LINEARITY IMPROVEMENT ON WIDE-RANGE LOG SIGNAL OF NEUTRON MEASUREMENT SYSTEM FOR HANARO

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ABSTRACT

This paper discusses engineering activities for improving the linearity characteristics of the Log Power signal from the neutron measurement system for HANARO. This neutron measurement system uses a fission chamber based detector which covers 10.3 decade wide range from 10^{-8}% full power(FP) up to 200%FP. The Log Power signal is designed to control the reactor at low power levels where most of the reactor physics tests are carried out. Therefore, the linearity characteristics of the Log Power signal is the major factor for accurate reactor power control.

During the commissioning of the neutron measurement system, it was found that the linearity characteristics of the Log Power signal, especially near 10^{-2}%FP, were not accurate enough for controlling the reactor during physics testing. Analysis of the system linearity data directly measured with reactor operating, determined that the system was not operating per the design characteristics established from previous installations. The linearity data, which were taken as the reactor was increased in power, were sent to manufacturer's engineering group and a follow-up measures based on the analysis were then fed back to the field. Through step by step trouble-shooting activities, which included minor circuit modifications and alignment procedure changes, the linearity characteristics have been successfully improved and now exceed minimum performance requirements. This paper discusses the trouble-shooting techniques applied, the changes in the linearity characteristics, special circumstances in the HANARO application, and the final resolution.

1. INTRODUCTION

The HANARO is a 30MW open-tank-in-pool type reactor with the capabilities of testing nuclear fuels, producing key radioisotopes, and performing neutron activation analysis and other nuclear physics researches. The first criticality has been achieved on February 1995 and now the reactor reached 20MW which is about 70% of its full rated power.

The neutron flux as the measure of reactor power is continuously monitored by six(6) fission chambers mounted on the outside wall of the reactor tank in the pool. Three(3) of the fission chambers are used for reactor power control, while the other three(3) neutron detectors are used for tripping the reactor in case of reactivity accident. Unlike other reactors, only the fission chamber system is employed for neutron power measurement at HANARO, since it is designed to measure the 10-decade neutron flux level from source range(shutdown) to 100% of full power operation. *This is why it is called "Wide Range(WR) neutron flux monitor"*. There are three Neutron Detector Housings located symmetrically around the reactor core, to accommodate the fission chambers. Each detector housing attached to the reactor vessel contains two sets of the fission chambers for power control and reactor trip respectively. As shown in Figures 1-1 and 1-2, the cylindrical basket holding the fission chamber is designed to move 200mm inward or outward from the reactor core for coarse calibration.

2. OPERATING PRINCIPLES OF WR NEUTRON FLUX MONITORING SYSTEM

The WR neutron flux monitoring system, supplied by GAMMA-METRICS for HANARO consists of a detector assembly, amplifier assembly and rack-mount signal processor. The detector assembly consists of a guarded fission chamber, connectors and cable assemblies. The cables from the detector to the amplifier are divided into two parts. One is mineral insulated cables passing through an aluminum conduit in the pool, the other is solid copper-sheathed coaxial cables, which runs through a stainless steel, flexible metal hose to the amplifier. The amplifier assembly houses the power supplies and the electronics that condition the detector signal for transmission to the signal processor. The electronics provide amplification of detector signals, discrimination and band pass filtering against alpha, gamma and electronic noise. The signal processors convert the signals from the amplifiers into signals that represent the percent of reactor power level on a linear scale, percent of reactor power level on a log scale, and the rate of change of the log power level in percent per second.

The neutron flux monitoring system measures the number of pulses per unit time from the detector over the range from source level to the level where the error from countrate loss due to coincident pulses becomes unacceptable. The lower range of the wide range logarithmic level signal is called COUNT mode and it provides an output that is proportional to the logarithm of the average countrate of pulses of the wide range signal over the range of about 10^{-8}%FP to 10^{-2}%FP. From around the upper end of the COUNT mode to full power, the system measures the Mean Square Value(MSV) of the time variant signal from the detector. The upper range of the logarithmic wide range level signal is called MSV mode, which provides an output that is proportional to the logarithm of the mean square variation of the wide range signal over the range of about five decades, from 10^{-3}%FP to 200%FP. The signal from the COUNT mode is processed by the Log Count and Rate(LCR) board, while the signal from the MSV mode is processed by the Log Amplifier board. These two signals are combined by an auctioneer circuit to provide one continuous output over the range of 10^{-8}%FP to 200%FP, which corresponds to 0 to 10.3 V DC output. For a typical neutron flux monitoring system, the switch over from the COUNT mode to MSV mode occurs at 5.6 V which is equivalent to 3×10^{-3}%FP(about 1.0KW). To avoid an unnecessary power fluctuation around this switch over region, there should be at least one decade, and preferably two decades, of range overlap on the output signal as shown in Figure 2-1.

3. TROUBLE-SHOOTING AND RESULTS

3.1 Original System Performance

It was found, on Sep. 13, 1996 that the neutron power was abruptly changed down at the level of the signal transfer from the COUNT to MSV. This observation was the decisive moment for performing linearity study on the HANARO neutron flux monitoring system. To clear up the cause of this behavior, the actual output voltages from the COUNT mode and the MSV mode were measured from the dedicated test points on the respective circuit boards, as reactor power level was increased step by step. At the same time, the current from two sets of Compensated Ionization Chambers(CIC), which were temporarily installed during commissioning, also were recorded for the use as a reference signal. Figure 3-1 shows the linearity behaviors from 70W to 30KW for the original system. The RPS Ch.A was initially selected, among six channels, for the subject of this study. As shown in Figure 3-1, there are two major problems in the linearity. One is that the voltage deviation at the crossover(5.6 Vdc) between the COUNT and the MSV is about 170mV causing the power discontinuity. The other is that the changing slope of the COUNT output compared with the CIC current is much different from that of the MSV output. Notice that both outputs have a tendency toward an increasing slope as the reactor power decreases. This may produce a faulty indication of reactor power at low power levels. Compared with a standard curve in Figure 2-1, the differences in shapes are readily apparent. The following sections of this paper describe in detail the kinds of activities that have been applied to the current neutron flux monitoring systems and how the system performances have been improved.

3.2 Adjustments on WR Log Amp Gain

Considering that the MSV output was 170mV lower in voltage compared with the COUNT output, the Gain of the MSV circuit was changed from 10.0V to 10.17V as a technical clarification in the Instruction Manual. This change in the alignment of the system was not specific to the HANARO installation.

During a startup early in the investigation, the reactor was brought from 70W up to 300KW. The Figure 3-2 indicates that the applied adjustments brought the MSV outputs much closer to the COUNT outputs than before the gain adjustment. Two outputs still show a difference in their slopes, especially at the low power range.

3.3 Linearity Test Data With Fresh Fuels

Previously, it's not possible to get the linearity data for power level below 10^{-4}%FP, due to the residual neutron flux from the irradiated fuel in the core. In March of 1997, fortunately we had a chance to start the reactor with fresh fuel newly loaded in the core. In addition, two sets of new CICs were installed around the core, instead of the old ones, to provide a more accurate reference. The Figure 3-3 shows the linearity behavior for the whole range, from zero power to 13MW. It is clearly indicated that the lower end of the MSV curve seems negatively saturated, even though it should approach to 2.0V. The notable observation is a noticeable difference between the slopes of the linear portions of the COUNT and MSV curves. If the straight line of the MSV is extended downward, it is not duplicated onto the line of the COUNT curve. We also concluded that the saturation voltage of the COUNT signal seemed too low, which is not desirable, considering the crossover point is too close to the saturation level.

3.4 LCR Board Upgrade(I)

The range of pulse counters to measure reactor power is limited by the instruments ability to discern and count individual neutron pulses from the fission chamber. Considering the output pulse width from the fission chamber is about 400nsec and the electronic circuits use pulse widths up to 700nsec, the maximum uniform pulse train frequency would be about 700 thousand counts per second (Kcps). With the random nature reactor neutron pulses, pulse pile-up effects can generate significant errors beginning at 100Kcps. The pulse pile-up effects up to about 400Kcps are both predictable and repeatable and thus can be compensated for by the Log Count circuitry. Above 400Kcps the use of pulse counters to measure reactor power is no longer viable and the instrument must use another method, in this case the MSV method.

Comparing the results in Figure 3-3 with those from previous installations showed the LCR output began to roll off too soon and saturate too early as reactor power level was increased. An analysis of the LCR board originally installed for HANARO showed the response above 100Kcps did not match the desired response typical of other GAMMA-METRICS installations. In particular, adequate compensation necessary to counter the pulse pile-up effects between 100Kcps and 400Kcps was missing. Based on this analysis, it was proposed to alter the values of R21, R23, and R31 on the LCR board in order to match the response characteristics in previous installations

We have been very encouraged by the result. While it may appear in Figure 3-4 that the problem was not solved or even may be worse, we were approaching the final solution. As expected, the saturation voltage of the COUNT output was increased from about 5.9V to 6.25V and the slope of the COUNT signal now looked parallel with the MSV output line. These behaviors are desirable. The lower part of the MSV signal is still deflected downward.

3.5 Readjustment on Band Pass Filter Offset

The MSV (mean square voltage) circuits are used to measure reactor power from about 10^{-3}% to 200% power and are based on Campbell's theorem relating the variations in a signal to the number of pulses in the signal. The circuit path for the MSV signal uses a bandpass filter/amplifier, a true root mean square (RMS) rectifier, a log amplifier, and gain/offset amplifiers. The rectifier circuit has an offset adjustment to correct for component variations and compensate for circuit noise. Note that because the offset adjustment is located on the bandpass Filter board it is called the bandpass filter offset adjustment. The output of the rectifier circuit is the input to the log amplifier circuit. Given that for proper operation of the log amplifier circuit its input must always be a positive and non-zero voltage, to avoid attempting to take the log of zero or a negative number, the output of the rectifier circuit must always be a positive and non-zero voltage. This is compatible with reactor power (neutron flux) which is always positive and non-zero. For this reason the rectifier offset is set to a minimum value of 1mV. From years of experience it was determined that offset adjustment should be made with reactor power not more than 10^{-8}% reactor power. This prevents the adjustment from offsetting any actual reactor power signal. By calculation, we can show that adjusting the offset for 1mV at 10^{-6}% power will produce a 50% error in indicated power.

Comparing the results in Figure 3-3 with those from previous measurements showed that the MSV output was lower than expected below 10^{-3}% power and even approach zero volts. Given a minimum rectifier value of 1mV, the minimum MSV would be 2.0V. An extrapolation analysis of the MSV output for this start-up showed the rectifier offset would be much less than 1mV at 10^{-8}%

power. Starting from the MSV output voltages the rectifier output voltage was calculated and then adjusted to produce a calculated MSV output that matched the desired response based on other installations. The additional adjustment necessary was determined to be 4mV. Therefore, during the last reactor shutdown the bandpass filter offset (rectifier offset) should have been adjusted to 5mV to compensate for the actual neutron flux level at shutdown at the detector as installed in the HANARO reactor

The results of increased bandpass filter offset voltage appear in Figure 3-5. Now, instead of the MSV and LCR outputs below 5V having different slopes, the outputs are parallel. Figure 3-5 also showed the difference in final offset voltage between the LCR and MSV outputs still remained.

It has been reviewed that the cause of the non-linear trend of the MSV signal at lower power comes from the setpoint value for the band pass filter offset voltage. This offset voltage is set to 1.0mV for the typical neutron flux monitor. The flux level at the detector for HANARO is typically too high for adjusting the band pass filter offset voltage to 1.0mV. The engineering review has concluded that the band pass filter offset voltage should be raised to 5.0mV to ensure the correct output.

3.6 Adjustments on LCR Gain and Zero

The alignment of the MSV and LCR circuits is based on producing the desired output indication from the fission chamber output. In this case, the desired output was 0-10VDC corresponding to 10^{-8}% to 100% power with a change of one volt per decade change in power. The basic MSV circuit design uses a 10V output from the band-pass filter and rectifier circuit to correspond to 100% power with the log amplifier gain and offset adjusted for 10V at 100% and a one volt per decade change in power. The pulse counting circuit design first establishes a pulse height discriminator threshold to eliminate small pulses due to gamma interactions and circuit noise. The remaining pulses, due to neutrons, are converted to a DC voltage by log diode pump circuits. The gain of the LCR circuit is set for a one volt per decade change in counts, correspond with a decade change in power. The offset of the LCR circuit is set such that both the MSV and LCR circuits produce the same output when both circuits are in a valid operating range. The range when both the LCR and MSV circuit outputs are considered for use as a valid operating range is called the overlap range. This range is typically from 10^{-3}% to 10^{-2}% power or 5V to 6V. This instrument uses an auctioneer circuit to switch the Log Power output signal between LCR and MSV at about 3×10^{-3}% power or 5.5V.

Assuming the MSV output is fixed, the necessary LCR offset voltage to match the MSV signal is a function of two sets of factors. The first set can be considered to be electronic-circuit-related factors and are a function of the types of circuits used to achieve the desired results. The second set can be considered to be fission-chamber-related factors. The construction of the fission chamber determines the pulse height and shape, and the number of pulses at a given flux level. The construction of the fission chamber also determines the shape of the varying (AC) signal used for the MSV output, and the magnitude of the signal at a given flux level. Given that a single fission chamber is producing one signal which is read by both the LCR and MSV circuit, once the necessary offset is determined it can be applied to all instruments with the same fission chamber style and the same electronic circuits. This was the case for previous installations using the standard GAMMA-METRICS detector and electronics.

At this point it was theorized that the difference in construction between the detector (guarded fission chamber) used at HANARO and that used in a typical GAMMA-METRICS installation had produced a different offset voltage requirement. The most common detector used in a GAMMA-METRICS power plant installation is an unguarded fission chamber with a 44" sensitive length and a U-235 coating thickness of 1.2 mg/cm2. The fission chamber used at HANARO is a guarded chamber with a 9.25" sensitive length and a U-235 coating thickness of 0.6 mg/cm2. All other factors for the two fission chambers are identical. Tests comparing an unguarded chamber to a guarded chamber of similar sensitive length and coating thickness showed no effect on the LCR and MSV signal and thus no effect on the offset voltage requirement. Currently several installations use guarded fission chambers with equal offset voltage requirements to the installations with unguarded chambers. When considering a reduction in sensitive length, it would seem logical that only the number of pulses per unit neutron flux would change and the change would be proportional to the change in sensitive length. Considering the varying signal used for the MSV output is a summation of pulses, it is expected that the magnitude of the MSV input signal would change exactly the same as the pulse countrate. One possible factor that could effect the MSV and pulse signal differently with a change in sensitive length is the change in chamber capacitance. The frequency content of the pulse signal is mostly greater than 1MHz while the frequencies in the MSV signal are mostly less than 100KHz. Thus a reduction in the chamber capacitance may allow a larger pulse signal and have minimal effect on the MSV signal. The effect of a change in coating thickness on the pulse and MSV signal has yet to be determined. While it is known that a thicker coating can produce a self shielding effect, it is not known if this produces a change in the signals, or more importantly, a difference in the change in the signals.

Using the results in Figure 3-5, a new desired LCR offset was calculated to produce an output that matched the MSV circuit response near 10^{-3}% power or 5V. This changed LCR output at 100KHz from 5.38V to 5.25V. The results of this alignment change appear in Figure 3-6. Now, the MSV and LCR outputs match at and below 5V. At this point the instrument met the specification accuracy requirements but did appear to have a deviation between 5V and 6V which is not seen in typical installations.

3.7 LCR Board Upgrade(II)

To improve LCR linearity between 5V and 6V the LCR board output was compared to both the MSV output (Figure 3-6) and results from previous installations. An analysis showed that about half of the linearity problem was due to the LCR board still showing a small deviation from previous installations and the other half was specific to this installation. Using the results in Figure 3-6 it was determined that altering the value of R32 would reshape the response of the LCR board optimally for HANARO.

The results of this change appear in Figure 3-7. Now, the MSV and LCR outputs match within specification from less than 4V to more than 6V. Within a range of 4.4V to 5.7V the instrument exceeds the specification accuracy requirements by a factor of 3. Further analysis of Figure 3-7 showed that the change of R32 produced a minor change in the LCR offset voltage required to best match the MSV output. This was expected considering how the LCR circuits operate but data necessary to predict and compensate was not available prior to the first reactor start-up after the new value of R32 was installed.

4.0 FINAL RESULTS

Using the results in Figure 3-7, a new desired LCR offset was calculated to produce an output that matched the MSV circuit response near 10-3% power or 5V. This changed LCR output at 100KHz from the last value used of 5.25V to 5.27V. The results of this alignment change appear in Figure 3-8. Now, the MSV and LCR outputs match within the specification accuracy requirements from less than 4V to just over 6V - over two decades. Over a one decade range from 4.75V to 5.75V the instrument exceeded the specification accuracy requirements by a factor of 10.

On previous installations, the MSV and LCR outputs best matched over a range from 5V to 6V and the circuitry was adjusted to switch the Log Power signal from LCR to MSV at about 5.6V on increasing power and from MSV to LCR at about 5.5V on decreasing power. For HANARO, it appears that the best switching points are 5.3V on increasing power and 5.2V on decreasing power. The hysteresis of the switching circuit is actually fixed, only the increasing power switch point is adjusted and the decreasing setpoint follows.

The changes made to the system can be summarized as follows:

1) The bandpass filter offset alignment procedure was changed from 1mV to 5mV to compensate for the higher flux levels at the detector when the HANARO reactor is shutdown.

2) Four resistors on the LCR board were changed to alter the shape of the circuit response above 100Kcps to restore the necessary pulse pile-up compensation.

3) The LCR alignment procedure was changed from 5.38V to 5.27V at 100KHz (and from 1.47V to 1.36V at 12.2Hz) based on achieving the best performance from the fission chamber used in this HANARO installation.

4) The auctioneer circuitry alignment procedure was changed to switch the Log Power signal from COUNT to MSV at 5.3V on increasing power based on achieving the best performance for this installation.

5.0 CONCLUSION

The study on the linearity improvement of the Log power, carried out together with GAMMA-METRICS engineering, has been successfully completed. The results show that the MSV and COUNT outputs now exceed the specification accuracy requirements over two decades. The neutron measurement system for HANARO provides stable switching at the crossover point without any power discontinuity which will contribute to more accurate reactor control at low power levels.

REFERENCES

[1] GAMMA-METRICS, "Neutron Flux Monitor for HANARO", Instruction Manual, 1991.

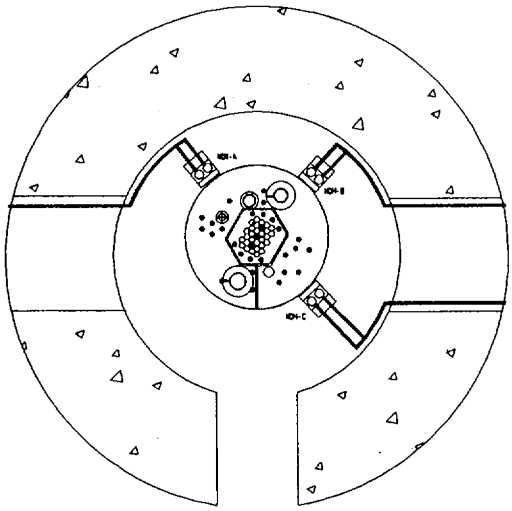

Figure 1-1 Rx Pool – Plan View

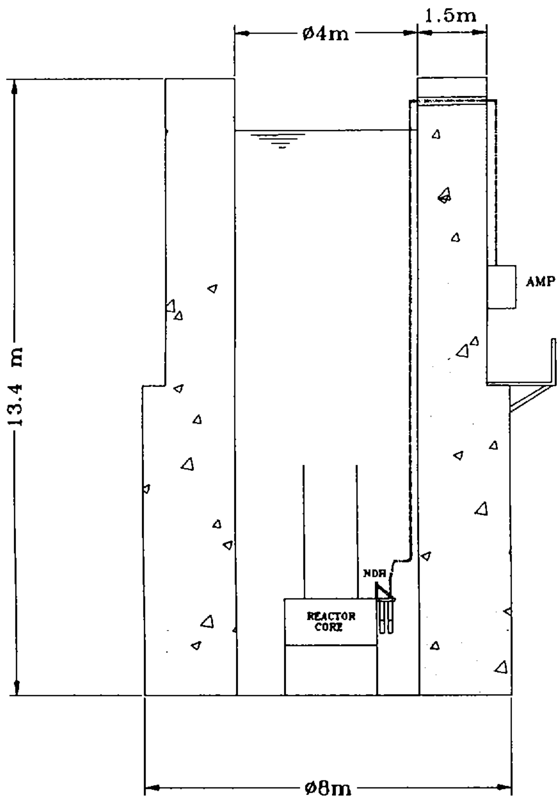

Figure 1-2 Rx Pool – Section View

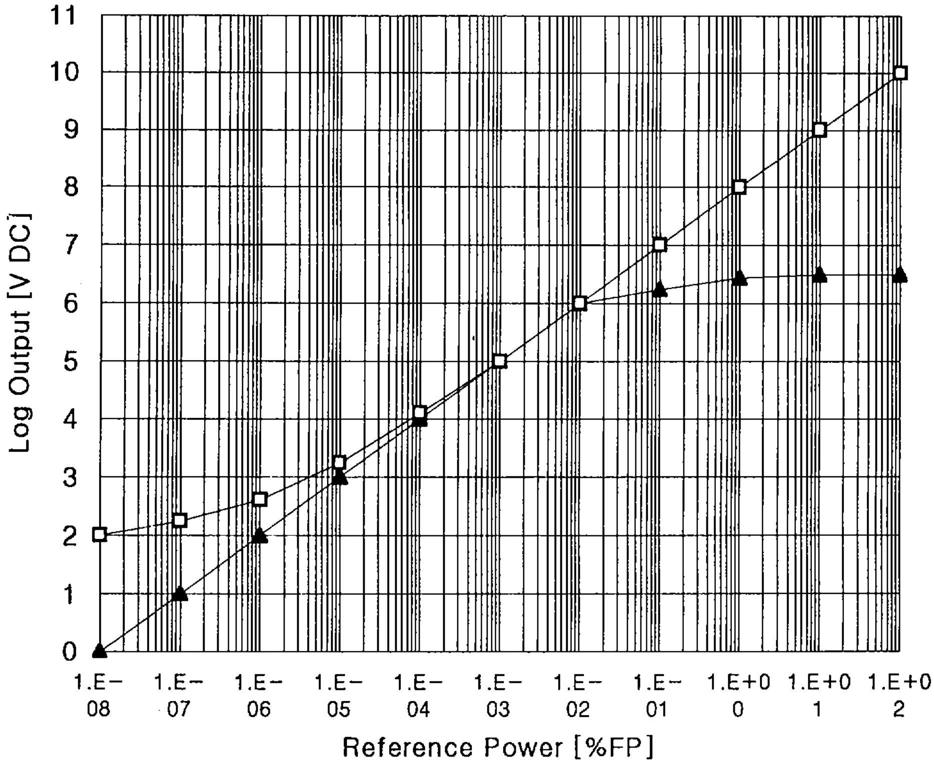

Figure 2-1 Standard Linearity Curve for WR Log Channel

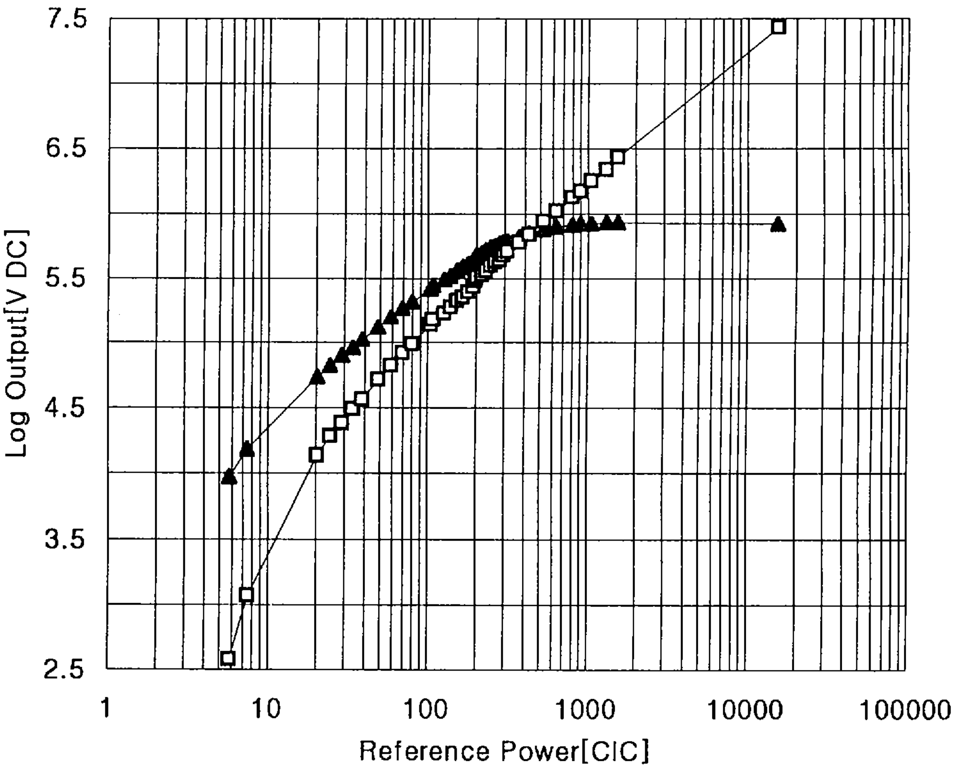

Figure 3-1 Linearity Curve for the Original System(96. 9. 13 : 70W to 30KW)

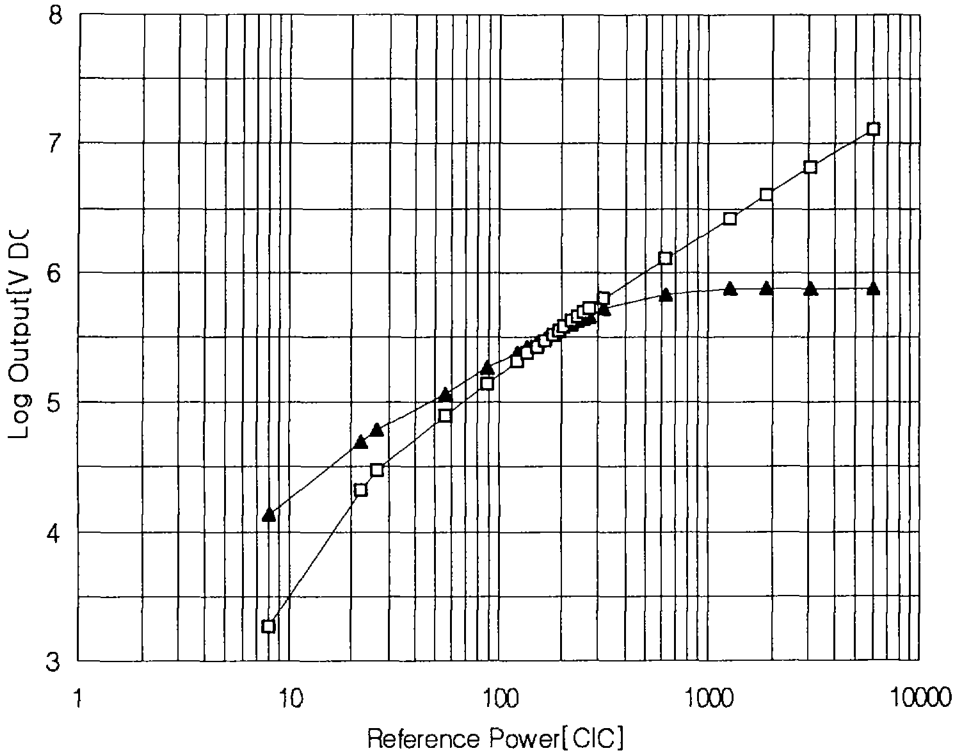

Figure 3-2 Linearity Curve after Adjustment of the MSV Gain(96. 9. 14 : 100W to 100KW)

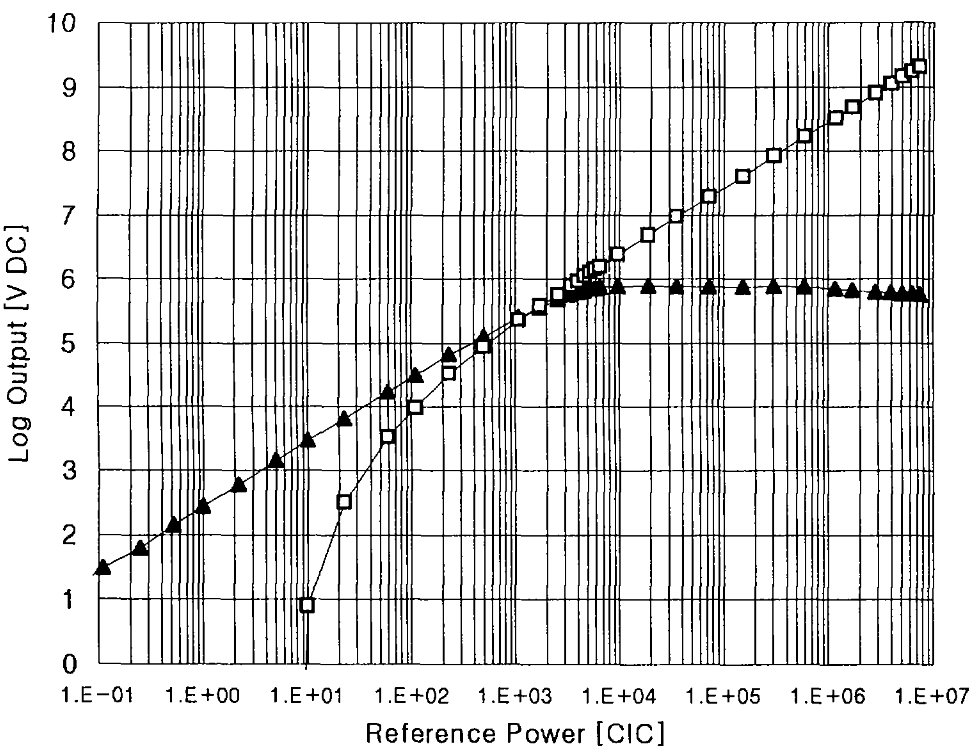

Figure 3-3 10-Decade Linearity Curve with Fresh Fuels(97. 3. 18 : 0.5W to 13MW)

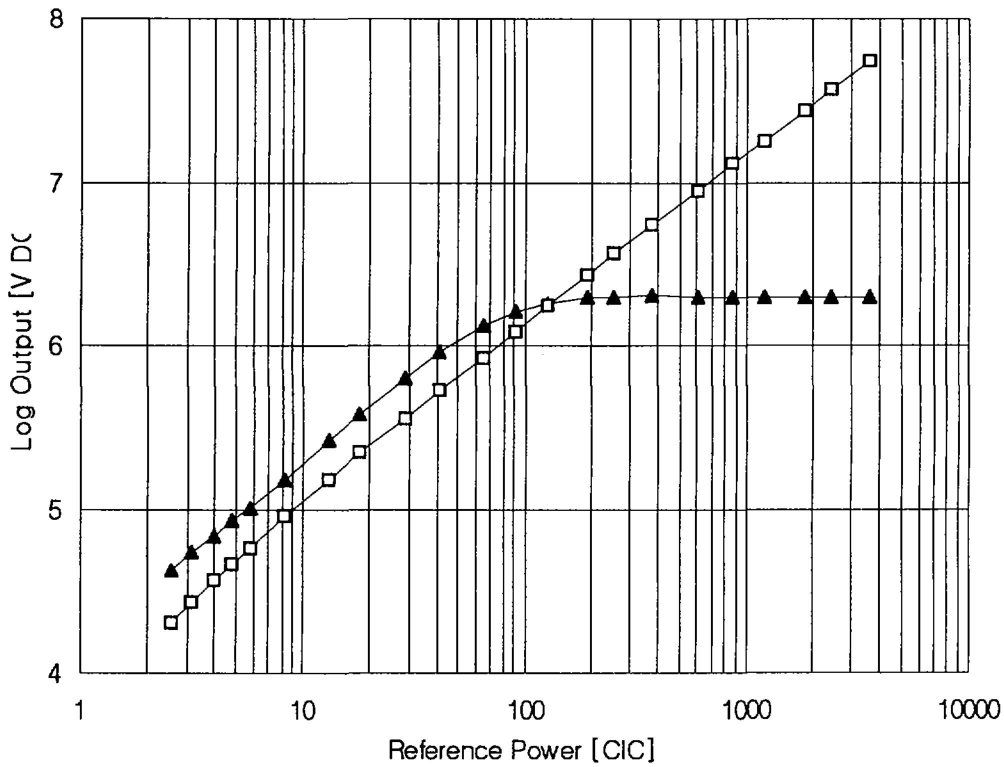

Figure 3-4 Linearity Curve after LCR Board Upgrade(97. 11. 17 : 300W to 300KW)

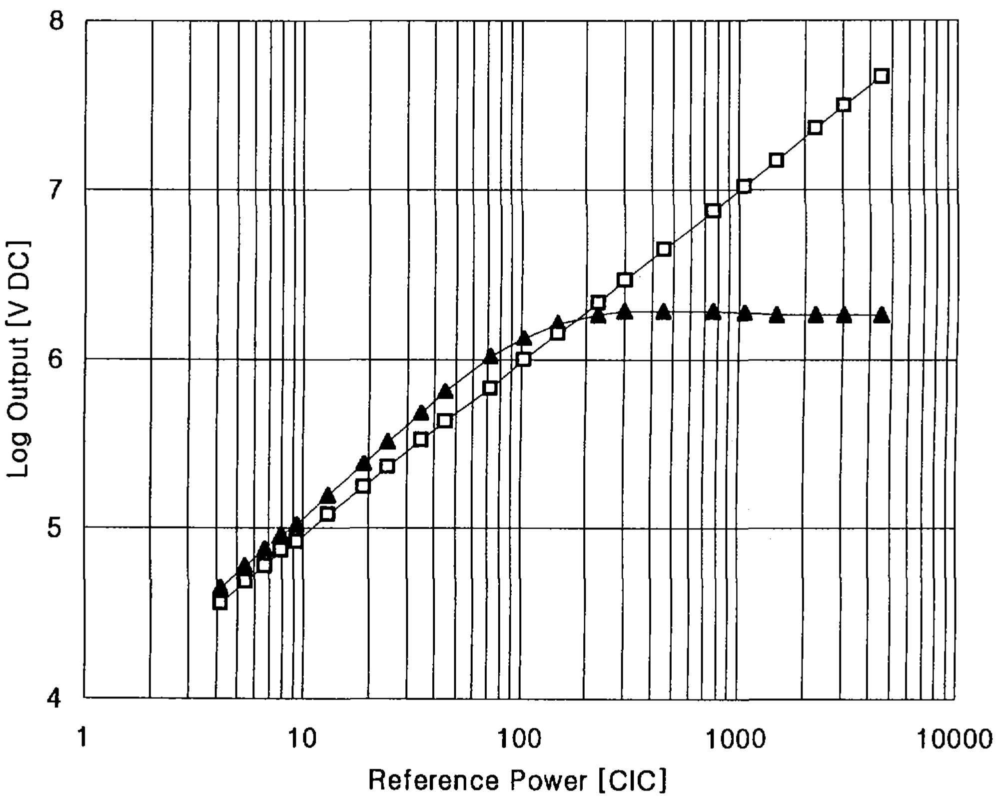

Figure 3-5 Linearity Curve after Adjustment of BP Filter Offset(97. 12. 16 : 300W to 300KW)

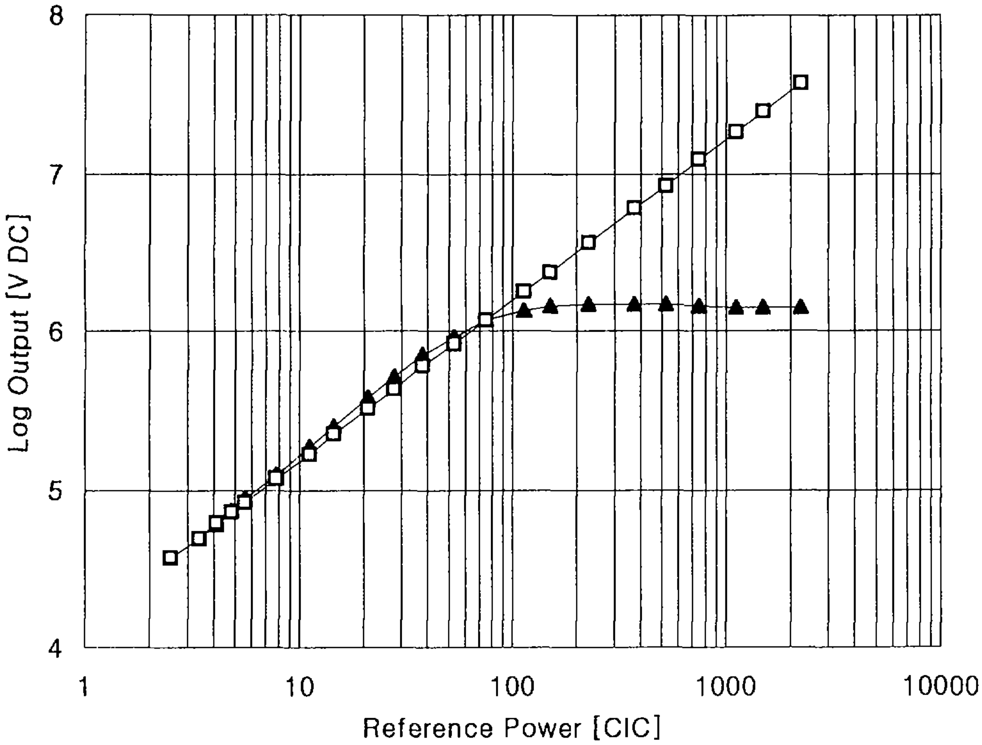

Figure 3-6 Linearity Curve after Adjustment of LCR Gain & Zero(98. 2. 11 : 300W to 300KW)

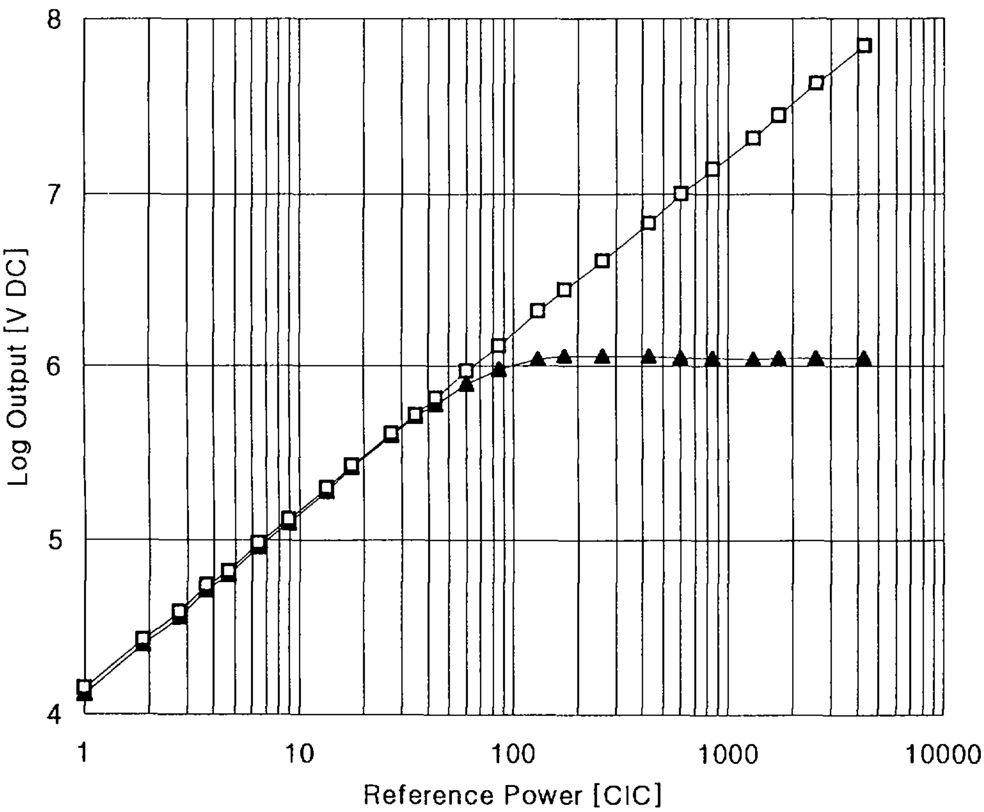

Figure 3-7 Linearity Curve after LCR Board Upgrade II(98. 3. 19 : 100W to 500KW)

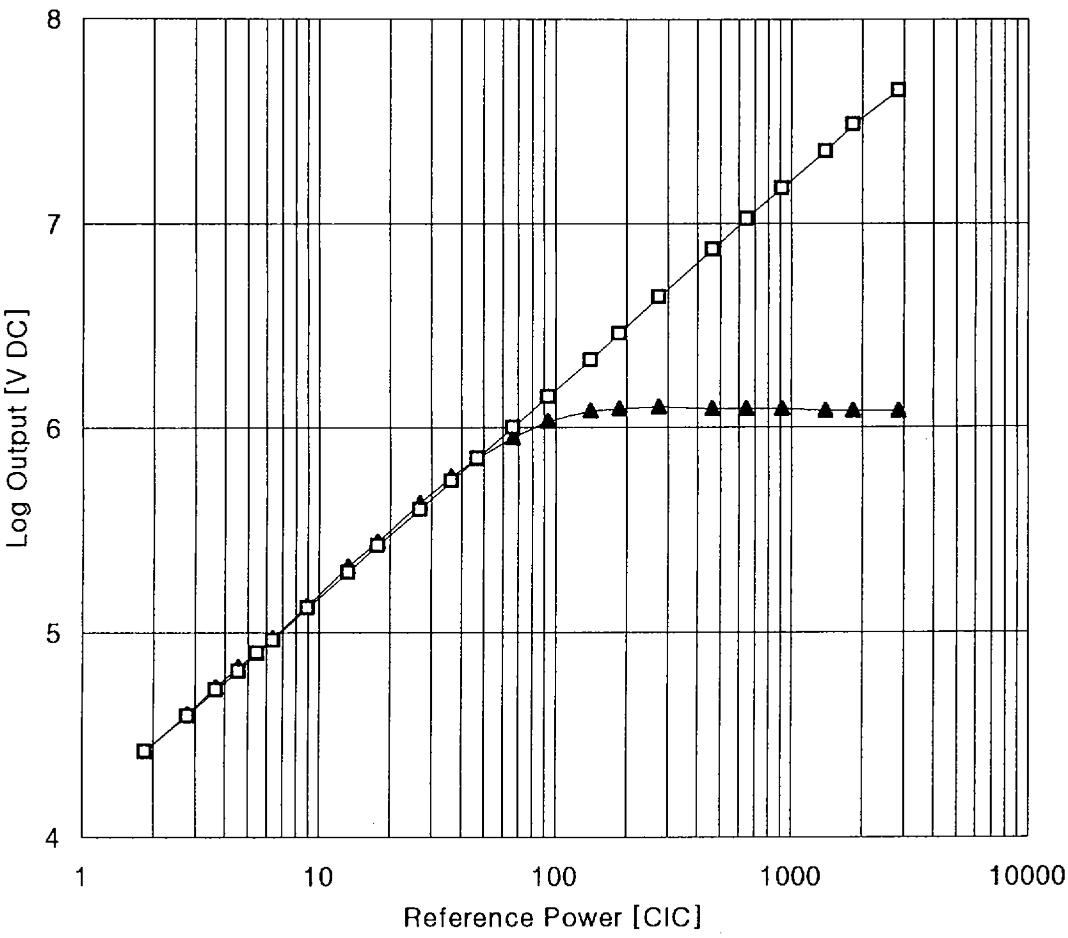

Figure 3-8 Final Results after Readjustment of LCR Gain & Zero(98. 3. 26 : 200W to 300KW)