on trip accuracy is being assessed. Remedial actions could include replacement of instruments with more accurate ones and or design changes to either testing or trip function loops.

- Procedures are being revised to ensure that calibration data is recorded in a manner to better support this type of analysis (Ref. Table 6).

- A program has been started under which field data obtained from calibrations of certain Safety System instrumentation will be entered into a spreadsheet file. Automatic "PASS" or "RE-CALIBRATE INSTRUMENT/LOOP" statements are generated depending on the "AS FOUND" status of the instrument. Tools are also being developed to assist reliability analysis staff to determine Safety System impairment levels.

- A database including calibration data of similar instruments working under similar environmental conditions is being developed. Properly maintained, this could simplify repetition of this exercise at other stations.

6.0 REFERENCES

1. Oliva, A.F., Balog, G., Parkinson, D.G., & Archinoff, G.H., "Development and Implementation of Setpoint Tolerances for Special Safety Systems". Presented at Technical Committee Meeting on the Exchange of Operating Safety Experience of Pressurized Heavy Water Reactors, Cordoba, Argentina, April 3-5, 1991.

2. ISA-RP67.04, Part II, "Methodologies for the Determination of Setpoints for Nuclear Safety-Related Instrumentation", September 94.

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TABLE 1

EVALUATION OF METHODOLOGIES FOR THE CALCULATION OF INSTRUMENT LOOP ERRORS

METHOD	ADVANTAGES	DISADVANTAGES	REMARKS
Manufacturers' data	No need to maintain a database for calculation purposes.	Specific plant conditions (e.g., vibration, radiation fields) are not always taken into consideration when specifying errors.	
	Manufacturer may have performed statistical analysis on a larger population.	Specifications could be ambiguous and/or not sufficiently detailed (e.g., manufacturers often omit the confidence level of the error specification). Manufacturers' experts may not always be available to clarify specifications. Effects of aging on accuracy not fully understood.	This could be of a limited value if the environmental conditions were not similar to those present in the installation of the instruments being analyzed.
Field calibration data	Field data reflects effects of the installation environment more accurately.	Accuracy of calculations depends on the quality of the database.	
	As Left/As Found data reflects effects of aging and any other contributor whose effects may not be well understood or accurately calculated.	Control Maintenance Procedures must be written with data analysis in mind.	
	Less reliance on manufacturers' support.	Adherence to Control Maintenance Procedures becomes more critical.	
	Indirectly leads to better tracking of instrument performance. Information in the database may be useful for predictive maintenance activities thereby reducing station downtime and trip unavailability.		
	Higher accuracy in error calculations may result in increased operating margins.		

TABLE 2. MANUFACTURERS' DATA FOR FIELD INSTRUMENTATION AND M&TE.

Maintenance and Test Equipment Uncertainty			
MTE 1			
Druck Portable Pressure Calibrator (Model DPI 601)(C11-18-XX)			
Accuracy: (based on 0-30 psig range)			0.15 % of span
	range (30 psig) =	831 " WG	
	span =	279.05 " WG	
Temp Effect:			0.108 % of span
(% reading/deg F) =	0.003		
Temp variation (deg F)	36		
MTE 1 uncertainty			**0.18394 % SPAN (30 psig)**
MTE 2			
FLUKE DVM (DC Current)(C39-13-XX)			
Accuracy (20mA Range):			0.3 % of Reading + 2 Digits
MTE 2 uncertainty			**0.3875 % SPAN (16 mA)**
		+	0.0263 % of Reading
		-	0.0625 % of Reading
MTE 3			
TRANSMATION Model 1040 (C09-03-XX)			
Accuracy of 0-22mA I/O Range:		0.12 % of Range	0.0264 mA
	plus	0.06 % of Reading (20mA)	0.012 mA
			0.0384 mA
MTE 3 uncertainty			**0.24 % SPAN (16mA)**

TABLE 3. FIELD DATA REQUIRED FOR ERROR CALCULATION.

UNIT	USI	DEVICE	IN UNITS	OUT UNITS	CAL DATE	Tc	AF 0	AF 1	AF 2	AF 3	AF 4	AL 0	AL 1	AL 2	AL 3	AL 4
[redacted]						Tc										
[redacted]			" H20	mADC	9/9/85		4.06	8.05	12.06	16.06	20.06	4.00	8.00	12.00	16.01	20.00
[redacted]			" H20	mADC	5/21/91	2080	4.18	8.17	12.16	16.16	20.15	4.00	7.97	11.96	15.95	19.96
[redacted]			" H20	mADC	8/1/93	803	3.86	7.87	11.86	15.88	19.90	4.00	8.00	12.00	16.01	20.03
[redacted]			" H20	mADC	8/21/93	20	3.86	7.87	11.86	15.88	19.90	4.00	8.00	12.00	16.01	20.03
[redacted]			" H20	mADC	2/6/95	534	4.13	8.12	12.10	16.11	20.13	4.00	8.00	12.00	16.00	20.00
[redacted]			" H20	mADC	8/6/95	181	3.88	7.87	11.86	15.86	19.89	4.00	7.99	11.99	16.00	20.01
[redacted]			" H20	mADC	6/18/83							4.00	8.00	12.00	16.00	20.00
[redacted]			" H20	mADC	6/27/84	375	3.79	7.82	11.82	15.85	19.93	3.96	7.98	12.00	16.01	20.04
[redacted]			" H20	mADC	7/23/85	391	4.11	8.09	12.10	16.09	20.08	4.01	8.01	12.00	16.00	20.00
[redacted]			" H20	mADC	8/15/90	1849	3.99	7.99	12.00	16.01	20.04	3.99	7.99	12.00	16.01	20.04
[redacted]			" H20	mADC	2/7/93	907	3.99	7.99	12.00	16.00	20.00	3.99	7.99	12.00	16.00	20.00
[redacted]			" H20	mADC	2/12/95	735	4.03	8.03	12.03	16.03	20.03	4.01	8.01	12.01	16.01	20.01
[redacted]			" H20	mADC	4/24/79							4.00	8.00	12.00	16.00	20.00
[redacted]			" H20	mADC	6/28/80	431	3.86	7.72	11.55	15.37	19.17	3.99	8.00	12.00	16.00	20.00
[redacted]			" H20	mADC	6/11/83	1078	3.76	7.82	11.88	15.94	19.96	4.00	8.00	12.00	16.00	20.00

TABLE 3 GLOSSARY OF TERMS

UNIT:	The Reactor Unit number where the instrument is installed.
USI:	Universal Subject Index. This number identifies the system of which the instrument is part. E.g., Boiler Low Level Trip
DEVICE:	The instrument functional code or Tag number. Indicates type of instrument, its number and channel of the Safety System of which it is part. E.g., LT2D is Level Transmitter 2 in Channel D.
IN UNITS:	The units of the calibration input signal. E.g., MPa. (Megapascals) for a Pressure Transmitter.
OUT UNITS:	The units of the calibration output signal. E.g., mA (milliamperes) for a Pressure Transmitter.
CAL DATE:	The date the instrument was calibrated.
T_C:	The period between the last and present calibration dates.
AF0 - AF4:	As Found calibration data corresponding to 0, 25, 50, 75 and 100% of the calibrated range respectively. E.g., for a Level Transmitter calibrated to deliver 4 to 20 mA corresponding to levels between 0 and 10 m, 12 mA would be the As Found value for 50% of the calibrated range if there were no instrument errors.
AL0 - AL4:	As Left calibration data corresponding to 0, 25, 50, 75 and 100% of the calibrated range respectively. E.g., for a Level Transmitter calibrated to deliver 4 to 20 mA corresponding to levels between 0 and 10 m, 12 mA would be the As Left value for 50% of the calibrated range if there were no instrument errors.

TABLE 4. SUMMARY OF RESULTS.

This table gives a comparison summary of uncertainties for calibration based data, manufacturer based data and CE (calibration error) on Boiler Level Low Trip loop USI # 63743					
Device Uncertainty					
INSTRUMENT		Calibration based device random uncertainty including CE (% Span)	Manufacturer's data based uncertainty (No CE included) (% Span)	Calibration uncertainty CE (% Span)	Device bias uncertainty (% Span)
LT2/3/4(D/F)	@ 0-100%Span	+/- 1.662	+/- 0.999	+/- 0.429	0.014
LT2/3(E)	@ Low Setpoint (50%)	+/- 1.721	+/- 0.999	+/- 0.429	-0.020
	@ Very Low Setpoint (25%)	+/- 1.628	+/- 0.999	+/- 0.429	0.047
LI5/6(D/E/F)	@ 0-100% Span	+/- 0.859	+/- 1.061	+/- 0.240	-0.015
	@ Low Setpoint (50%)	+/- 0.779	+/- 1.061	+/- 0.240	-0.024
	@ Very Low Setpoint (25%)	+/- 0.802	+/- 1.061	+/- 0.240	0.035
LIA2/3/4(D/F)	@ 0-100%Span (indication)	+/- 0.426	+/- 1.061	+/- 0.240	0.010
LIA2/3(E)	@ 50% Span (indication)	+/- 0.659	+/- 1.061	+/- 0.240	-0.051
	@ 25% Span (indication)	+/- 0.339	+/- 1.061	+/- 0.240	0.038
	@ Low Setpoint (Trip)	+/- 0.326	+/- 0.464	+/- 0.240	0.032
	@ Very Low Setpoint (Trip)	+/- 0.327	+/- 0.464	+/- 0.240	0.000

LX2/3/4(D/F)	@ 0-100% Span	+/- 2.177	+/- 0.520	+/- 0.456	0.635
LX2/3(E)	@ Low Setpoint (50%)	+/- 1.811	+/- 0.520	+/- 0.456	0.655
	@ Very Low Setpoint (25%)	+/- 1.763	+/- 0.520	+/- 0.456	0.636
Loop Uncertainty					
	INSTRUMENT	**Calibration based uncertainty including CE (% Span)**	**Manufacturer's uncertainty (No CE included) (% Span)**		
Total Loop Error	@ 0-100% Span indication using LI6 indicator	+ 3.5041 - 2.2367	+/- 1.5470		
Total Loop Error	**@ Low Setpoint Trip (50%)**	**+ 1.7628** **- 1.7398**	**+/- 1.1010**		
Total Loop Error	@ Low Trip Test (50%) using LI5 indicator	+ 0.8514 - 0.8367	+/- 1.1576		
Total Loop Error	@ Low Trip Test (50%) using LI6 indicator	+ 2.2504 - 0.9266	+/- 1.2692		
Total Loop Error	**@ Very Low Setpoint Trip (25%)**	**+ 1.7080** **- 1.6135**	**+/- 1.1010**		
Total Loop Error	@ Very Low Trip Test (25%) using LI5 indicator	+ 0.9012 - 0.8315	+/- 1.1576		
Total Loop Error	@ Very Low Trip Test (25%) using LI6 indicator	+ 2.6356 - 1.2935	+/- 1.2692		

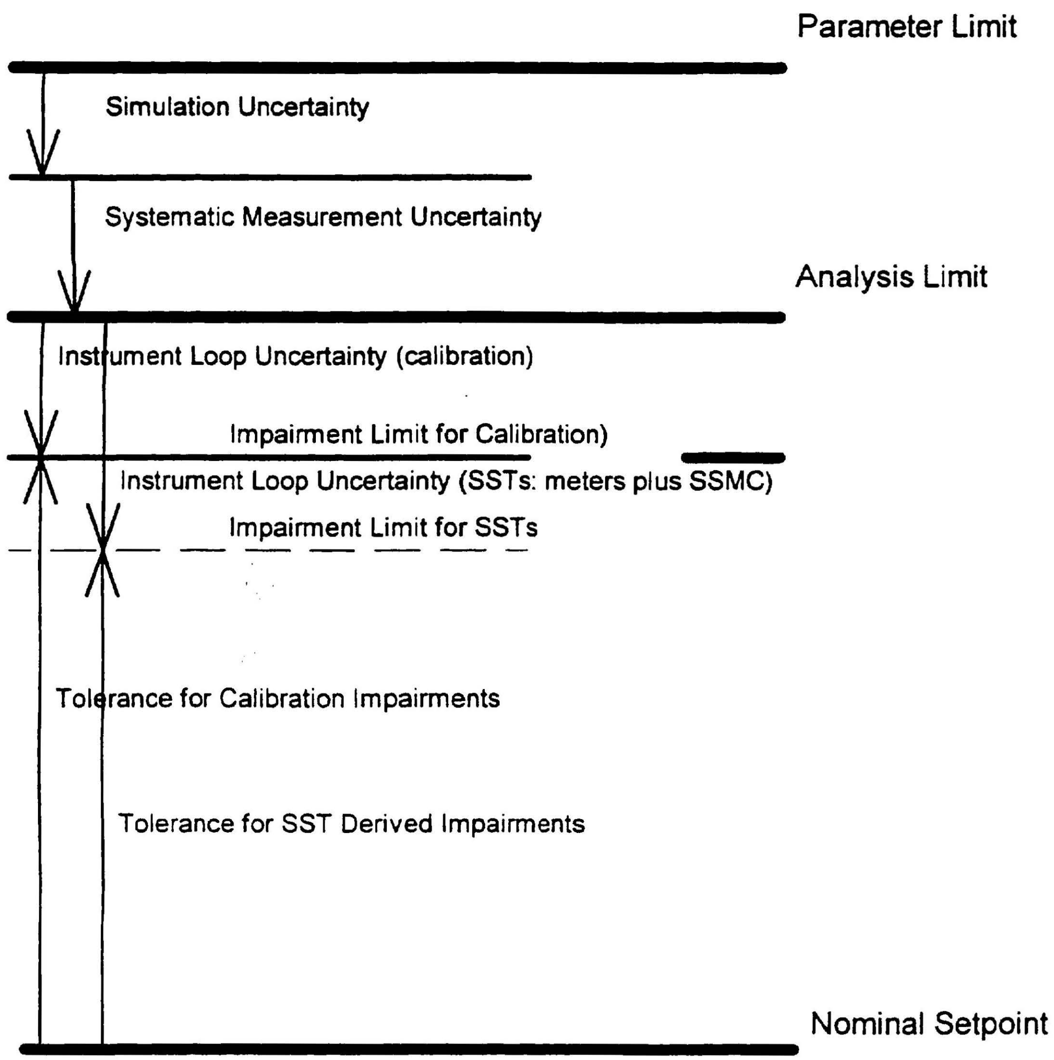
TABLE 5 INSTRUMENT ERROR CLASSIFICATION

ERROR COMPONENT	CLASSIFICATION METHOD	CONCLUSIONS (ERROR TYPE)	REMARKS (REFERENCES)
Drift errors	Plotting AL-AF calibration values vs. cal. period. Plotting Frequency Distribution of drift.	Random	Plots of drift vs. period between calibrations (Fig. 3) show no time dependence of drift. Plots of frequency distribution of drift (Fig. 4)shows a skewed distribution. Population was large enough to treat distribution as normal. It is recognized that the difference between As Left and As Found data could include effects of other types of errors such as the Reference Accuracy of the instrument. For practical reasons and because it was concluded that separating As Left/As Found data into its basic components would not result in a more accurate error calculation, it was decided that the combination of all these effects would be treated as drift.
As Left calibration errors	See Remarks column	Random	Initially, an assumption was made that when recalibrating, an attempt would be made to calibrate as closely as possible to the expected values. Consequently, the As Left errors are expected to be small compared to other contributors. This was confirmed later by inspection of the calibration data. Also, a recommendation is being made (Ref. Table 6) to perform calibrations in such a way as to ensure, whenever possible, that any As Left errors are in the safe direction of the trip. Therefore, treating this error as a random or systematic type would not result in significant differences in the total error results. Moreover, if this error was treated as random (Ref. Eq. 1) and the above recommendation regarding calibration was followed, any differences between the calculated and the true error, would be in the safe direction of the trip.
Errors from calibration equipment (M&TE)	As per manufacturer's specifications.	Combination of random and systematic errors.	
Human Factors	Ref. ISA-RP67.04, Part II		Generally negligible compared to other error components

TABLE 6
FINDINGS AND RECOMMENDATIONS

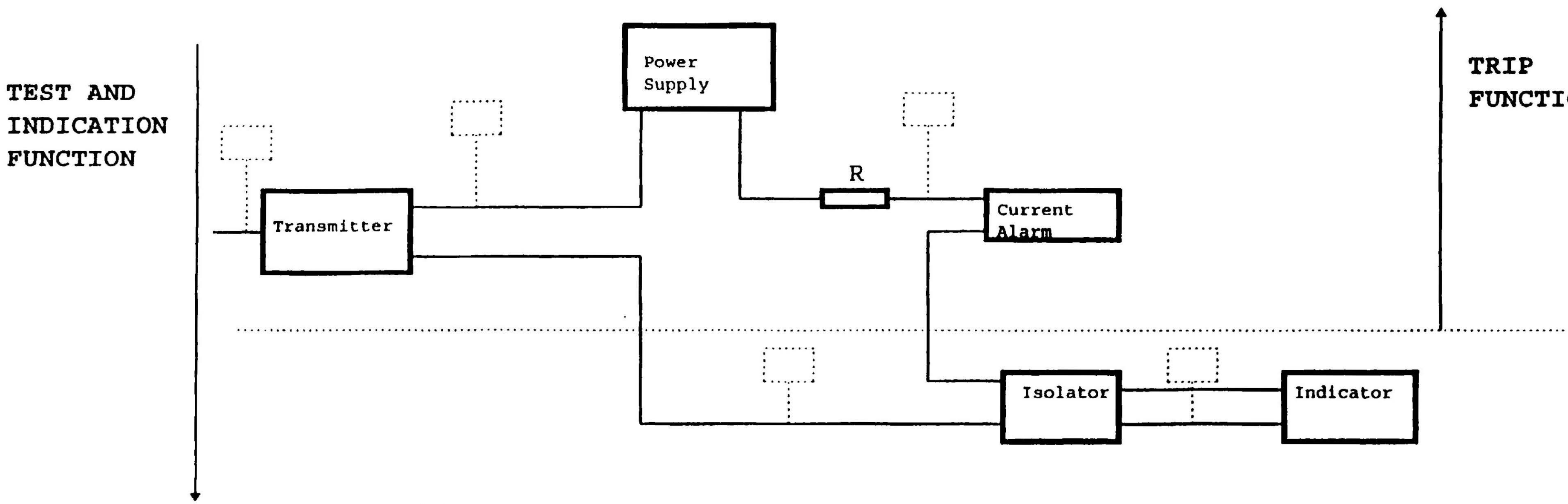
FINDINGS	RECOMMENDATIONS
Errors for some of the devices found to be in excess of those specified by manufacturers.	Assumptions made in Safety Analysis to be revisited. Where necessary, field instrumentation or M&TE to be replaced.
Additional data to be documented at calibration time(e.g., ambient temp., in-situ vs. shop calibration)	Revise calibration procedures to ensure recording of data is consistent with error calculation requirements.
	1. Train personnel conducting calibrations to ensure that the importance of high quality data recording is recognized.
	2. Institute mechanisms whereby calibration would be invalidated whenever data recording is insufficient or inadequate.
	3. Consideration should be given to inputting data directly into an electronic database with a minimum degree of data validation capability.
Any As Left errors should be in the safe direction of the trip.	Revise calibration procedures so that calibrations will be performed in such a way as to ensure, whenever possible, that any As Left errors are in the safe direction of the trip.

Figure 1. Build Up of Tolerances for Instrument Uncertainty



Not to scale: Relative sizes of uncertainties are schematic only.

FIGURE 2. DEFINITION OF INSTRUMENT LOOP BOUNDARIES



Note: Dotted boxes represent MTE

FIGURE 3. DRIFT VS. CALIBRATION INTERVALS.

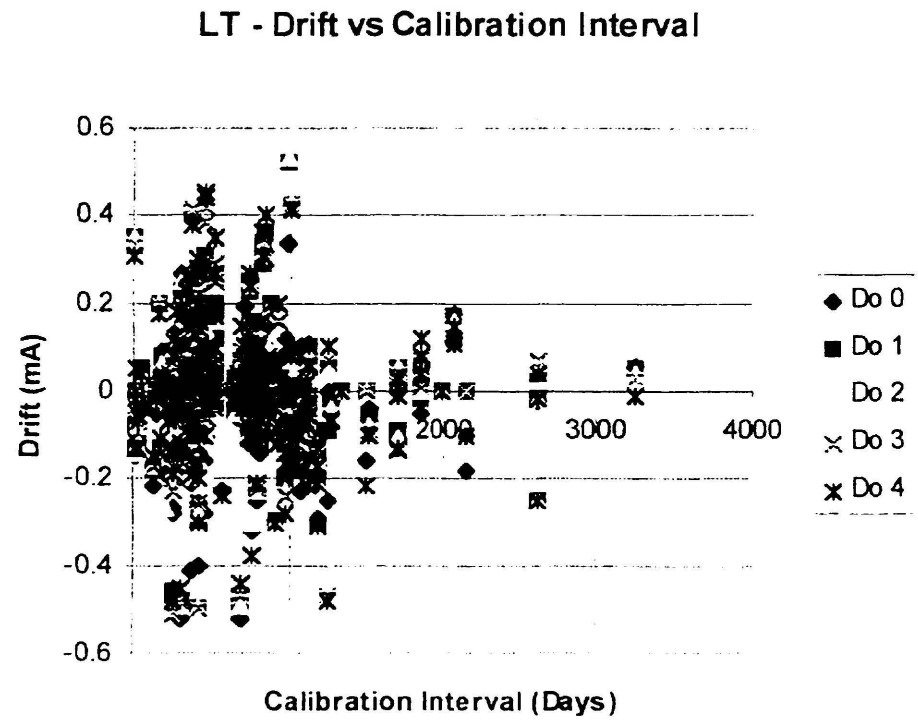


FIGURE 4. EXAMPLE OF FREQUENCY DISTRIBUTION OF DRIFT.