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VALIDATION AND VERIFICATION OF THE FIELD PROGRAMMABLE GATE ARRAY BASED CHARGE COLLECTION EFFICIENCY MEASUREMENT SYSTEM

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ABSTRACT

Based on field programmable gate array (FPGA), we propose a QA/QC test procedures to validate and verify the operation and the data obtained from newly developed charge collection efficiency (CCE) measurement system. The QA/QC test procedures were able to detect, in the system, the Multi-Channel Analyser (MCA)'s improper operation. This could not be detected by a normal test run whilst the operation of the amplifier; counter; and timer were validated and verified.

ABSTRAK

Prosedur pengujian QA/QC telah dicadangkan untuk menentusahkan sistem pengukuran kecekapan kutipan cas (CCE) berasaskan papan lapangan barisan get terprogram (FPGA). Prosedur pengujian QA/QC berupaya mengesan kendalian tak wajar penganalisa berbilang saluran (MCA) yang tidak boleh dikesan oleh ujilari biasa. Manakala kendalian penguat, pembilang dan pemasa telah ditentusahkan.

Keywords: Charge Collection Efficiency (CCE); Field Programmable Gate Array (FPGA); Nuclear Instruments (NIs); Quality Assurance (QA); Quality Control (QC)

INTRODUCTION

Based on field programmable gate array (FPGA), we developed a charge collection efficiency (CCE) measurement system in order to characterize a semiconductor nuclear detector. The developed measurement system consisted basically of Nuclear Instrument Modules (NIMs) to setup a nuclear counting system and a field programmable gate array (FPGA). This was based on a multipurpose card, namely a UnIO52 card, to use Multi Channel Analyser (MCA) functions and to interface the nuclear counting system with a computer. The UnIO52 card is the International Atomic Energy Agency (IAEA)'s customized design multifunction card which is dedicated for nuclear instruments refurbishment and upgrading (Rongen, 2003). Functions available on a single card such as, Analog Digital Converter (ADC); Digital Analog Converter (DAC); parallel IN/OUT; Liquid Crystal Display (LCD) display; Single Channel Analyser (SCA); MCA functions; and stepper motor controller (Rongen, 2003) make this UnIO52 card very useful for system development tasks.

Since this CCE measurement system was developed to measure CCE and to evaluate a semiconductor nuclear detector's detection ability, there was a need to test the system's trustworthiness; correctness; reliability; and stability. If these parameters were ignored, it would lead to the whole system being inaccurate. Trustworthiness and correctness were the most demanded aspects which Quality Control (QC) and Quality Assurance (QA) sought to cover (Liu et al., 2011). Therefore, QC and QA implemented to verify and validate the whole system.

In order to achieve the above mentioned goals, a series of experiments, namely QA/QC test procedures, were carried out on this system.

A QA/QC test procedure is a specially designed test procedures to verify and validate the operation of NIs. It was reported that this test had been implemented successfully to validate and verify the operation of the refurbished or modernized NIs (Kasige and Mahakumara, 2006; Mansor et al., 2006; Uddin et al., 2006). Due to the usage of NIMs, the developed CCE measurement system was a NI and its performance had to be evaluated in order to ensure that it was within an acceptable range (IAEA, 1991). Failure or poor performance, of dedicated NIs such as personal radiation detection systems or safety related systems, could lead to critical errors (IAEA, 1991). Zanzonico (Zanzonico, 2008) reported that nuclear medical instruments were critically dependent on the accuracy and reproducible performance.

This paper aims to introduce the performed QA/QC procedures through using an inexpensive test instrument to the newly developed NIs in order to verify and to validate the whole system.

MATERIALS AND METHODS

Bairi et al. (Bairi et al., 1994) stated that the equipment selection for QA/QC ought to be made to suit the specific requirements of the NIs' practice. It ought to be able to give a reliable performance and be capable of being maintained in a good condition with existing facilities and manpower (Bairi et al., 1994). The conducted QC test procedures used inexpensive test instrument such as pulse generator (only BNC Berkley pulse generators were suitable because of their specifications); and classical NIMs such as amplifier; Single Channel Analyzer (SCA) and counter/timer in order to compare a System Under Test (SUT) with specified NIMs of well-known manufacturers (for example, Canberra; Intertechnique; Ortec Silena; and Tennelec) (Engels and Kaufmann, 2007). Engels and Kaufmann (Engels and Kaufmann, 2007) stated that this technique avoided the utilization of the absolute but costly test instruments such as time markers; and pulse generators (simulating a nuclear pulse coming from detector), which were very precise in frequency and amplitude. In QC test procedures, several applicable tests were implemented in order to verify and validate the CCE measurement system's proper operations. For this newly developed system, we conducted applicable tests: these were count accuracy; clock or time accuracy; count rate non-linearity (CNRL); integral non-linearity (INL); differential non-linearity (DNL); peak shift versus count rate; and a chi square test. As a reference point in the QA/QC of this FPGA based CCE measurement system and, as stated in IAEA-TECDOC-602, we used an IAEA acceptable range of such a test used.

COUNT ACCURACY

Theoretically, all counts from detectors ought to be registered in the counting system. The developed CCE measurement system was a modified nuclear counting system to measure the CCE value. Therefore, we had to test this system's count accuracy. As shown in Figure 1, we conducted the count accuracy test by injecting a pulse from pulse generator (BNC DB-2 or equivalent BNC Berkeley pulse generator) to the input of the CCE measurement system. We used the specified NIMs system as a reference system.

Both systems in Figure 1, were started and stopped manually when the selected counting time was reached. We took a set of measurement with different repetition rates: 500 Hz; 1000 Hz, 1500 Hz; 5000 Hz; 10000 Hz; and 15000 Hz. Count accuracy was defined, in percentage terms, by the deviation, D, as follows:

$$D = [(C_r - C_t)/ C_r] \times 100\% \quad (1)$$

where C_t was the counts registered in the CCE measurement system and C_r was the counts registered in the NIMs system.

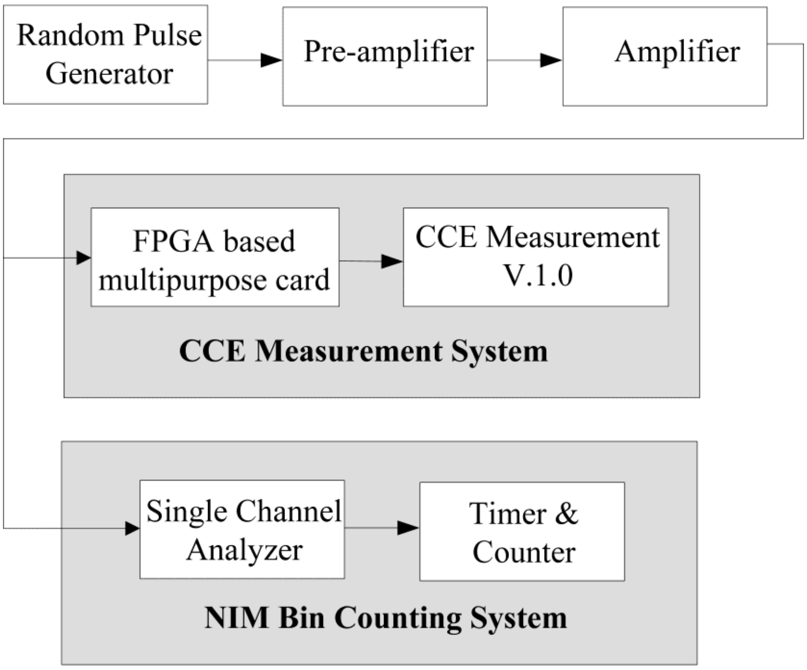

Figure 1. Test setup for count accuracy measurements.

CLOCK/ TIME ACCURACY

We carried out a clock or time accuracy test to check the counting time accuracy of the SUT. As shown in Figure 2, this test was conducted by injecting pulse from the pulse generator to the input of the CCE measurement system; the specified NIMs system; and the reference counter (Ortec 871 or equivalent). All these systems ought to be started almost simultaneously so that all the systems saw the same frequency jitter caused by the pulse generator (Engels and Kaufmann, 2007). We used a reference counter to observe any deviation in the NIMs test electronics time base.

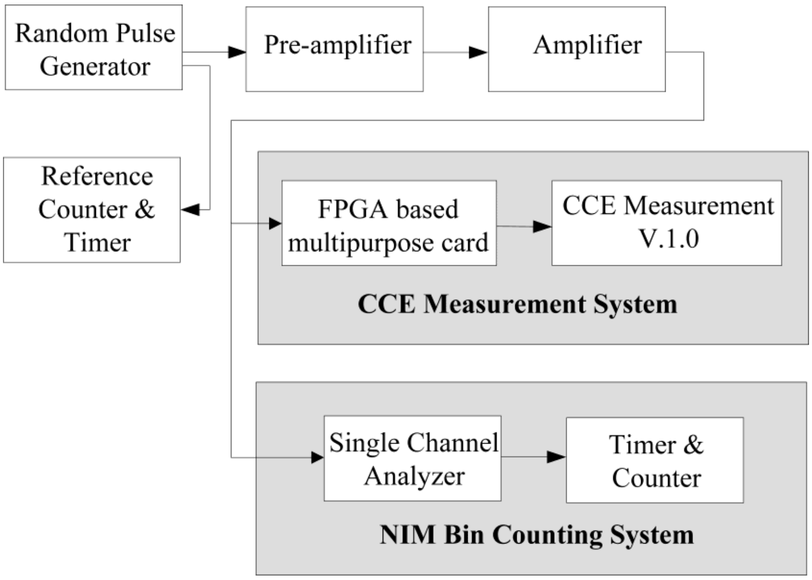

Figure 2. Test setup for clock or time accuracy measurements.

In relation to count accuracy, this test applied the same set of measurements. Clock or time accuracy was defined, also, as the percentage deviation of counts registered in the CCE measurement system and the counts, registered in NIMs system were used in count accuracy.

COUNT RATE NON-LINEARITY (CRNL)

During nuclear counting, count rate changes would result in errors in total counting. Therefore, count rate non-linearity (CRNL) was an importance parameter to be tested on any NIs. This test had to be performed using a random pulse generator. In this test, the pulse generator's repetitive pulse mode changed to random pulse mode to create a pile-up effect of the output pulse. The CRNL test was slightly different from the count accuracy test since, as shown in Figure 3, the pulse was injected to the preamplifier's input.

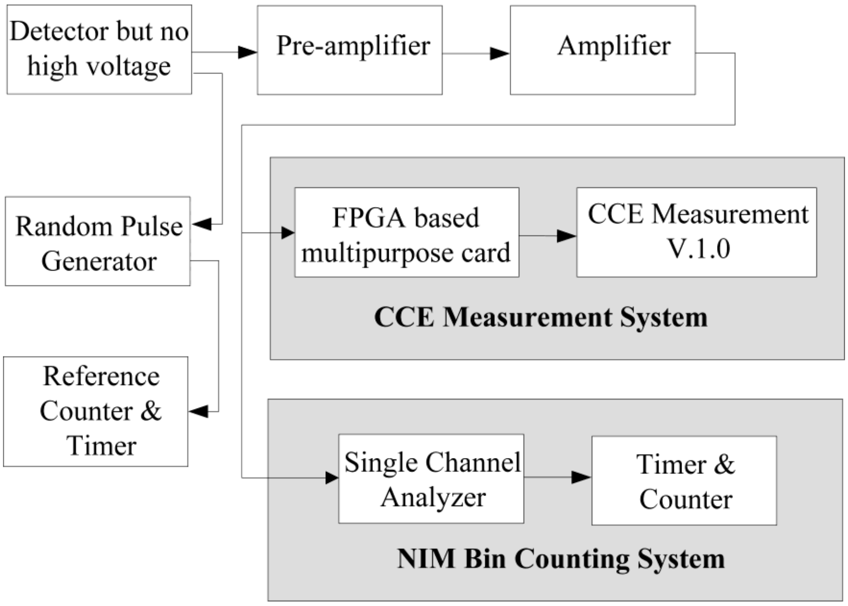

Figure 3. Test setup for count rate non-linearity (CNRL) measurements.

The CRNL test used, also, the same set measurement as for the count accuracy and clock/ time accuracy tests. The CRNL was determined, in percentage terms, by using the same equation to calculate both count accuracy and clock/ time accuracy.

INTEGRAL NON-LINEARITY (INL)

Integral non-linearity (INL) was important for NIs which analysed multiple energy lines. Due to the nature of the CCE measurement based on channel locations in the MCA, the INL test was compulsory.

For INL, the test set up was similar to the count accuracy test in Figure 1 but the test method was totally different. The frequency, of the pulse, was fixed at any repetition rate but the pulse's amplitude, deposited to both systems, had to be increased until the counter began counting. The pulse generator's amplitude setting had to be noted and registered. With an increasing low level discriminator (LLD) setting, we took a set of measurements: 0.2 V; 0.4 V; 0.6 V; 0.8 V; 1.0 V, 1.4 V; 1.6 V; and 1.8 V. We used only the LLD in this test. Therefore, the SCA ought to be set at the integral (INT) mode and the MCA's windows ought to be set at the maximum value. The INL was defined as a deviation of a dial spacing values compared to average dial setting spacing value. These were as follows:

$$INL\% = [((DS_{Av} - DS_{min}) - (DS_{Av} - DS_{max}))/DS_{Av}] \times 100\% \qquad (2)$$

where DS_{Av} was the dial setting spacing average; DS_{max} was a maximum dial spacing value; and DS_{min} was a minimum dial spacing value. The dial setting spacing value, DS, was a spacing of the dial reading between two adjacent LLD settings.

DIFFERENTIAL NON-LINEARITY (DNL)

In MCA, the registered nuclear pulse's peak channel is one of the parameter used in CCE measurement. Therefore, in MCA, the channel width's uniformity was very important because a slight deviation, in the channel width, resulted in inaccurate CCE measurement and analysis.

A Differential Non-Linearity (DNL) is a test to check the MCA channel width and SCA windows width uniformity. Therefore, this test is carried out on a CCE measurement system.

Using a similar test setup for INL and count accuracy test as in Figure 1, the amplitude of pulse, deposited to both systems, had to be increased until the counter began counting. The pulse generator's amplitude setting had to be noted and registered. Then, the pulse's amplitude had to be increased until the counter stops counting and, again, the amplitude setting had to be noted and registered. The pulse's frequency was fixed at any repetition rate. With an increasing low level discriminator (LLD) setting, we took a set of measurements: 0.2 V; 0.4 V; 0.6 V; 0.8 V; 1.0 V; 1.4 V; 1.6 V; and 1.8 V. The SCA's windows setting, in the reference system, and the MCA, in the CCE measurement system, had to be fixed at a single value. We obtained the tested system's DNL by using the following equation.

$$DNL\% = [((W_{Av} - W_{min}) - (W_{Av} - W_{max}))/W_{Av}] \text{ x } 100\% \qquad (3)$$

where W_{Av} was the windows average; W_{max} was a maximum windows value; and W_{min} was a minimum windows value. The windows value, W, was a subtracted value of a dial setting when the counter stopped and started counting.

PEAK SHIFT VERSUS COUNT RATE

In nuclear pulses, peak shift occurred due to a high count rate in a nuclear counting system. It was caused by poor baseline restoration in an amplifier and could affect the counts obtained in a counting system.

The peak shift test was carried out, also, by using the test setup in Figure 1 and the pulse generator was set at random mode. Starting with low count rates, the pulse generator's amplitude dial was increased until the counter only began counting. This value was recorded as D_o and repeated to the higher count rates, D_i. The SCA and MCA LLD were set at a fixed level throughout the test. In this test, we used the same set of measurements as in count accuracy test but with a random mode.

The peak shift versus count rate was calculated as deviation, D, as follows:

$$D = [(D_0 - D_i)/ D_o] \text{ x } 100\% \qquad (4)$$

where D_0 was a dial setting for the lower count rate and D_i was a dial setting for all other count rates.

CHI SQUARE TEST

The Chi square test was compulsory since it was an overall QC test and, when applying random pulses from a radioactive source, it gave an indication of the NIs' proper operation. Ten measurements would be taken and, as stated in the IAEA-TECDOC-602, the chi square, χ^2 test results ought to be within 3.325 and 16.919.

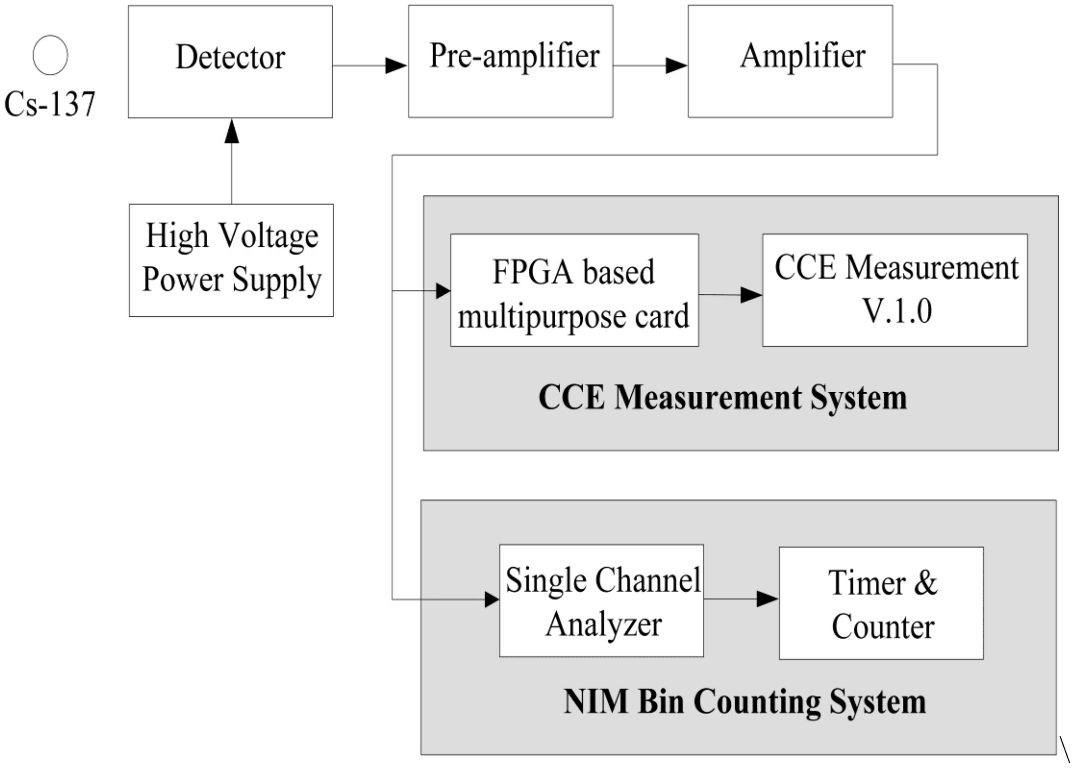

Figure 4. Test setup for chi square test.

The test setup, in Figure 4, was used to take 10 measurements from a radioactive source, cesium-137. The counters, of the CCE measurement system and the reference system, started simultaneously in order to avoid deviation of the registered pulses because they occurred randomly in time [9].

The chi square, χ^2 was defined as follows:

$$\chi^2 = \sum_{i-1}^{N} \left(X_i - \overline{X} \right)^2 \Big/ \overline{X} \tag{5}$$

where X_i was a series of N measurements and $\overline{X}$ was a mean value of N measurements.

RESULTS AND DISCUSSION

COUNT ACCURACY

Table 1 shows the count accuracy, of the CCE measurement system, was in the range of +0.067% to -0.027%. The CCE measurement system seemed to have increasing deviation at low frequencies, from 500 Hz to 1500 Hz, and, then, began to stabilize at high frequencies, from 5000Hz to 15000 Hz. A stable deviation, with an average of 0.026% at higher frequencies, showed that the CCE measurement system had a better count accuracy after 5000 Hz. With reference to IAEA-TECDOC-602, the CCE measurement system had good count accuracy since the deviation was less than ±0.3%; this proved that the system's counter was working correctly. If the deviation was more than 0.3%, a corrective action had to be done in order to avoid misinterpretation of the results.

Table 1. Count accuracy of the CCE measurement system.

Counting repetition rate (Hz)	**Counter contents (Hz)**		**Deviation (%)**
	NIMs system	**CCE measurement system**	
500	4988	5004	+0.067
1000	10030	10021	+0.090
1500	15038	15040	-0.093
5000	50122	50113	-0.024
10000	99270	100202	+0.026
15000	150086	150346	-0.027

CLOCK/TIME ACCURACY

The CCE measurement system had a good clock or time accuracy; this was less than ±0.3%. Tab. 2 shows that the system's clock or time accuracy was in the range of -0.167% to -0.227%. The CCE measurement system's counter contents showed a clear trend of counts deviation with increasing frequencies. Tab. 3 shows a deviation trend of n_0, $2n_0$ and $3n_0$ where n_0 was 500 Hz at lower counting rate from 500 Hz to 1500 Hz. Where n_1 was 5000 Hz, the same trends, n_1; $2n_1$; and $3n_1$ occurred at a higher counting rate from 5000 Hz to 15000 Hz.

Table 2. Clock/time accuracy of the CCE measurement system.

	Counter contents (Hz)		**Deviation (%)**
Reference	**NIMs system**	**CCE measurement system**	
500	5003	5011	-0.167
1000	10000	10022	-0.227
1500	15000	15033	-0.224
5000	50000	50111	-0.222
10000	99999	100222	-0.223
15000	149999	150333	-0.223

Table 3. Counts deviation trend during clock/time accuracy test of the CCE measurement system.

Counting repetition rate (Hz)	**Multiplication**	**Deviation (%)**	
		Counts	**Trends**
500	X 1	11	n_0
1000	X 2	22	$2n_0$
1500	X 3	33	$3n_0$
5000	X 10	111	n_1
10000	X 20	222	$2n_1$

15000	X 30	333	$3n_1$

These counts deviation were obviously related to counting rate changes. For example, as shown in Tab. 3, when 500 Hz was multiplied by 2 to become 1000 Hz, the counts deviation, at 500 Hz, would be multiplied by 2, also. The count deviation trends, Δ in Tab. 3, could be expressed in the following equation:

$$\Delta = \left(C_{t0} - C_{R0}\right) X \left(r/r_0\right) \tag{6}$$

where C_{to} was the lowest counts registered in the CCE measurement system; C_{Ro} was the lowest counts registered on the reference counter; r was the counting rate; and r_o was the lowest counting rate.

In a CCE measurement system, counting is based on a software generated timer. Probable delays existed during each time cycle and contributed to the systematic deviation trend. An adjustable offset value had to be included in the data acquisition programming in order to solve the systematic deviation trend.

COUNT RATE NON-LINEARITY

In a CRNL test, random pulse usage creates pile-up effects which result in not all pulses being registered by the CCE measurement system and the reference system. In this test, the reference counter acted as a reference because it measured the actual number of counts and verified the NIMs system; also, this lost counts.

Table 4. Count rate non-linearity (CRNL) of the CCE measurement system.

Count rate (cps)	**Counter contents (Hz)**			**Deviation (%)**
	Reference	**NIMs system**	**CCE measurement system**	
500	4611	4595	4608	-0.297
1000	9338	9333	9324	+0.100
1500	14067	14057	14018	+0.273
5000	47095	46709	46895	-0.399
10000	94305	92215	92547	-0.359
15000	141106	136108	136798	-0.507

In Tab. 4, the CCE measurement system's CRNL shows an increasing deviation with a higher count rate. Higher count rate results increased the probability of pile-up effects; some events were outside the windows region which could not be registered by both the NIMs system and the CCE measurement system. A negative deviation at lower and higher count rates, at 500 cps and after 5000 cps, showed that, since it could register more events than the NIMs system, the CCE measurement system performed better than the NIMs system at lower and higher count rates. We undertook a further investigation of the CRNL at a lower count rate, less than 1000 cps, in order to understand the pile-up effects on the CCE measurement system.

IAEA-TECDOC-602 stated that the count rate was not easy to adjust but ought to be within ±5.0%. With reference to IAEA-TECDOC-602, this system was very satisfactory since the CCE measurement system's CRNL was in the range of -0.297% to +0.273%.

INTEGRAL NON-LINEARITY (INL)

In Tab. 5, when compared to the NIMs system's value of +4.316% , the CCE measurement system showed that it has a better INL with a value of +2.667%. In NIs, the INL value describes the non-linearity characteristic of the SCA or MCA. In theory, a LLD ought to be uniformly parallel to the uniform increase of an input signal; this means that, for any repetition rate pulses, the dial setting spacing, between two adjacent LLD settings, ought to be uniform at all times.

IAEA-TECDOC-602 stated that the NIs' INL ought to be less than ±0.1%. However, both INL results were more than acceptable limits. Therefore, the INL tests ought to be repeated to validate these results. If the repeated test obtained the same results, a corrective action would be taken.

Table 5. Integral non-linearity (INL) of the CCE measurement system.

LLD (V)	**Dial setting spacing between two adjacent LLD setting**		**INL (%)**	
	NIMs system	**CCE measurement system**	**NIMs system**	**CCE measurement system**
0.4	0.06300	0.0760	4.316	2.667
0.6	0.06333	0.0753		
0.8	0.06200	0.0747		
1.0	0.06067	0.0740		
1.2	0.06100	0.0743		
1.4	0.06100	0.0747		
1.6	0.06200	0.0760		
1.8	0.06133	0.0750		

DIFFERENTIAL NON-LINEARITY (DNL)

IAEA-TECDOC-602 stated that the NIs' DNL ought to be less than ±1.0%. As shown in Tab. 6, the tested systems' DNL showed that the NIMs system's DNL satisfied the acceptable limits which was +0.649%. However, the CCE measurement system's DNL, of +1.046%, was slightly higher than the acceptable limits. Theoretically, with any repetition rate pulses, the windows width, of the SCA and MCA ought to be uniform at all times. As shown in Tab. 6, except at 0.2 and 0.6 V, The NIMs system showed the uniformity characteristics at the LLD setting.

Table 6. Differential non-linearity (DNL) of the CCE measurement system.

LLD (V)	**Difference of the dial setting**		**DNL (%)**	
	NIMs system	**CCE measurement system**	**NIMs system**	**CCE measurement system**
0.2	0.3090	0.3810	0.649	1.046
0.4	0.3080	0.3803		
0.6	0.3070	0.3823		
0.8	0.3080	0.3837		

1.0	0.3080	0.3843

Similar to the INL test, the DNL test ought to be repeated, also, to validate these results. If the same results were obtained, a corrective action would be taken.

PEAK SHIFT VERSUS COUNT RATE

As shown in Tab. 7 and with regard to the peak shift of both CCE measurement system and the reference system, the NIMs system occurred at 10000 cps. The peak shift was more visible at 15000 cps since deviations of both systems increased by more than +10%. The results showed that the optimum performance, of CCE measurement system and NIMs system baseline restorer, was 10000 cps; this meant that the amplifier's baseline restorer was able to restore the nuclear pulses' baseline of up to 10000 cps. Therefore, both systems' counting rates limitation was up to 10000 cps and it could not give a reliable measurement for radiation events more than 10000 cps.

Table 7. Peak shift versus count rate of the CCE measurement system.

Count rate (cps)	**Dial setting pulse generator when system under test start counting**			
	NIMs system	**Deviation (%)**	**CCE measurement system**	**Deviation (%)**
500	0.1057	0	0.1127	0
1000	0.1057	0	0.1127	0
1500	0.1057	0	0.1127	0
5000	0.1057	0	0.1127	0
10000	0.1053	+0.378	0.1123	+0.355
15000	0.0890	+15.799	0.0937	+16.859

CHI SQUARE TEST

As shown in Tab. 8, the CCE measurement system's chi square test result was 15.31. This result was verified by the NIMs system which had a chi square value of 11.29. With reference to IAEA-TECDOC-602 and since both systems chi square test values were within 3.325 and 16.919 respectively, these showed that both measurements were within the normal statistical fluctuations.

Table 8. Chi squares test results of CCE measurement system.

Measurement, i	**Counts, X_i**	$\left(X_i - \overline{X}\right)^2$	**Chi square, χ^2**
1	2153	19.36	
2	2175	696.96	
3	2058	8208.36	
4	2265	13548.96	15.31
5	2100	2361.96	
6	2134	213.16	
7	2145	12.96	

8	2111	1413.76
9	2121	761.76
10	2224	5685.16
Mean value, $\overline{X}$	**2148.6**	

Since it was within the IAEA-TECDOC-602 acceptable range, the chi square value verified that the CCE measurement system had a stable high voltage (HV); MCA settings; amplifier; and counter. This value proved, also, that the system was not influenced by either electromagnetic interference from ground loops or interference with radio power stations or control signal for electrical devices.

CONCLUSIONS

NIs, dedicated for medical; and health and safety applications, needed more than a common test check. In the case of a new developed NIs based system, a test run of the system was not enough. A test run checked only the system's functionality; however, but it did not validate or verify that the data, obtained from the referred system, was of an acceptable standard.

The QA/QC test procedure was a powerful tool in the validation and verification of newly developed NIs. In this paper, the QA/QC test procedures were implemented to the newly developed CCE measurement in order to validate and verify the operation and the obtained data. The results, from these tests, showed that the count accuracy; clock or time accuracy; CRNL; peak shift versus count rate; and chi square satisfied the limits in IAEA-TECDOC-602 whilst the INL and DNL results had to be reviewed. This system's test run showed that everything functioned. However, the QA/QC test procedures showed that certain parts, of the newly developed system, did not operate according to standards.

The QA/QC test procedures proved the weakness of test running or test checking NIs due to their failures in recognizing any deviations in the obtained data. In conclusion, the QA/QC test procedures, implemented in the newly developed CCE measurement system, were able to recognize improper operations in certain parts of the system. Consequently, a corrective action would be taken to improve the operation of that part in order to validate and verify the system.

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