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Analysis of Cygnus Anodization 2014-2015 Test Series

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Executive Summary

The two Cygnus pulsed power X-ray sources at the Nevada National Security Site (NNSS) generate brehmsstrahlung X-rays inside of a vacuum chamber. The inside of the chamber – the so-called spool – is anodized to reduce electron emissions and allow for greater voltage hold off. A new anodization process was implemented, and this report details an assessment of machine diagnostics before and after the new process was implemented. The diagnostics assessed were (i) an IPLT unit composed of 3 b-dot detectors whose response is a function of the magnetic field and (ii) two VSTK units composed of two d-dot detectors whose response is a function of the electric field. Statistical hypothesis tests were formulated to determine whether there is a statistically significant difference between the pulse shapes and characteristics under the old anodization process and those under the new. The primary results are:

- Voltage detector pulses from shots using the new spools were shorter and wider than those using the old spools for both C1 and C2.
- The changes in C1 from the old anodization to new were the opposite of the changes old to new on C2.
- The new anodization process
    - shows a statistically significant impact on
        * pulse height and width for the VSTK units on C1, and
        * pulse width for the C1 IPLT unit.
    - did *not* show a statistically significant impact on the characteristics of
        * the VSTK units on C2,
        * pulse width on the C2 IPLT unit, and
        * pulse height on the C1 and C2 IPLT unit.

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1 Introduction

Cygnus is a dual axis radiography machine, with two axes, C1 and C2, each consisting of a Marx Generator, Pulse Forming Line (PFL), Coaxial Transmission Line (CTL), 3-cell Inductive Voltage Adder (IVA) and a diode. Although axes C1 and C2 are both made with these components, each axis varies in capacitance and performance, and multiple detectors are used to measure their performance. This study assesses pulse characteristics from voltage and current measurements using d-dot and b-dot detectors. The d-dot detectors are a capacitave measurement, which means their response is due to a changing electric field, whereas the b-dot detectors use wire loops to generate current in response to a changing magnetic field. The plate current (IPLT) unit is made of three b-dot detectors and measures current on the front end of the machine, past the diode. The VSTK units are made of two d-dots detectors, and data is taken from VSTK5 and VSTK3 to give voltage at different locations. The VSTK5 unit is on the back end of the machine before the diode, and VSTK3 is behind VSTK5 farther away from the diode. A schematic with detector locations can be seen in Appendix B. The IVA spools are anodized – a process that increases the oxidation layer on surfaces – to increase the dielectric strength. A new anodization process was implemented to reduce electron emissions and allow for a greater voltage hold off, and series of shots were taken with the new and old spools. Pulse characteristics between the new and old spools were compared using data recorded from the IPLT, VSTK3 and VSTK5 units.

2 Results

Shot pulses taken with the old and new anodized spools were used to determine if the new anodization process had an effect on the pulse characteristics, specifically each pulses maximum height and each pulses width, as measured by full width at half maximum (FWHM). A sample of 26 pulses from the new anodization population and a sample of 32 pulses from the old anodization population were used in this analysis. The height and FWHM were computed for the 32 "old" shots and the 26 "new" shots, and a so-called students' t-test was used to statistically evaluate whether these two collections of heights and widths have the same means. (This is used as a first-order assessment of whether the collections are samples from the same or differing populations.)

The t-test used has a null hypothesis that the 32 old process shots and the 26 new process shots come from populations with equal means. A p-value less than 0.05 suggests that the two collections actually come from populations with unequal means, which are thus clearly not the same population. In this case we say that the data gives evidence that the new anodization process results in statistically significantly different machine performance. A more detailed description of the t-test is given in the methods section and the script used in R is given in Appendix A.

The mean values of the pulse heights and widths, and the associated p values from the t-test, are given in Table 1.

Table 1: The mean values of the pulse height and pulse width for the "old" and "new" shots on C1 and C2 from each of IPLT, VSTK3, and VSTK5, along with the p-value of the t-test determining whether the "old" shots were from a population with the same mean as the "new" shots. The p-values highlighted in bold are those less than 0.05

IPLT	C1 Height	C2 Height	C1 Width	C2 Width
New mean	50.5 A	31.6 A	78.2 ns	73.1 ns
Old mean	51.2 A	30.6 A	96.8 ns	77.5 ns
p Value	0.23	0.22	**0.0003**	0.23
VSTK3	C1 Height	C2 Height	C1 Width	C2 Width
New mean	0.357 V	0.348 V	60 ns	60 ns
Old mean	0.367 V	0.352 V	59 ns	60 ns
p Value	**0.021**	0.27	$\mathbf{8 \times 10^{-5}}$	0.1
VSTK5	C1 Height	C2 Height	C1 Width	C2 Width
New mean	0.338 V	0.335 V	62 ns	64 ns
Old mean	0.351 V	0.338 V	61 ns	63 ns
p Value	**0.01**	0.35	$\mathbf{6 \times 10^{-3}}$	0.33

2.1 IPLT

The IPLT is a unit made of three b-dot detectors to measure current on the front end of the machine after the diode; see Appendix B for a schematic of the detector locations. Example plots for C1 and C2 IPLT pulses with the new and old spools are shown in Fig. 1. The mean values for the pulse height and pulse width are given in Table 1, along with the corresponding P value of the associated hypothesis test.

Main Results:

- For C2, there is *no statistically significant difference* between the old and new anodization processes, with respect to pulse height and pulse width.
- For C1, the new anodization process results in a statistically significantly narrow pulse width, but not statistically significantly different pulse height.
- The mode of the C1 pulse widths is the same for the new and old anodization processes, but the new anodization process results in a distribution of pulse widths with much lower variance. Basically, the new anodization process results in more consistent pulse width performance than the old anodization process. The same appears to be true for the C1 pulse heights.

Fig. 2 shows histograms of the pulse heights (top) and pulse widths (bottom) for C1 (left) and C2 (right). Though the differences were not statistically significant, the pulse height for C1 decreased and for C2 increased from the old to the new anodization process. The pulse width for C1 decreased and pulse width for C2 increased, showing that C1 and C2 showed qualitatively opposite reactions to the change in anodization.

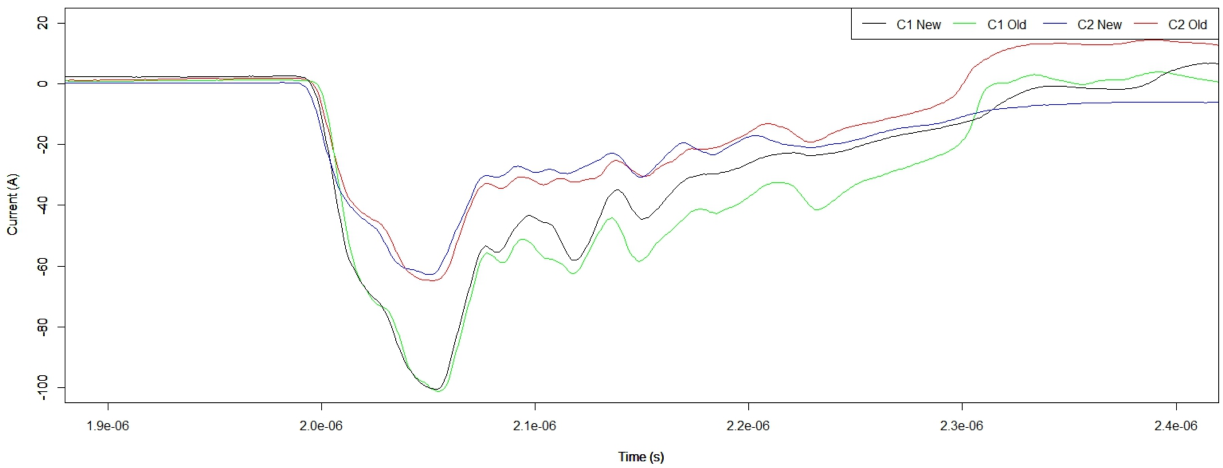

Figure 1: IPLT pulses from the C1 new anodization Shot 2745 (black), C1 old anodization Shot 2533 (green), C2 new anodization Shot 2742 (blue), and C2 old anodization Shot 2530 (red) are given.

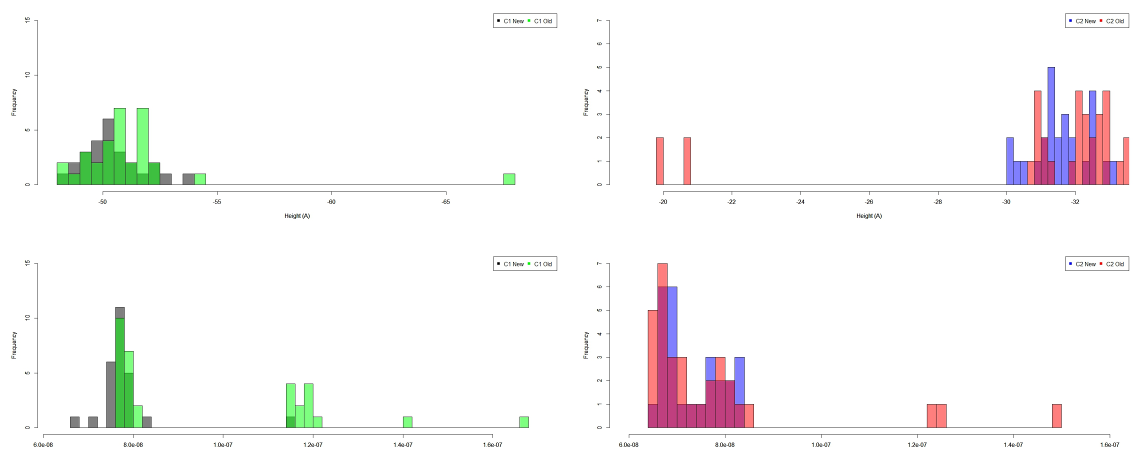

Figure 2: Histograms of pulse height (top) and pulse width (bottom) for C1 (left) and C2 (right) for IPLT. The results for the new spool are in gray for C1 and purple for C2. The results for the old spool are in green for C1 and in peach for C2.

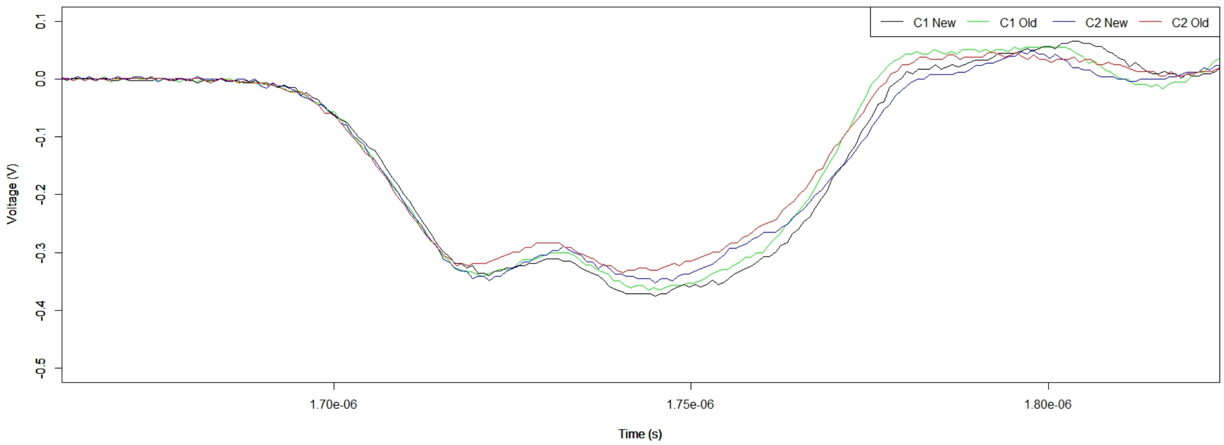

Figure 3: VSTK3 pulses from the C1 new anodization Shot 2851 (black), C1 old anodization Shot 2590 (green), C2 new anodization Shot 2742 (blue) and C2 old anodization Shot 2532 (red) are given.

2.2 VSTK3

The VSTK3 unit is made of two d-dot detectors on the back end of the machine before the diode, farther away from the diode than the VSTK5 unit. See Appendix B for the schematic of detector locations. Example pulses of VSTK3 for C1 and C2 are shown in Fig. 3.

Main Results:

- For C2, there is *no statistically significant difference* between the old and new anodization processes, with respect to pulse height and pulse width.
- For C1, the new anodization process results in a pulse width that is, on average, 1 ns larger than the pulse widths for the old anodization process. Despite being such a small increase, the difference is statistically significant.

Fig. 4 shows histograms of the pulse heights (top) and pulse widths (bottom) for C1 (left) and C2 (right). Though the differences were not statistically significant, the pulse heights for C1 and C2 both decreased from the old to the new anodization process. The pulse widths for C1 increased and pulse width for C2 remained the same.

2.3 VSTK5

The VSTK5 unit is made of two d-dot detectors on the back end of the machine behind the diode, but closer to the spool than the VSTK3 unit. See Appendix B for the schematic of the detector locations. VSTK5 had similar pulse height and width to VSTK3, but the pulse shapes were different as shown in Fig. 3.

Main Results:

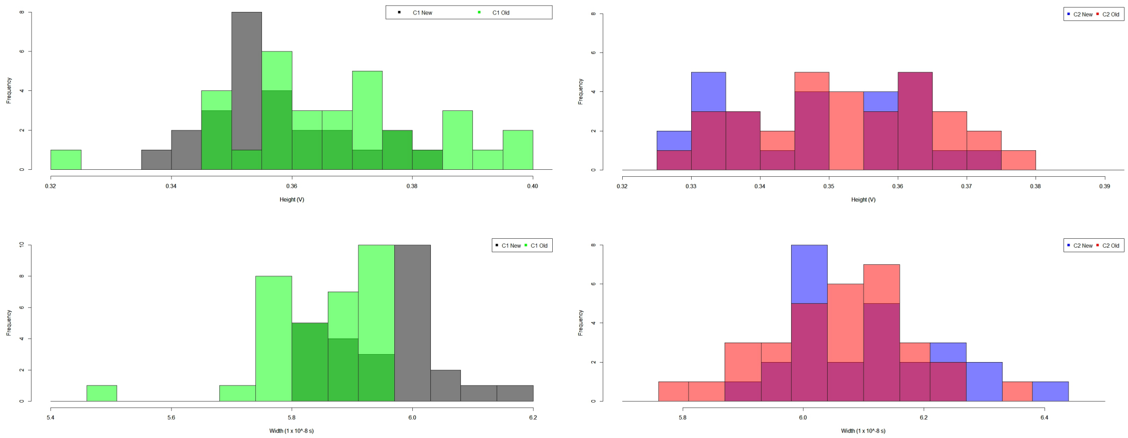

Figure 4: Histograms of pulse height (top) and pulse width (bottom) for C1 (left) and C2 (right) for VSTK3. The results for the new spool are in gray for C1 and purple for C2. The results for the old spool are in green for C1 and in peach for C2.

- For C2, there is *no statistically significant difference* between the old and new anodization processes, with respect to pulse height and pulse width.
- For C1, the new anodization process results in a pulse width that is, on average, 1 ns larger than the pulse widths for the old anodization process, and the pulse width is decreased. Both of these changes are statistically significant.

Fig. 6 shows histograms of the pulse heights (top) and pulse widths (bottom) for C1 (left) and C2 (right). The pulse height for C1 decreased statistically significantly, and the pulse height for C2 also decreased, though not statistically significantly. The pulse width for C1 increased statistically significantly–though only 1 ns–and the pulse height for C2 also increased 1 ns, though not statistically significantly.

3 Conclusions

The significance of the t-test results varied for each shot, but the general trend was that shots using the new spools produced shorter and wider pulses. When the t-test failed to recognize a difference in the mean values, the result is inconclusive. In such event, additional tests would be necessary to confirm or deny that the samples belong in the same population.

4 Methods

The standard t-test function used in R is a Welch t-test. This is also known as an unequal variance t-test or an independent samples t-test. It is a two tailed t-test that can be used

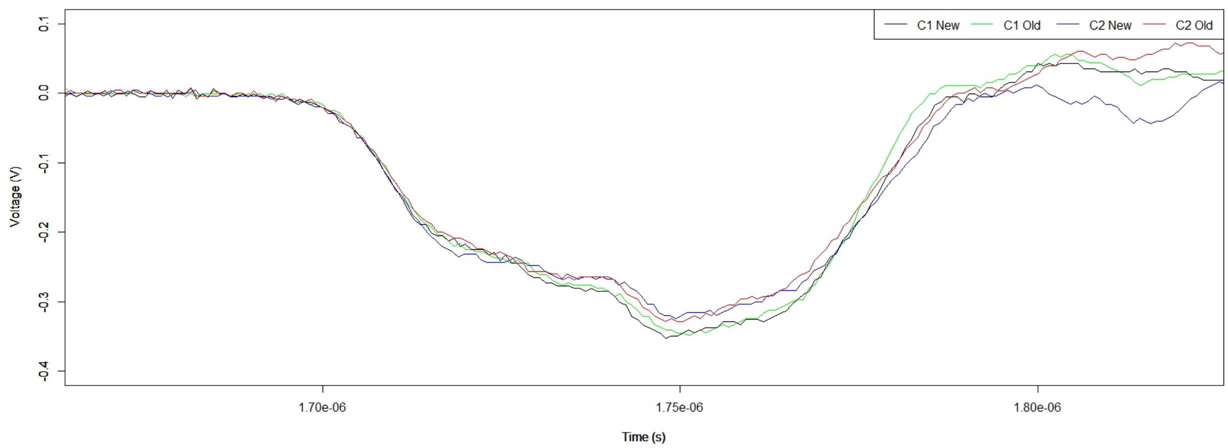

Figure 5: VSTK5 pulses from C1 new anodization Shot 2851 (black), C1 old anodization Shot 2590 (green), C2 new anodization Shot 2742 (blue) and C2 old anodization Shot 2532 (red) are given.

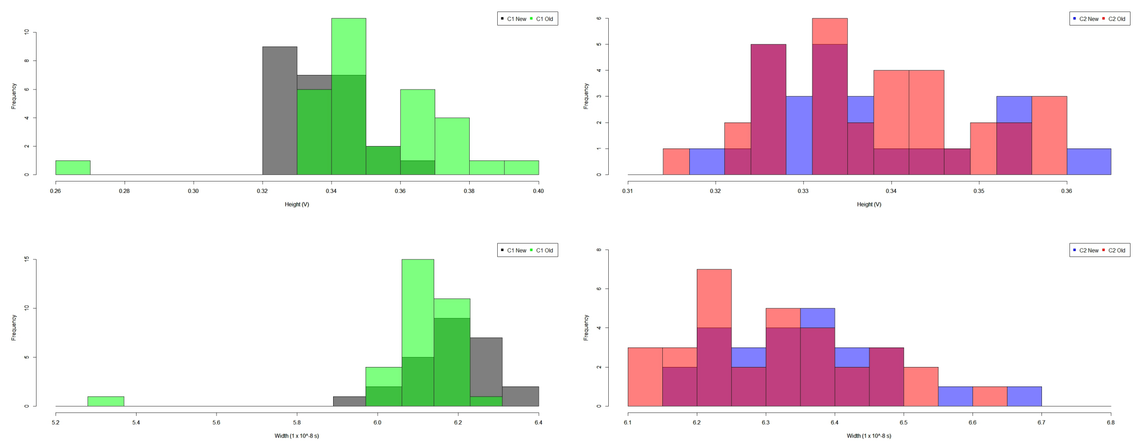

Figure 6: Histograms of pulse height (top) and pulse width (bottom) for C1 (left) and C2 (right) for VSTK5. The results for the new spool are in gray for C1 and purple for C2. The results for the old spool are in green for C1 and in peach for C2.

with samples of different size and variance. The t value is given by

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}}, \tag{1}$$

where $\bar{x}$ is the mean, s^2 is the sample variance and N is the sample size. The degrees of freedom ν are given by

$$\nu = \frac{\left(\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}\right)^2}{\frac{s_1^4}{N_1^2 \nu_1} + \frac{s_2^4}{N_2^2 \nu_2}}, \tag{2}$$

where N and s are the same as (1), $\nu_1 = N_1 - 1$ and $\nu_2 = N_2 - 1$. Once t and ν are calculated, they can be plugged into the t distribution function

$$f(t) = \frac{\Gamma(\frac{\nu+1}{2})}{\sqrt{\nu\pi}\,\Gamma\left(\frac{\nu}{2}\right)} \left(1 + \frac{t^2}{\nu}\right)^{-\frac{\nu+1}{2}}, \tag{3}$$

where Γ is the gamma function and all other variables are the same as previously defined. By integrating this t-distrubution function over the tails beyond ± t, we obtain the probability (or P value) that the null hypothesis cannot be rejected. A small p-value will reject the null and a large one will fail to reject the null. The null hypothesis is that the means are equal. For identical data sets $t = 0$ gives $P = 1$, since the entire area under the curve is integrated. For small areas under the curve, the null hypothesis can be rejected. Any area less than 5% of the total, or $p = 0.05$, is considered significant evidence to reject the null hypothesis.

5 Appendix A – Shot List

The shots used in this analysis were

C1 New:
2741, 2743, 2745, 2747, 2749, 2751, 2753, 2755, 2757, 2759, 2761, 2763, 2765, 2767, 2769, 2831, 2833, 2835, 2837, 2839, 2841, 2843, 2845, 2847, 2849, 2851

C2 New:
2742, 2744, 2746, 2748, 2750, 2752, 2754, 2756, 2758, 2760, 2762, 2764, 2766, 2768, 2770, 2832, 2834, 2836, 2838, 2840, 2842, 2844, 2846, 2848, 2850, 2852

C1 Old:
2530, 2531, 2533, 2535, 2537, 2539, 2541, 2543, 2545, 2547, 2549, 2551, 2553, 2556, 2558, 2560, 2562, 2564, 2565, 2568, 2569, 2571, 2574, 2575, 2577, 2579, 2582, 2583, 2585, 2587, 2590, 2592

C2 Old:
2530, 2532, 2534, 2536, 2538, 2540, 2542, 2544, 2546, 2548, 2550, 2552, 2554, 2556, 2558, 2560, 2562, 2564, 2566, 2568, 2570, 2572, 2574, 2576, 2578, 2580, 2582, 2584, 2586, 2588, 2590, 2592

6 Appendix B – *R* Code

R Script

```
files <- list.files(path="C:/Users/fusselza/Desktop/Misc/Cygnus/Pulses/IPLTold/C1",pattern=
".txt",full.names=T,recursive=FALSE)
for(j in 1:length(files))
{
#Pulse Height and Width Script
#start baseline correction
mydata = read.csv(files[3])
names(mydata) <- c("c","d")
attach(mydata)
newdata <- mydata[(c < .000002400),]
detach(mydata)
attach(newdata)
x = min(unlist(d))
y=x/2
newdata2 <- newdata[(d <= y),]
newdata3 <- newdata[(d >= y),]
z = which.min(d >= y)
w = newdata[z,1]
detach(newdata)
attach(newdata2)
names(newdata3) <- c("e","f")
attach(newdata3)
```

```
newdata4 <- newdata3[(e <= w),]
names(newdata4) <- c("k","J")
attach(newdata4)
detach(newdata2)
detach(newdata3)
S = tail(k,n=1)
T = 0.8*S
newdataa <- newdata4[(k < T),]
names(newdataa) <- c("G","H")
attach(newdataa)
U = mean(n=1,H)
#stop baseline correction
#start integration
detach(newdata4)
detach(newdataa)
MYdata = read.csv(files[3])
names(MYdata) <- c("C","D")
attach(MYdata)
for(i in 1:9998)
{
MYdata[i+1,2] = MYdata[i,2] + MYdata[i+1,2] - U
}
rm(S)
rm(T)
rm(x)
rm(y)
rm(U)
rm(z)
rm(w)
plot(MYdata)
#stop integration
#Record pulse width and height
Newdata <- MYdata[(C < .00000300),]
detach(MYdata)
attach(Newdata)
X = min(unlist(D))
Y=X/2
Newdata2 <- Newdata[(D <= Y),]
Newdata3 <- Newdata[(D >= Y),]
Z = which.min(D >= Y)
W = Newdata[Z,1]
detach(Newdata)
attach(Newdata2)
names(Newdata3) <- c("E","f")
attach(Newdata3)
```

```
Newdata4 <- Newdata3[(E <= W),]
names(Newdata4) <- c("K","J")
Newdata5 <- Newdata3[(E > W),]
detach(Newdata3)
names(Newdata5) <- c("G","H")
attach(Newdata5)
s = tail(C,n=1)
u = G[1]
Newdata7 <- Newdata2[(C < u),]
detach(Newdata2)
attach(Newdata7)
attach(Newdata4)
o = tail(K,n=1)
p = tail(J,n=1)
s = tail(C,n=1)
t = tail(D,n=1)
q = C[1]
r = D[1]
v = H[1]
detach(Newdata4)
detach(Newdata5)
detach(Newdata7)
m1 = (r-p)/(q-o)
m2 = (v-t)/(u-s)
b1 = p-(m1*o)
b2 = t-(m2*s)
time1 = (Y-b1)/m1
time2 = (Y-b2)/m2
width = time2-time1
print(width)
print(Y)
print(j)
}
```

7 Appendix C – Diagnostic Schematic