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**EXPERIMENTAL AND MATHEMATICAL SIMULATION TECHNIQUES FOR
DETERMINING AN IN-SITU RESPONSE TESTING METHOD FOR
NEUTRON SENSORS USED IN REACTOR POWER PLANT PROTECTION
SYSTEMS**

The Ohio State University

Ph.D. 1983

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DETERMINING AN IN-SITU RESPONSE TESTING METHOD FOR
NEUTRON SENSORS USED IN REACTOR POWER
PLANT PROTECTION SYSTEMS

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

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* * * * *

The Ohio State University

1983

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LIST OF SYMBOLS

m	=	mass (gr or amu)
E	=	energy (ev)
t	=	sample thickness
t	=	time
R	=	effective range of the α particle
$\bar{E}$	=	average energy
N	=	number of atoms
ϕ	=	flux
σ	=	cross section
σ	=	gas conductivity
A	=	atomic weight
$\langle v \rangle$	=	average velocity
$\vec{E}$	=	electric field
λ	=	mean free path at unit pressure
u	=	agitation velocity
P	=	gas pressure
μ	=	mobility, $(\frac{\text{cm}}{\text{sec}})(\frac{\text{volt}}{\text{cm}})^{-1}(\text{mmHg})$
W^+	=	drift velocity for positive ions
W^-	=	drift velocity for electrons
D^-	=	diffusion coefficient for electrons
D^+	=	diffusion coefficient for positive ions
n^+	=	positive ion density
n^-	=	electron density
e	=	electron charge
T	=	temperature

α = recombination coefficient
 N_o = rate of ion-pair production per unit volume
 K = dielectric constant
 ϵ_o = permittivity of vacuum
 ϵ = dielectric permittivity of gas
 μ = magnetic permeability of gas
 J_F = free current density, that part of current density J which varies with field
 $\vec{B}$ = magnetic flux density
 $\vec{D}$ = electric flux density
 $\vec{H}$ = magnetic field
 r = radius
 l = largest linear dimension of CIC
 c = velocity of light = 3×10^{10} cm/sec
 c = capacitance
 ϵ_r = dielectric constant of transmission line insulation (relative permittivity)
 Z_o = surge impedance of transmission line
 v_p = propagation velocity
 D = diameter of the inner surface of outer axial conductor
 d = diameter of center conductor
 R = cable resistance
 f = frequency
 I = current
 $W(jw)$ = transfer function with Laplace variable replaced by jw

$E/p = X/p$ = ratio of electric field and pressure

K_e = mobility coefficient

K = Boltzman constant = 8.61707×10^{-5} eV/°K

b = friction factor

ρ = reactivity

n = neutron density, n/cm^3

β = total delayed neutron fraction

ℓ = neutron lifetime

λ_1 = decay constant of the precursor, sec^{-1}

C_1 = precursor density, n/cm^3

Z = atomic number

h = Planck's constant

ρ_i = density of i element

LIST OF ABBREVIATIONS

USED IN CIC MODEL (COMPUTER PROGRAM)

EC	ELECTRON CHARGE, COULOMBS
P	GAS PRESSURE INSIDE CIC, MMHG
ANP	NO. OF POSITIVE IONS/CM**3
ANN	NO. OF ELECTRONS/CM**3
ANZ	NO. OF ION-PAIRS/CM**3 - SECOND
V	HIGH VOLTAGE INPUT TO ELECTRODE, VOLTS
PHI	NEUTRON FLUX, NO. OF NEUTRONS/CM**2-SEC.
APMOB	MOBILITY OF POSITIVE IONS, (CM**2/VOLT-SEC)MMHG
ANMOB	MOBILITY OF ELECTRONS, (CM**2/VOLT-SEC)MMHG
DP	DIFFUSION COEFFICIENT FOR POSITIVE IONS IN XE GAS,CM**2/SEC
DN	DIFFUSION COEFFICIENT FOR ELECTRONS IN XE GAS,CM**2/SEC
RALPHA	N2 GAS RECOMBINATION COEFFICIENT,CM**3/SEC
RB	RADIUS OF THE H.V. ELECTRODE,CM
RA	RADIUS OF THE INNER ELECTRODE,CM
DL	DETECTOR LENGTH, CM
E1	CONSTANT ELECTRIC FIELD AT A GRID POINT,VOLT/CM
CRNTP	CURRENT DUE TO POSITIVE IONS, AMP
CRNTN	CURRENT DUE TO ELECTRONS, AMP
CRNT	TOTAL CIC CURRENT OUTPUT, AMP
CD	DETECTOR CAPACITOR(SIG. TO H.V.),F
RM	OSCILLOSCOPE OR MEASUREMENT SYSTEM INPUT RESISTANCE, OHM
RC	DETECTOR RESISTANCE (SIG. TO H.V.), OHM
CC	CABLE CAPACITANCE, F

CM	OSCILLOSCOPE OR MEASUREMENT SYSTEM INPUT RESISTANCE, OHM
VOSC	CIC VOLTAGE OBSERVED AT THE OSCILLOSCOPE, VOLT
EDV	ELECTRON DRIFT VELOCITY, CM/SEC
W1	ELECTRON DRIFT VELOCITY AT A GRID POINT, CM/SEC

CHAPTER I

INTRODUCTION

1.1 Historical Background and Significance

Periodic surveillance of reactor protection system instrument channel response time has been considered an important and essential element for safe reactor operation. Due to difficulty with exclusive measurement of neutron detector response time in-situ, it has been industry practice to measure the safety channel response time excluding the neutron sensor. The inherent fast neutron sensor response time compared with other components of the safety channel has led some to suggest that sensor response time measurement is needless. However, since there exists a potential degradation of neutron sensors and their cables, there is a need for detection of any changes in the detector dynamics by measuring its response time. Some of the degradation mechanisms which may occur in neutron sensors instrumentation are:

- intrusion of fill-gas impurities (such as air, oxygen, etc.)
and the effects of electron attachment
- change in fill-gas humidity levels due to detector puncture and
formation of water vapor inside the detector
- change in gas-fill pressure due to detector puncture and
pressure changes in the reactor vessel caused by accidents

- internal chamber mechanical failure resulting from vibration, shock, or temperature extremes
- "burn-up" of neutron conversion material (U-235 in FCs and B-10 in CICs and UICs)
- change in the signal and/or high voltage insulator resistivity
- failure of the signal and/or high voltage cable connector
- change in the signal cable properties (such as capacitance, loss factor, etc.)
- temperature changes due to loss of coolant (or any other) accident
- change in detector high voltage bias due to high voltage malfunction
- degradation in measuring system and changes in the input resistance and capacitances

Recent revisions to the Institute of Electrical and Electronic Engineers (IEEE) Standard 338 [1], Nuclear Regulatory Guide 1.118 [2], and Instrument Society of America Standard Draft (Sd67.06) relative to response time of detectors [3] calls for response time verification of safety related instrument channels. Thus, a method for surveillance of neutron detector response time must be developed which will not require the reactor to be shut down or cause any interference with normal reactor operation, does not require sensor modification, and can be adapted to detectors in current use.

During the past several years there have been several advances in response time verification for platinum resistance thermometers (RTDs) and pressure sensors [6,7]. However, there is no in-situ

(in-situ in this context implies a method that can be implemented during normal operation of a nuclear plant and does not require neutron flux perturbation) method for neutron sensor response measurements. The only effort related to neutron sensors was reported by Edelmann [4], in which noise analysis techniques were used to monitor the response time of neutron and temperature instrumentation. In this method, the cross-correlation function between random signals coming from neutron and temperature instrumentation channel were utilized to indicate any significant sensor failure.

The motivation for this work began with NRC recommendations (stated in Regulatory Guide 1.118 and IEEE Standard 338-1977) for periodic testing of safety systems including safety channel response time. In conjunction with the present study, Stultz [5] performed a preliminary study of a possible CIC response time measurement technique using high voltage perturbation suggested first by Bailey [5]. Stultz used a high voltage switch consisting of a common emitter transistor amplifier coupled to an emitter-follower transistor amplifier. The rise time of his switch system was about 2 microseconds. However, this is not fast enough to observe the CIC response time. For the present study, a high voltage switch consisting of a mercury-wetted contact relay with other electronic components was designed and constructed for high voltage perturbation experiments for use with in-situ CIC response time measurements. The rise time of this switch is less than 10 nanoseconds.

There are other methods for CIC response time measurement used in this study. These methods are: step and impulse response using

x-rays, noise analysis, ramp response using a reactor scram, and sinusoidal frequency response. The results of these methods are also used to support a physical and mathematical transient response model. These methods are explained in detail in this report,

1.2 Objectives

The primary objective of this research was to investigate techniques to measure and detect changes in the intrinsic time response of neutron sensors used in reactor protection systems. The neutron sensor used in this research was a compensated ion chamber (CIC).

Relevant to the primary objective is the analytical modeling of the physical phenomena significant to the dynamic response of neutron sensors. The objectives of the analytical modeling using computer simulation are twofold: 1) comparison of the analytical model with the experimental results to identify specific physical phenomena important to detector response, and in the future, 2) identification of the mechanisms which may lead to degradation of the response of neutron sensors.

1.3 Organization of Work

The general theory of the CIC is presented in Chapter II and is used to develop a mathematical model for computer simulation of the response of a compensated ion chamber detector. Also included in Chapter II is a comparison of theoretical results for a normal and degraded CIC.

The experimental procedures used in this work are described in Chapter III. The experimental set-up is included for each experimental method.

Chapter IV presents the experimental results and analyses of the measurements described in Chapter III. At the end of Chapter IV, a comparison of experimental and theoretical results is included.

The conclusions of this work and recommendations for future work are presented in the final chapter (V).

There are several appendices included as reference and background for the reader. Appendix A presents a comprehensive description of the apparatus for the experiments, and Appendix B presents the high voltage bias curves obtained for the CIC used in this experiment.

Appendix C shows the raw data for sinusoidal frequency response analysis. Appendix D presents the frequency response of the current amplifier and the coaxial cables used in the experiments. Appendix E explains the stability analysis, time step, and error analysis of the computer program written to simulate the CIC response time. Finally, Appendix F lists the computer programs written and used in this study.

CHAPTER II

ANALYTICAL MODELING OF A NEUTRON SENSOR INSTRUMENTATION CHANNEL

2.1 Introduction

Theoretical modeling of the CIC can be divided into several different phenomena, some of which have faster response than others. These phenomena are shown in the block diagram in Figure 2.1. In modeling the CIC, it is assumed that the compensating electrode is grounded or inactive. Thus, for simplicity, no compensation of gamma radiation is considered. As will be shown later in more detail, the electromagnetic signal produced by gas ionization is small compared with the pre-existing electric field. Thus, the electric field is assumed to be time independent. The major factors determining the time dependent response of the CIC are the diffusion, recombination, and charge transport of ions and electrons through the gas.

2.2 Detection and Charge Collection Processes

2.2.1 Thermal Neutron Detection Process

The thermal neutron detection process in a CIC is possible using a thin lining of boron ($B-10$) in the chamber. This is required because boron, which has a very high neutron absorption cross-section, caused production (from non-ionizing) of charged particles

Figure 2.1: Block diagram of different events in the neutron detector

which are required for gas ionization. The reaction process of 8
neutrons with Boron is shown below [8].

For the excited state we can find the energy of individual α particles using the conservation of energy and momentum,

$$E_{\text{Li}} + E_{\alpha} = Q = 2.310 \text{ MeV} \quad (2-1)$$

$$m_{\text{Li}} v_{\text{Li}} = m_{\alpha} v_{\alpha}, \quad \sqrt{2m_{\text{Li}} v_{\text{Li}}} = \sqrt{2m_{\alpha} v_{\alpha}}. \quad (2-2)$$

Solving for E_{Li} and E_{α} yields

$$E_{\text{Li}} = 0.845 \text{ MeV}, \quad E_{\alpha} = 1.465 \text{ MeV}.$$

For the ground state we can do a similar calculation;

$$E_{\text{Li}} + E_{\alpha} = Q = 2.792 \quad (2-3)$$

$$\begin{aligned} m_{\text{Li}} v_{\text{Li}} &= m_{\alpha} v_{\alpha} \\ \sqrt{2m_{\text{Li}} E_{\text{Li}}} &= \sqrt{2m_{\alpha} E_{\alpha}} \end{aligned}$$

Solving for E_{Li} and E_{α} yields

$$E_{\text{Li}} = 1.021 \text{ MeV}, \quad E_{\alpha} = 1.771 \text{ MeV} \quad (2-4)$$

Since 6 percent of the time the ground state occurs, and 94 percent the excited state occurs, the resulting average α energy is

$$E_{\alpha} = 0.94(1.465) + 0.06(1.771) \quad (2-5)$$

$$E_{\alpha} = 1.483 \text{ MeV}$$

Self Absorption Process of α Particles in the Boron Linings

The fraction of the α particles lost in a 2π counter due to self absorption within the α emitting sample was found [9,10] to be

$$\text{Fraction lost} = 1/2 \frac{t}{R} \quad (2-6)$$

where t : sample thickness

R : effective range of the α particles in the source of material (assumed to be the α range in boron)

The range of the α particles in boron can be calculated by [11]:

$$R_{B-10} \text{ (mg/cm}^2\text{)} = 0.56 R \text{ (cm)} A^{1/3} \quad (2-7)$$

where R : α range in air

A : atomic weight of B-10

Using $E_{\alpha} = 1.483$ MeV and Figure 2.2, the range of α particles in air is found to be 0.73 cm.

The atomic weight of boron (92% B-10) can be calculated from the relation [28]:

$$M_{B-10(92\%)} = 1/(0.92/10.012939 + 0.08/10.811) = 10.0724. \quad (2-8)$$

Thus the range of α in boron is

$$R_{B-10} = (0.56)(0.73)(10.0724)^{1/3} = 0.883 \text{ mg/cm}^2,$$

$$\text{and the fraction lost} = \frac{1}{2} \frac{0.4 \text{ mg/cm}^2}{0.883 \text{ mg/cm}^2} = 0.227 = 22.7\%$$

$$\text{the fraction of } \alpha \text{ transmitted} = 100.0 - 22.7 = 77.3\%$$

Figure 2.2: Range-Energy Curves for Alpha Particles in Air (15 °C, 760 mm)[12]

Energy of α Particles at the Free Surface of The Boron Layer on the High Voltage Electrode

Alpha particles, upon crossing the boron layer, lose their energy (see figure 2.3). As was previously shown, the range, $R_1 = R_{B-10}$ for $E_0 = 2.483$ MeV is 0.883 mg/cm^2 .

$$R_2 = R_1 - t = 0.883 - 0.4 = 0.483 \text{ mg/cm}^2 \quad (2-9)$$

$$R_2 = R_{B-10} = 0.483 \text{ (mg/cm}^2\text{)} = 0.56 R_{\text{air}} \text{ (cm)} (10.0724)^{1/3}$$

solving for R_{air} results in

$$R_{\text{air}} = 0.399 \text{ cm.}$$

From Figure 2.2 we see that for

$$R_{\text{air}} = 0.399 \text{ cm, } E_t = 0.75 \text{ MeV.}$$

Thus if we assume that α particles are generated at the surface of the boron (outside), their energy will be reduced to 0.75 MeV due to boron attenuation. However, some α 's may be produced at the opposite side of boron ($E = 1.483$ MeV) and not lose their energy in the boron layer. Therefore, a better estimate of α energy is an average of the energy at the two surfaces thus:

$$E_{\alpha} = \text{average } \alpha \text{ energy} = \frac{0.75 + 1.483}{2} = 1.117 \text{ MeV}$$

Calculation of the Volume of Boron in the CIC

The volume of boron used in the CIC is composed of two separate parts: one on the H.V. electrode, and one in the signal electrode. Referring to Figure 2.4, these volumes can be calculated from

Figure 2.3: Energy Lose of Alpha Particles in Boron

Neutron Cross-section is
small for N_2 and Al.

Thus neutron
Attenuation is ignored

Figure 2.4: Cross-sectional Area of the CIC for Volume Calculation

$$\text{volume} = \ell \pi (r_2^2 - r_1^2)$$

where: ℓ is sensitive length of the detector

r_1 is radius of the inner boron layer

r_2 is radius of the outer boron layer

Therefore, v_1 = volume of Boron on the H.V. electrode

$$= 14\pi \left[(1.125)^2 - (1.125 - 6.847 \times 10^{-5})^2 \right]$$

$$+ 6.7756 \times 10^{-3} \text{ in}^3 = 0.111032 \text{ cm}^3.$$

and

$$v_2 = \text{volume of Boron in the signal electrode}$$

$$= 14\pi \left[(1 + 6.847 \times 10^{-5})^2 - 1^2 \right]$$

$$= 6.02316 \times 10^{-3} \text{ in}^3 = 9.87018 \times 10^{-2} \text{ cm}^3.$$

Thus the total Boron volume used is:

$$v_{\text{total}} = v_1 + v_2 = 0.209734 \text{ cm}^3$$

Interaction Rate in the First Boron Layer of H.V. Electrode

The interaction rate in the first Boron layer of H.V. electrode can be calculated from:

$$\alpha \text{ reaction rate} = N \sigma \phi \quad (2-10)$$

where: N = number of Boron atoms

σ = (n, α) cross section for Boron = 3836 barns

ϕ = neutron flux

The number of Boron atoms in the first layer is:

$$N = \left[\left(\frac{6.023 \times 10^{23} \text{ atom/mole}}{10.0724 \text{ gm Boron/mole}} \right) (0.111032 \times 0.92 \text{ cm}^3) \right]$$

$$(2.3 \text{ gm Boron/cm}^3)$$

$$N = 1.405 \times 10^{22} \text{ atoms of Boron.}$$

Then, the alpha reaction rate is

$$\begin{aligned}\frac{\text{Number of } \alpha}{\text{sec}} &= (1.405 \times 10^{22} \text{ atom}) (3836 \times 10^{-24} \text{ cm}^2) \phi \\ &= 53.89 \phi\end{aligned}$$

The number of ion-pairs generated by the α particles for the nitrogen-filled CIC, using self absorption and geometry factor, is therefore:

$$\begin{aligned}\frac{\text{Number of ion-pairs}}{\text{second}} &= \left(\frac{\text{Number of } \alpha}{\text{second}} \right) \left(\frac{i - p}{\alpha \text{ particle}} \right) \\ &= (53.89 \phi) \underset{\substack{\uparrow \\ \text{geometry}}}{(1/2)} \underset{\substack{\uparrow \\ \text{self absorption}}}{(0.773)} \left(\frac{1.117 \times 10^6 \text{ ev}}{36 \text{ ev/ion-pair}} \right) \\ \frac{\text{Number of ion-pairs}}{\text{second}} &= 6.463 \times 10^5 \phi \quad (\text{for } N_2)\end{aligned}$$

The ion-pair density/second can be calculated by dividing the above number by the first layer of sensitive volume, thus:

$$\begin{aligned}\frac{\text{Number of ion-pairs}}{\text{second}} &= \frac{6.463 \times 10^5 \phi}{191.237 \text{ cm}^3} \\ &= 3.379 \times 10^3 \phi\end{aligned}$$

Similarly, for the xenon-filled CIC the ion-pair density/second is $5.505 \times 10^3 \phi$.

Neutron Attenuation in the First Layer of Boron

Not all of the neutrons incident in the first layer will produce α particles. Some will pass through and will be detected by the second layer. The neutron flux at the second boron layer (signal electrode), assuming no attenuation in the nitrogen gas is:

$$\phi = \phi_o e^{-N \sigma t} \quad (2-11)$$

where: ϕ = neutron flux at the second boron layer

ϕ_o = neutron flux before attenuation

N = atom density of boron in the first layer

σ = total neutron cross-section in boron

t = thickness of boron

$$\phi_2 = \phi \text{ EXP } \left(- \frac{6.023 \times 10^{23} \text{ atom/mole}}{10.0724 \text{ gm Boron/mole}} (2.3 \text{ gm Boron/cm}^3) \right. \\ \left. (3836 \times 10^{-24} \text{ cm}^2) (0.92) (1.739 \times 10^{-4} \text{ cm}) \right)$$

$$\phi_2 = \phi e^{-0.08} = 0.9191 \phi .$$

Interaction Rate in the Second Boron Layer of Signal Electrode

The number of Boron atoms in the second layer is:

$$N = \frac{6.023 \times 10^{23} \text{ atom/mole}}{10.0724 \text{ gm Boron/mole}} (9.8701 \times 10^{-2} \text{ cm}^3) (0.92) \\ (2.3 \text{ gm Boron/cm}^3) \\ = 1.249 \times 10^{22} \text{ atoms.}$$

The interaction of neutrons is then

$$\frac{\text{Number of } \alpha \text{ particles}}{\text{sec}} = ((1.249 \times 10^{22} \text{ atom}) (3836 \times 10^{-24} \text{ cm}^2) \\ (\phi_2)) \\ = 47.91 \phi_2 .$$

The number of ion-pairs/sec is therefore

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$$\begin{aligned} \frac{\# \text{ of i-p}}{\text{sec}} &= (47.91 \phi_2) \underset{\substack{\uparrow \\ \text{geometry}}}{\left(\frac{1}{2}\right)} \underset{\substack{\uparrow \\ \text{self-absorption}}}{(0.773)} \frac{1.117 \times 10^6 \text{ ev}/\alpha}{36 \text{ ev/i-p}} \\ &= 5.745 \times 10^5 \phi_2 \end{aligned}$$

The density of ion-pairs/second for the nitrogen-filled CIC is:

$$\begin{aligned} \frac{\text{i-p}}{\text{cm}^3 \text{-sec}} &= \frac{5.745 \times 10^5 \phi}{191.237} = 3.004 \times 10^3 \phi_2 \\ &= (3.004 \times 10^3) (0.9191 \phi) \\ &= 2.761 \times 10^3 \phi \quad (\text{for } N_2) . \end{aligned}$$

Similarly, the density of ion-pair/sec for the xenon-filled CIC is $4.498 \times 10^3 \phi$.

Total Interaction Rate in the Sensitive Volume of the Detector

The total rate of ion-pair formation per unit for the nitrogen-filled CIC is simply the sum of the interaction rate in the first and second layer of the boron or simply,

$$\begin{aligned} \frac{\# \text{ of ion-pair}}{\text{cm}^3 \text{-sec}} &= 3.379 \times 10^3 \phi + 2.761 \times 10^3 \phi \\ \frac{\# \text{ of ion-pair}}{\text{cm}^3 \text{-sec}} &= 6.140 \times 10^3 \phi \quad (\text{for } N_2) \end{aligned}$$

The total rate of ion-pairs formation per unit volume for xenon is similarly $1.000 \times 10^2 \phi$.

The measured response of the CIC does not include the transit time of the neutrons in the detector wall, and the transit time of alpha particles in the boron and the nitrogen gas. This is due to the fact that as long as no ion-pairs are generated, there is no way to detect the time in the detector response time measurement. The only effect observed in the CIC response time is a deadtime. This is the time period from when a neutron comes into the detector until the first ion-pair is generated in the chamber, even if no ion-pairs have been collected.

The calculation of the transit time of neutron and alpha are included here for completeness:

Neutron Travel in the Detector Wall

Assuming that the thermal neutrons do not lose their energy in the Al wall of the CIC detector, the transit time can be calculated as (see Figure 2.5)

$$\begin{aligned} T &= \frac{x_1}{v} = \frac{(0.125 + 0.1876 + 0.125) (2.54 \times 10^{-2} \text{ m/inch})}{2200 \text{ m/sec}} \\ &= \frac{0.0111}{2200} = 5.05 \times 10^{-6} \text{ sec.} \end{aligned}$$

Transit Time of the Alpha Particles in Boron

The transit time of α particles in the boron can be calculated from:

Figure 2.5: CIC Detector wall

$$T = \frac{t}{\langle v \rangle} \quad (2-12)$$

where: T = time

$\langle v \rangle$ = average velocity of α 's .

The velocity of the α particles can be calculated from

$$v = \sqrt{\frac{2E}{m}} = c \sqrt{\frac{2E}{mc^2}} = c \sqrt{\frac{mc^2}{931 \text{ MeV/amu}}} \quad (2-13)$$

where: m is the α particle mass in amu and is calculated from the mass of ${}^4_2\text{He}$ ($m = 4.003873$ amu) minus the mass of two electrons (0.001098 amu)

Assuming $\langle v \rangle = 0.6 v$

$$\begin{aligned} T &= \frac{t}{0.6 v} = \frac{t}{0.6 c} \sqrt{\frac{(mc^2)}{2E}} \\ &= \frac{\left(0.4 \frac{\text{mg}}{\text{cm}^2}\right) \left(2.3 \times 10^3 \frac{\text{mg}}{\text{cm}^3}\right)}{0.6 (3 \times 10^8 \text{ m/sec})} \sqrt{\frac{931 \frac{\text{MeV}}{\text{amu}} \cdot 4.002775 \text{ amu}}{(2) (1.752 \text{ MeV})}} \\ T &= 3.1509 \times 10^{-13} \text{ sec.} \end{aligned}$$

2.2.2. Gamma and X-ray Detection Process

The passage of gamma and x-rays through the detector results in a loss of energy due to an electromagnetic interaction with the atoms and molecules of the detector wall and Nitrogen gas. The gamma or x-ray interaction with the detector wall and gas results in the transfer of all or part of the x- or gamma ray energy to electrons.

These electrons are called secondary electrons. The stopping of electrons in the detector wall and gas and loss of their entire energy is the detection mechanism of such particles by CIC through ion-pair production.

A large number of possible interaction mechanisms of gamma and X-rays is possible with matter. The most important interactions are photoelectric absorption, Compton scattering, and pair production. Through these three mechanisms, the photon (γ or X-ray) transfers part or all of its energy to electron energy. These electrons, due to interaction with the detector wall or detector gas, will lose part or all of their energy in the sensitive detector volume (see Fig 2.6).

CIC Gamma Interaction Rate

Assuming that the energy of the gamma rays in the Central Irradiation Facility (CIF) of the OSU Reactor is 1 MeV, ($E_\gamma = 1$ MeV), and the dose rate is 3×10^6 R/nr (at 10 kW), the gamma flux can be calculated from the conversion factor [13] for $E_\gamma = 1$ MeV:

$$561 \frac{\text{photon}}{\text{cm}^2\text{-sec}} / \text{mR/hr}$$

thus the gamma flux is

$$\phi_\gamma = (3 \times 10^9 \text{ mR/hr}) \left(561 \frac{\text{photon}}{\text{cm}^2\text{-sec}} / \text{mR/hr} \right)$$

$$\phi_\gamma = 1.683 \times 10^{12} \frac{\text{photon}}{\text{cm}^2\text{-sec}}$$

The nitrogen density in the sensitive volume can be calculated from

Figure 2.6: Gamma and/or X-ray Interaction Mechanism in the CIC

the number of atoms of nitrogen gas in the sensitive volume can be calculated from

$$N = \frac{(6.023 \times 10^{23} \frac{\text{atom}}{\text{mole}})(191.237 \text{ cm}^3)(0.0013 \text{ g/cm}^3)}{14.008 \text{ gN}_2/\text{mole}}$$

$$N = 1.0689 \times 10^{22} \quad \# \text{ of atoms of N}_2/\text{cm}^3$$

The Interaction rate of γ with nitrogen gas is therefore

(assumed $E_\gamma = 1 \text{ MeV}$)

$$\text{Interaction rate} = \left(\phi_\gamma \frac{\text{photon}}{\text{cm}^2 \text{ sec}} \right) \exp \left(\frac{-\mu(0.125 + 0.175)^\rho}{\rho} \right) (\sigma_{\text{abN}_2})(N)$$

$$\frac{\text{Number of } \gamma}{\text{sec}} = (\phi_\gamma) \exp \left(\frac{-(0.0614)(.25)(2.699 \text{ g/cm}^3)(2.54 \text{ cm/in})}{\text{cm}^2/\text{g}} \right)$$

$$(1.85 \times 10^{-24} \text{ cm}^2)(1.0689 \times 10^{22}) = 0.02 \phi_\gamma$$

$$\frac{\# \text{ of ion-pairs}}{\text{cm}^3\text{-sec}} = \frac{\left(0.02 \phi_\gamma \frac{\# \text{ of } \gamma}{\text{sec}} \right) \frac{1}{2} \frac{10^6 \text{ ev}}{35 \text{ ev/i-p}}}{191.237 \text{ cm}^3}$$

$$\frac{\# \text{ of i-p}}{\text{cm}^3\text{-sec}} = 1.330 \phi_\gamma$$

The number of ion-pairs generated due to gamma rays in the CIC at a reactor power of 10 kW is estimated to be

$$\frac{\# \text{ of ion-pairs}}{\text{cm}^3\text{-sec}} = (1.330)(1.683 \times 10^{12})$$

$$\frac{\# \text{ of ion-pairs}}{\text{cm}^3\text{-sec}} = 2.24 \times 10^{12}$$

On the other hand, with the number of ion-pairs generated due to neutrons (at 10 kW) in the CIC is estimated to be

$$\frac{\# \text{ of ion-pairs}}{\text{cm}^3\text{-sec}} = (6.140 \times 10^3) \overbrace{(3.4058 \times 10^{10})}^{\text{neutron flux}} = 2.091 \times 10^{14} \quad 24$$

X-Ray Interaction in the CIC for LINAC Experiments

Using the computer program explained in Section A.2 (see Appendix F), the total Bremsstrahlung energy detected was estimated and is summarized in Table 2.1 for different detector gas filling.

The density of the ion-pairs generated per unit time in the CIC was calculated from the relation

$$\frac{\# \text{ of ion-pairs}}{\text{cm}^3\text{-sec}} = \frac{\left(\frac{\text{Total Bremsstrahlung energy detected per absorbed } e^-, \text{ ev/e}^-}{\left(\frac{\text{electron charge}}{\text{coul/e}^-} \right)} \right) \left(\frac{\text{Beam current, coul/sec}}{\left(\frac{\text{Detector Sensitive Volume, cm}^3}{\text{W, ev/ion pair}} \right)} \right)}{\left(\frac{\text{electron charge}}{\text{coul/e}^-} \right) \left(\frac{\text{W, ev/ion pair}}{\left(\frac{\text{Detector Sensitive Volume, cm}^3}{\text{W, ev/ion pair}} \right)} \right)}$$

For example, for the N_2 -filled detector, the density of ion-pair formation per unit time in the case of Long pulse (1 microsecond width) is:

$$\begin{aligned} \frac{\# \text{ of ion-pairs}}{\text{cm}^3\text{-sec}} &= \frac{(2.3262 \text{ ev/e}^-)(0.32 \text{ coul/sec})}{(1.6021 \times 10^{-19} \text{ coul/e}^-)(35 \text{ ev/i-p})(191.237 \text{ cm}^3)} \\ &= 6.9418 \times 10^{14} \text{ i-p/cm}^3\text{-sec} \end{aligned}$$

For other cases of the ion-pair density rate, refer to Table 2.2

2.2.3 Charge Transport: Electrons and Positive Ions Motion and the Concepts of Recombination and Diffusion

The behavior of electrons after generation in the chamber gas depends on several factors such as type of gas, pressure, temperature,

Table 2.1 COMPARISON OF THE TOTAL DETECTED BREMSSTRAHLUNG ENERGY FOR DIFFERENT DETECTOR GAS FILLINGS.

Type of Gas Filling	Total Bremsstrahlung Energy (detected) MeV/Absorbed Electron
N ₂ -filled CIC	0.23304×10^{-5}
Xe-filled CIC	0.34183×10^{-4}

Table 2.2 COMPARISON OF THE ION-PAIR DENSITY/SEC FOR DIFFERENT PULSE WIDTH AND DETECTOR GAS FILLINGS

Type of Pulse	Beam Current (Amp)	N ₂ -filled detector (1 atm)			Xe-filled detector (4 atm)		
		ev/i-p	ev/e ⁻	i-p/cm ³ -sec	ev/i-p	ev/e ⁻	i-p/cm ³ -sec
Long Pulse (1 μsec)	0.32	35	2.3262	6.9418×10^{14}	22.1	34.183	1.6155×10^{16}
Short Impulse (20 nsec)	0.6	35	2.3262	1.30157×10^{15}	22.1	34.183	3.0291×10^{16}

and the electric field. Free electrons make many collisions with the gas molecules as they move toward the positive electrode. The average distance the electrons travel between collisions (i.e., mean free path) in the gas is inversely proportional to the number of gas molecules per unit volume. The electron motion in the gas is random, but the net drift is in the direction opposite to that of the electric field. The average drift velocity for electrons is approximately

$$\vec{W}^- = \left(\frac{2e\lambda}{3mu} \frac{\vec{E}}{p} \right) = \mu^- \frac{\vec{E}}{p} \quad (2-14)$$

where:

- $\vec{E}$ = electric field
- λ = mean free path at unit pressure
- m = mass of electron
- u = agitation velocity of e^- (r.m.s. value)
- p = gas pressure

μ^- is called mobility of the electrons in the detector gas (this varies with the type of gas).

The mobility of electrons is typically 1000 times that of positive ions. The mobility of electrons is not constant, but varies with the electric field and gas pressure.

The drift velocity of positive ions in the detector gas is approximately

$$\vec{W}^+ = \mu^+ \frac{\vec{E}}{p} \quad (2-15)$$

where:

- $\vec{E}$ = electric field
- p = gas pressure
- μ^+ = mobility of positive ions

The mobility of positive ions remains fairly constant over wide ranges of pressure and electric field (insensitive to changes in electric field and gas pressure). This is discussed in detail in section 2.5.2.

The motion of electrons and positive ions in a gas under the influence of an electric field results in the generation of charge or current in an external circuit. In the absence of an electric field (absence of high voltage), a current may exist due to the nonuniformity of the charge distribution. This current is represented by the relationship

$$\vec{J}_D^- = eD^- \nabla n^- \quad (2-16)$$

$$\vec{J}_D^+ = -e D^+ \nabla n^+ \quad (2-17)$$

where:

D^- and D^+ are diffusion
coefficients for electrons
and positive ions
 n^- and n^+ are the electron
and positive ion densities

The diffusion coefficient D^+ can be related to mobility μ^+ by

$$D^+ = \frac{E' k T}{e} \mu^+ \quad (2-18)$$

where:

$\frac{kT}{e} = 2.5 \times 10^{-2}$ volts if T = ambient
temperature

$E' \approx 1$ = ratio of the average agitation energy
of positive or negative ions to thermal
agitation energy at 15°C

Thus, D^+ , the diffusion coefficient for positive ions is

$$D^+ \approx 2.5 \times 10^{-2} \mu^+ \quad (2-19)$$

where: μ^+ is positive ion mobility

The current densities shown in Equations (2-16) and (2-17) are called diffusion effects of ions and electrons. In the presence of an electric field, there is a net drift of the charged particles in the directions of the electric field. The current densities due to this effect are:

$$\vec{J}_E^- = -n^- e \vec{W}^- \quad (2-20)$$

$$\vec{J}_E^+ = n^+ e \vec{W}^+ \quad (2-21)$$

where: $\vec{W}^-$ and $\vec{W}^+$ are drift velocities of electrons and positive ions respectively.

In the presence of positive ions and electrons in the same region, there is the tendency for recombination to form neutral molecules. The rate of recombination of positive ions and electrons is

$$\frac{\partial n^-}{\partial t} = -\alpha n^+ n^- = -\frac{\partial n^+}{\partial t} \quad (2-22)$$

where: α is the recombination coefficient.

In the above equation, it is assumed that the positive ions and electrons are uniformly distributed in the active region of the detector. This implies that the detector is uniformly irradiated throughout the active region.

In the sensitive volume of the detector where charges are present, several processes, including charge production, recombination, diffusion and current flow take place. The rate of change of positive ions and electrons, $\frac{\partial n^+}{\partial t}$ and $\frac{\partial n^-}{\partial t}$, can be expressed by the application of the principle of conservation of charge. Assuming a bounded region it follows that

$$\frac{\partial n^-}{\partial t} = -\nabla \cdot (\vec{J}^- / e) \quad (2-23)$$

$$\frac{\partial n^+}{\partial t} = -\nabla \cdot (\vec{J}^+ / e) \quad (2-24)$$

where: $\vec{J}^+$ and $\vec{J}^-$ are in the ion and electron current densities, respectively

Since for a bounded region:

$$\left\| \begin{array}{l} \text{Rate of change of the} \\ \text{number of Particles} \\ \text{in the region} \end{array} \right\| = \left\| \begin{array}{l} \text{Rate of flow of} \\ \text{particles leaving the} \\ \text{bounded region} \end{array} \right\|$$

Therefore,

$$\int_A \left(\frac{\partial n^-}{\partial t} \right) dA = \frac{-1}{e} \int_S \vec{J}^- \cdot \vec{K} ds$$

where: K is the unit vector normal to the surface
A is the volume
S is the surface

Using Divergence Theorem,

$$\int_A \left(\frac{\partial n^-}{\partial t} \right) dA = -\frac{1}{e} \int_A (\nabla \cdot \vec{J}^-) dA, \quad (2-25)$$

where: $\vec{J}^- = \vec{J}_D^- + \vec{J}_E^-.$

Similarly,

$$\int_A \left(\frac{\partial n^+}{\partial t} \right) dA = -\frac{1}{e} \int_A (\nabla \cdot \vec{J}^+) dA, \quad (2-26)$$

where: $\vec{J}^+ = \vec{J}_D^+ + \vec{J}_E^+.$

In equations (2-25) and (2-26) since integration is done over any volume, the integrands on the two sides of the same equation can be equated. Using the results from equation (2-16), (2-17), (2-20), and (2-21) for the current densities, it can be shown that

$$\frac{\partial n^-}{\partial t} = D^- \nabla^2 n^- - \nabla \cdot (n^- \vec{w}^-) \quad (2-27)$$

$$\frac{\partial n^+}{\partial t} = D^+ \nabla^2 n^+ - \nabla \cdot (n^+ \vec{w}^+) \quad (2-28)$$

If we consider the recombination of positive ions with electrons, then $\alpha n^+ n^-$ represents the rate of recombination per unit volume. Therefore, the net rate of change of electrons and positive ions is

$$\frac{\partial n^-}{\partial t} = D^- \nabla^2 n^- - \nabla \cdot (n^- \vec{w}^-) - \alpha n^+ n^- + N_0 \quad (2-29)$$

$$\frac{\partial n^+}{\partial t} = D^+ \nabla^2 n^+ - \nabla \cdot (n^+ \vec{w}^+) - \alpha n^+ n^- + N_0 \quad (2-30)$$

where: α = recombination coefficient for positive

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ion and electrons in the Nitrogen gas

N_0 = the rate of ion-pair production per unit volume

The space charge equation in three dimensional cylindrical coordinates can be written as:

$$\begin{aligned} \frac{\partial n^-(r, \theta, z, t)}{\partial t} = N_0(r, \theta, z, t) - \nabla \cdot [n^-(r, \theta, z, t) \vec{W}^-(r, \theta, z, t, p)] \\ + D^- \nabla^2 n^-(r, \theta, z, t) - \alpha n^+(r, \theta, z, t) n^-(r, \theta, z, t) \end{aligned} \quad (2-31)$$

$$\begin{aligned} \frac{\partial n^+(r, \theta, z, t)}{\partial t} = N_0(r, \theta, z, t) - \nabla \cdot [n^+(r, \theta, z, t) \vec{W}^+(r, \theta, z, t, p)] \\ + D^+ \nabla^2 n^+(r, \theta, z, t) - \alpha n^+(r, \theta, z, t) n^-(r, \theta, z, t) \end{aligned} \quad (2-32)$$

where: $N_0(r, \theta, z, t)$ = number of ion-pairs produced per cm^3 -sec and is uniform throughout the region

: $n^+(r, \theta, z, t)$ and $n^-(r, \theta, z, t)$ are the number of positive ions and electrons at the location (r, θ, z) and time t respectively

Substituting the approximate equivalent for $\vec{W}^+$ and $\vec{W}^-$, the above equations can be written in the simplified form

$$\frac{\partial n^-}{\partial t} = N_0 - \nabla \cdot \left(n^- \mu^- \frac{\vec{E}}{p} \right) + D^- \nabla^2 n^- - \alpha n^+ n^- \quad (2-33)$$

$$\frac{\partial n^+}{\partial t} = N_0 - \nabla \cdot \left(n^+ \mu^+ \frac{\vec{E}}{p} \right) + D^+ \nabla^2 n^+ - \alpha n^+ n^- \quad (2-34)$$

For a cylindrical geometry we have:

$$\nabla \cdot \vec{E} = \frac{1}{r} \frac{\partial}{\partial r} (r E_r) + \frac{1}{r} \frac{\partial E_\theta}{\partial \theta} + \frac{\partial E_z}{\partial z} \quad (2-35)$$

$$= \frac{\partial E_r}{\partial r} + \frac{E_r}{r} + \frac{1}{r} \frac{\partial E_\theta}{\partial \theta} + \frac{\partial E_z}{\partial z} \quad (2-36)$$

$$\nabla^2 n(r, \theta, z, t) = \frac{\partial^2 n}{\partial r^2} + \frac{1}{r} \frac{\partial n}{\partial r} + \frac{1}{r^2} \frac{\partial^2 n}{\partial \theta^2} + \frac{\partial^2 n}{\partial z^2} \quad (2-37)$$

$$\begin{aligned} \frac{\partial n^-}{\partial t} = N_0 - \frac{\mu^-}{p} \left[\frac{1}{r} \frac{\partial}{\partial r} (r n^- E_r) + \frac{1}{r} \frac{\partial (n^- E_\theta)}{\partial \theta} + \frac{\partial (n^- E_z)}{\partial z} \right] \\ + D^- \left[\frac{\partial^2 n^-}{\partial r^2} + \frac{1}{r} \frac{\partial n^-}{\partial r} + \frac{1}{r^2} \frac{\partial^2 n^-}{\partial \theta^2} + \frac{\partial^2 n^-}{\partial z^2} \right] - \alpha n^+ n^- \end{aligned} \quad (2-38)$$

$$\begin{aligned} \frac{\partial n^+}{\partial t} = N_0 - \frac{\mu^+}{p} \left[\frac{1}{r} \frac{\partial}{\partial r} (r n^+ E_r) + \frac{1}{r} \frac{\partial (n^+ E_\theta)}{\partial \theta} + \frac{\partial (n^+ E_z)}{\partial z} \right] \\ + D^+ \left[\frac{\partial^2 n^+}{\partial r^2} + \frac{1}{r} \frac{\partial n^+}{\partial r} + \frac{1}{r^2} \frac{\partial^2 n^+}{\partial \theta^2} + \frac{\partial^2 n^+}{\partial z^2} \right] - \alpha n^+ n^- \end{aligned} \quad (2-39)$$

One-dimensional Charge Transport Equations

Solving for n^- and n^+ in four dimensions (r, θ, z, t) is a tedious process even utilizing computer analysis. If we assume that the detector is uniformly irradiated (because neutron flux is constant in the z and θ direction) the space charge transport equations may be solved in one dimension (r) and then integrated over the spatial dimensions (θ , and z). The one-dimensional space charge equations in the cylindrical coordinates can be represented as:

$$\frac{\partial n^-}{\partial t} = N_0 - \left[\frac{\partial}{\partial r} (n^- \vec{W}) + \frac{n^- \vec{W}}{r} \right] + D^- \left(\frac{\partial^2 n^-}{\partial r^2} + \frac{1}{r} \frac{\partial n^-}{\partial r} \right) - \alpha (n^+) (n^-) \quad (2-40)$$

$$\frac{\partial n^+}{\partial t} = N_0 - \left[\frac{\partial}{\partial r} (n^+ \vec{W}) + \frac{n^+ \vec{W}}{r} \right] + D^+ \left(\frac{\partial^2 n^+}{\partial r^2} + \frac{1}{r} \frac{\partial n^+}{\partial r} \right) - \alpha (n^+) (n^-) \quad (2-41)$$

or equivalently

$$\frac{\partial n^-}{\partial t} = N_0 - \frac{\mu^-}{p} \left[\frac{\partial}{\partial r} (n^- \vec{E}) + \left(\frac{n^- \vec{E}}{r} \right) \right] + D^- \left(\frac{\partial^2 n^-}{\partial r^2} + \frac{1}{r} \frac{\partial n^-}{\partial r} \right) - \alpha (n^+) (n^-) \quad (2-42)$$

$$\frac{\partial n^+}{\partial t} = N_0 - \frac{\mu^+}{p} \left[\frac{\partial}{\partial r} (n^+ \vec{E}) + \left(\frac{n^+ \vec{E}}{r} \right) \right] + D^+ \left(\frac{\partial^2 n^+}{\partial r^2} + \frac{1}{r} \frac{\partial n^+}{\partial r} \right) - \alpha (n^+) (n^-) \quad (2-43)$$

One-dimensional Charge Transport Equations for Constant Electric Field

If the electric field is not time-dependent, it can be found in the following manner (see Figure 2.7). Since the length of the CIC detector is much larger than the radius b ($\ell = 14'' \gg 1.125''$), then the fringing of the lines of force at the ends can be ignored. Applying Gauss's theorem to a closed cylindrical surface of radius r (See Figure 2.7) and length ℓ then the only part of the cylindrical surface which has a field intensity normal to the surface will be the cylindrical walls, therefore:

$$\epsilon_0 \oint \vec{E} \cdot d\vec{S} = q - q' \quad (2-44)$$

$$\epsilon_0 \oint K \vec{E} \cdot d\vec{S} = q = K \epsilon_0 E 2 \pi r \ell \quad (2-45)$$

solving for E results

$$E(r) = \frac{q}{2 \pi r \epsilon_0 \ell K} \quad (2-46)$$

where: ϵ_0 is the permittivity of vacuum

K is the dielectric constant (for nitrogen gas at

STP = 1.000588 (for vacuum, $K = 1$)

q is the charge in the sensitive length of the detector

Since $\nabla V = -E$ or $V = -\int E \cdot dr$, the potential between two cylinders is defined by

$$V = V_{ba} = V_b - V_a = -\int_a^b E(r) dr = -\int_a^b \frac{q}{2 \pi K \epsilon_0 \ell} \frac{dr}{r} \quad (2-47)$$

$$= \frac{-q}{2 \pi K \epsilon_0 \ell} \ln(b/a)$$

$$V = -E r \ln(b/a)$$

Figure 2.7: An Approximate Coaxial Cylindrical Detector

Therefore the electric field resulting from application of a high voltage is

$$E(r) = \frac{-V}{r \ln(b/a)} \quad (2-48)$$

The derivative of the electric field as a function of r is

$$\frac{\partial E}{\partial r} = \frac{\partial}{\partial r} \left(\frac{-V}{r \ln b/a} \right) = \left(\frac{-V}{\ln b/a} \right) \frac{\partial}{\partial r} \left(\frac{1}{r} \right) = \frac{-V}{\ln b/a} \left(\frac{-1}{r^2} \right) = \frac{-E}{r} \quad (2-49)$$

Applying the above to the one-dimensional geometry of the charge transport equations results in

$$\begin{aligned} \frac{\partial n^-}{\partial t} = N_0(t) - \frac{\mu^+}{p} \left[\frac{-V(t)}{r \ln(b/a)} \left(\frac{\partial n^-}{\partial r} \right) - \cancel{\frac{n^- E}{r}} + \cancel{\frac{n^- E}{r}} \right] \quad (2-50) \\ + D^- \left(\frac{\partial^2 n^-}{\partial r^2} + \frac{1}{r} \frac{\partial n^-}{\partial r} \right) - \alpha(n^-)(n^+) \end{aligned}$$

or

$$\begin{aligned} \frac{\partial n^-}{\partial t} = D^- \left(\frac{\partial^2 n^-}{\partial r^2} \right) + \left(-\frac{\mu^-}{p} \frac{V(t)}{\ln(b/a)} + D^- \right) \left(\frac{1}{r} \right) \left(\frac{\partial n^-}{\partial r} \right) \quad (2-51) \\ - \alpha(n^+)(n^-) + N_0(t) \end{aligned}$$

and similarly

$$\begin{aligned} \frac{\partial n^+}{\partial t} = D^- \left(\frac{\partial^2 n^+}{\partial r^2} \right) + \left(\frac{\mu^+}{p} \frac{V(t)}{\ln(b/a)} + D^+ \right) \left(\frac{1}{r} \right) \left(\frac{\partial n^+}{\partial r} \right) \quad (2-52) \\ - \alpha(n^+)(n^-) + N_0(t) \end{aligned}$$

2.2.4 Charge Collection

General Consideration of Charge Collection, and Current Density Using Maxwell's Equations

The presence of an electric field affects the charge density or the ionization in the ionization chamber. In the case of large number of charges, and very rapid change in flux, the electric field encountered by the ions is modified as predicted by Maxwell's equations. Using Maxwell's equations, one can determine the time varying (dependent) electric field. Generalized Maxwell's equations, however, were not solved, due to complexity in the solution in the computer simulation. However, only a simplified representation of Maxwell's Equations was considered in this study. One can also find the current density, charge density, and etc. by using Maxwell's equations.

The general Maxwell's equations are:

$$\text{curl } \vec{E} = \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} = -\mu \frac{\partial \vec{H}}{\partial t} \quad (2-53)$$

$$\begin{aligned} \text{curl } \vec{H} = \nabla \times \vec{H} &= \frac{\partial \vec{D}}{\partial t} + \vec{J}_F = \epsilon \frac{\partial \vec{E}}{\partial t} + \vec{J}_F \\ &= \epsilon \frac{\partial \vec{E}}{\partial t} + \sigma \vec{E} \end{aligned} \quad (2-54)$$

$$\text{Div } \vec{B} = \nabla \cdot \vec{B} = 0, \quad \text{or } \text{Div } \vec{H} = \nabla \cdot \vec{H} = 0, \quad (2-55)$$

$$\text{Div } \vec{E} = \nabla \cdot \vec{E} = \frac{\rho}{\epsilon} = \frac{e(n^+ - n^-)}{\epsilon} \quad (2-56)$$

where:

$$\vec{D} = \epsilon \vec{H} \quad (2-57)$$

$$\vec{B} = \mu \vec{H} \quad (2-58)$$

J_F = that part of current density J which varies with field

$$= \text{Free current density} = \sigma \vec{E} = \rho \vec{w} \quad (2-59)$$

$$= e(n^+ \vec{w}^+ - n^- \vec{w}^-)$$

$$= \rho^+ \vec{w}^+ - \rho^- \vec{w}^-$$

$$\rho^+ = en^+ \quad (2-60)$$

$$\rho^- = en^- \quad (2-61)$$

$$\rho = e(n^+ - n^-) = \text{charge density (or space charge distribution)} \quad (2-62)$$

ϵ = dielectric permittivity of gas

μ = magnetic permeability of gas

σ = gas conductivity (is not constant due to radiation charges)

$\vec{E}$ = electric field intensity

$\vec{B}$ = magnetic flux density

$\vec{D}$ = electric flux density, electric displacement

$\vec{H}$ = magnetic field intensity

Taking the curl of Equation (2-54); we obtain

$$\begin{aligned} \nabla \times (\nabla \times \vec{H}) &= \epsilon \frac{\partial}{\partial t} (\nabla \times \vec{E}) + \sigma (\nabla \times \vec{E}), \\ &= \epsilon \frac{\partial}{\partial t} (\nabla \times \vec{E}) + \nabla \times \vec{J}_F. \end{aligned} \quad (2-63)$$

Substituting for $\nabla \times \vec{E}$ from Equation (2-53) and transposing

$$\begin{aligned} \nabla \times (\nabla \times \vec{H}) &= \epsilon \frac{\partial}{\partial t} \left(-\mu \frac{\partial \vec{H}}{\partial t} \right) + \sigma \left(-\mu \frac{\partial \vec{H}}{\partial t} \right), \\ &= \epsilon \frac{\partial}{\partial t} \left(-\mu \frac{\partial \vec{H}}{\partial t} \right) + \nabla \times \vec{J}_F. \end{aligned} \quad (2-64)$$

or equivalently

$$\nabla \times \nabla \times \vec{H} + \mu\epsilon \frac{\partial^2 \vec{H}}{\partial t^2} + \mu\sigma \frac{\partial \vec{H}}{\partial t} = 0.$$

$$\nabla \times (\nabla \times \vec{H}) + \mu\epsilon \frac{\partial^2 \vec{H}}{\partial t^2} + \nabla \times \vec{J}_F = 0 \quad (2-65)$$

A similar approach for Electric Field results in

$$\nabla \times (\nabla \times \vec{E}) + \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} + \mu\sigma \frac{\partial \vec{E}}{\partial t} = 0.$$

$$\nabla \times (\nabla \times \vec{E}) + \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} + \epsilon\mu \frac{\partial}{\partial t} (n^+ \vec{w}^+ - n^- \vec{w}^-) = 0. \quad (2-66)$$

Now by making the use of the vector identity

$$\nabla \times (\nabla \times \vec{A}) = \nabla(\nabla \cdot \vec{A}) - \nabla^2 \vec{A}$$

and the use of Maxwell's 3rd and 4th equations (2-55, 2-56) we can write

$$\nabla(\nabla \cdot \vec{H}) - \nabla^2 \vec{H} + \mu\epsilon \frac{\partial^2 \vec{H}}{\partial t^2} + \mu\sigma \frac{\partial \vec{H}}{\partial t} = 0.$$

$$= 0$$

$$-\nabla^2 \vec{H} + \mu\epsilon \frac{\partial^2 \vec{H}}{\partial t^2} + \nabla \times \vec{J}_F = 0. \quad (2-67)$$

Similarly:

$$\nabla(\nabla \cdot \vec{E}) - \nabla^2 \vec{E} + \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} + \mu \frac{\partial \vec{J}_F}{\partial t} = 0.$$

$$\parallel$$

$$\rho$$

$$\epsilon$$

$$\nabla \left(\frac{\rho}{\epsilon} \right) - \nabla^2 \vec{E} + \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} + \mu \frac{\partial \vec{J}_F}{\partial t} = 0. \quad (2-68)$$

substituting the following:

$$\rho = e(n^+ - n^-)$$

$$\vec{w}^+ = \mu^+ \frac{\vec{E}}{p}$$

$$\vec{w}^- = \mu^- \frac{\vec{E}}{p}$$

$$\vec{J}_F = e(n^+ \vec{w}^+ - n^- \vec{w}^-)$$

we have:

$$\frac{e}{\epsilon} \nabla (n^+ - n^-) - \nabla^2 \vec{E} + \mu\epsilon \frac{\partial^2 \vec{E}}{\partial t^2} \quad (2-69)$$

$$+ \frac{\mu e}{p} \frac{\partial}{\partial t} (\mu^+ n^+ \vec{E} - \mu^- n^- \vec{E}) = 0$$

Generally, the above equation, when written in cylindrical coordinates is separated into three equations; one for each spatial variable, r , θ , and z . But since the dimensions of the detector are much smaller than reactor dimension, therefore, in the detector:

(1) the flux is constant in the Z direction, hence

$$E(Z) = \text{constant}$$

(2) flux is isotropic, hence $E(\theta) = \text{constant}$.

As a consequence we can write the above equations in the r coordinate, only, and we have

$$\begin{aligned} \frac{e}{\epsilon} \nabla (n^+_{(r,t)} - n^-_{(r,t)}) - \nabla^2 \vec{E}_{(r,t)} + \mu\epsilon \frac{\partial^2 \vec{E}_{(r,t)}}{\partial t^2} \quad (2-70) \\ + \frac{\mu e}{p} \frac{\partial}{\partial t} \left(\mu^+ n^+ \vec{E}_{(r,t)} - \mu^- n^- \vec{E}_{(r,t)} \right) = 0 \end{aligned}$$

Since all vectors in the above equation are in the same direction (Electric Field), then we can eliminate the vector notation and consider only the magnitude.

$$\begin{aligned} \frac{e}{\epsilon} \nabla \left(n_{(r,t)}^+ - n_{(r,t)}^- \right) - \nabla^2 E_{(r,t)} + \mu \epsilon \frac{\partial^2 E_{(r,t)}}{\partial t^2} \\ + \frac{\mu e}{p} \frac{\partial}{\partial t} \left(\mu^+ n^+ E_{(r,t)} - \mu^- n^- E_{(r,t)} \right) = 0 \end{aligned} \quad (2-71)$$

Now substituting the following operators in cylindrical coordinates (one dimension) for ∇ and ∇^2 we have

$$\nabla A = \frac{\partial A}{\partial r} \quad (2-72)$$

$$\begin{aligned} \nabla^2 A &= \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial A}{\partial r} \right) \\ &= \frac{1}{r} \frac{\partial A}{\partial r} + \frac{\partial^2 A}{\partial r^2} \end{aligned} \quad (2-73)$$

$$\begin{aligned} \frac{e}{\epsilon} \left(\frac{\partial n^+}{\partial t} - \frac{\partial n^-}{\partial t} \right) - \left(\frac{\partial^2 E}{\partial r^2} + \frac{1}{r} \frac{\partial E}{\partial r} \right) + \mu \epsilon \frac{\partial^2 E}{\partial t^2} \\ + \frac{\mu e}{p} \frac{\partial}{\partial t} \left(\mu^+ n^+ E - \mu^- n^- E \right) = 0 \end{aligned} \quad (2-74)$$

The radiation in the chamber causes the production of charge and these charges in the detector cause a current. The production of current causes change in the magnetic and electric field with time. Since the ionization current (CIC current) undergoes only negligible changes of intensity during times of the order of the transient time of an electromagnetic disturbance through the chamber and also since the electric field from the ionization is small compared to that existing from the bias voltage, therefore we

assume that the electric field is constant with time. Thus, there is no need to solve equation (2-74). The justification is also shown by the following analysis:

$$(1) \quad \lambda = \frac{\ell}{c} = \frac{14 \times 2.54 \text{ cm}}{3 \times 10^{10} \text{ cm/sec}} \approx 10^{-9} \text{ sec}$$

where:

ℓ = largest linear dimension of the CIC = 14 inches

c = velocity of light = 3×10^{10} cm/sec.

- (2) Since the variation of magnetic energy is sufficiently small we can ignore it in the energy balance equations which will be discussed later.
- (3) The drift velocities of electrons and positive ions are much smaller than the velocity of light.

For the case of intense and rapid ionization one must normally solve the above Equation (2-74) simultaneously with the charge transport equations and find the electric field. Then we can find the current density, which is the current from transport of positive ions and negative electrons.

CIC Current Response for a Time Independent Electric Field

Starting with Maxwell's third equation (2-55) we have:

$$\nabla \cdot \vec{E}_\rho = \frac{\rho}{\epsilon}$$

where:

$$\frac{\rho}{\epsilon} = \frac{e}{\epsilon} (n^+ - n^-)$$

But since

$$\vec{E}_\rho = -\nabla V_\rho \quad , \quad (2-75)$$

We have

$$\nabla \cdot \nabla V_\rho = -\rho = -\frac{e}{\epsilon} (n^+ - n^-)$$

or

$$\nabla^2 V_\rho = -\rho/\epsilon \quad (2-76)$$

Now consider the detector shown in Figure 2.8.

Figure 2.8: CIC Schematic Diagram

The electric field in the CIC results from two effects: one due to application of high voltage, the other is due to space charge effect. Using the notation $\vec{E}_0$ and $\vec{V}_p$ as the electric field and voltage due to space charge, then the total electric field due to both is:

$$\vec{E}_{\text{total}} = \vec{E}_{\text{H.v.}} + \vec{E}_\rho$$

Thus using the equation (2-77) which is due space charge results,

$$\nabla^2 V_\rho = -\rho/\epsilon = \frac{e}{\rho} (n^+ - n^-), \quad (2-77)$$

where: $V_\rho = 0$ at both electrodes (B.C.),

and equation (2-78) which is due to high voltage results in

$$-\nabla \cdot \vec{E} = \nabla^2 V = 0 \quad (\text{Laplace Equation}) \quad (2-78)$$

where: $V = 0$ at the collecting electrode,
(signal electrode),

and $V = V_0$ at the high voltage electrode.

The electrostatic field energy can be written as

$$\frac{\epsilon}{2} \int_A (\vec{E} + \vec{E}_\rho)^2 dA = \frac{\epsilon}{2} \int_A E^2 dA + \frac{\epsilon}{2} \int_A E_\rho^2 dA + \epsilon \int_A \vec{E} \cdot \vec{E}_\rho dA \quad (2-79)$$

where:

A = chamber sensitive volume.

The last integral in equation (2-79) is

$$\begin{aligned}
 \int_A \vec{E} \cdot \vec{E}_\rho \, dA &= - \int_A \vec{E} \cdot \nabla V_\rho \, dA \quad (\text{vector identity}) \\
 &= - \int_A \nabla \cdot (V_\rho \vec{E}) \, dA + \int_A V_\rho \nabla \cdot \vec{E} \, dA \\
 &= \int_A V_\rho \nabla \cdot \vec{E} \, dA - \int_S V_\rho E_n \, dS
 \end{aligned} \tag{2-80}$$

where:

S = combined surfaced area of the H.V. and signal electrode

E_n = component of electric field perpendicular to S

Since $\nabla \cdot \vec{E} = 0$ and V_ρ (at surface S) = 0,

then,

$$\int_A \vec{E} \cdot \vec{E}_\rho \, dA = 0 \tag{2-81}$$

then the total electrostatic energy is:

$$W_{\text{total}} = W + W_\rho = \frac{\epsilon}{2} \int_A (\vec{E} + \vec{E}_\rho)^2 \, dA. \tag{2-82}$$

where, W is electrostatic energy due to application of high voltage

and, W_ρ is electrostatic energy due to space charge.

Now using the principles of conservation of energy we have:

$$e \int_A (\vec{E} + \vec{E}_\rho) \cdot (n^+ \vec{w}^+ - n^- \vec{w}^-) \, dA + \underbrace{\frac{dW_\rho}{dt}}_{\text{electrostatic variation}} = V_o I \tag{2-83}$$

$\frac{dW}{dt} = 0$. (The variation in the electrostatic energy corresponding to $E = 0$, since E was assumed to be time independent)

Since we have the relation:

$$\int_A \nabla \cdot \left(v_\rho (n^+ \vec{w}^+ - n^- \vec{w}^-) \right) dA = 0, \quad (2-84)$$

$$\text{and } \int_A \nabla \cdot v_\rho \frac{\partial \vec{E}_\rho}{\partial t} dA = 0, \quad (2-85)$$

where $v_\rho = 0$ at surface S ,

then:

$$\int_A \vec{E}_\rho \cdot (n^+ \vec{w}^+ - n^- \vec{w}^-) dA = \int_A v_\rho \nabla \cdot (n^+ \vec{w}^+ - n^- \vec{w}^-) dA \quad (2-86)$$

$$\int_A \vec{E}_\rho \cdot \frac{\partial \vec{E}_\rho}{\partial t} dA = \int_A v_\rho \nabla \cdot \left(\frac{\partial \vec{E}_\rho}{\partial t} \right) dA = \frac{1}{\epsilon} \int_A v_\rho \frac{\partial \rho}{\partial t} dA. \quad (2-87)$$

Energy due to an electric field is given by,

$$W_\rho(t) = \int_A \frac{\epsilon}{2} (\vec{E}_\rho)^2 dA$$

therefore,

$$\frac{\partial W_\rho}{\partial t} = \epsilon \int_A \vec{E}_\rho \cdot \frac{\partial \vec{E}_\rho}{\partial t} dA \quad (2-88)$$

and

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$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \left(e(n^+ \vec{w}^+ - n^- \vec{w}^-) \right) \quad (2-89)$$

From equations (2-86) to (2-89) it can be concluded that:

$$e \int_A \vec{E} \cdot (n^+ \vec{w}^+ - n^- \vec{w}^-) dA + \frac{\partial W}{\partial t} = 0. \quad (2-90)$$

Subtracting above equation from the equation we have:

$$I = \frac{e}{V_0} \int_A \vec{E} \cdot (n^+ \vec{w}^+ - n^- \vec{w}^-) dA \quad (2-91)$$

Substituting for dA , the volume element in the cylindrical coordinates:

$$dA = r dr d\theta dz \quad (2-92)$$

$$I = \frac{e}{V_0} \int_0^{2\pi} \int_0^{\ell} \int_a^b \vec{E} \cdot (n^+ \vec{w}^+ - n^- \vec{w}^-) r dr d\theta dz \quad (2-93)$$

$$= \frac{e}{V_0} (2\pi \ell) \left(\int_a^b r n^+ \vec{E} \cdot \left(\frac{\mu^+}{p} \vec{E} \right) dr \right. \\ \left. + \int_a^b r n^- \vec{E} \cdot \left(\frac{\mu^-}{p} \vec{E} \right) dr \right)$$

or:

$$I = \frac{2\pi e \ell}{p(V(t))} \left(\mu^+ \int_a^b r (n^+ E^2) dr + \mu^- \int_a^b r (n^- E^2) dr \right) \quad (2-94)$$

where:

ℓ = detector length (sensitive)

Using a summation instead of an integral yields

$$I(t) = \frac{2\pi e \ell}{p \cdot V(t)} \left(\mu^+ \sum_i (n_i^+ (t)) (E^2) (r_i) (\Delta r) \right. \quad (2-95)$$

$$\left. + \mu^- \sum_i (n_i^-) (E^2) (r_i) (\Delta r) \right)$$

Equation (2-95) indicates that the CIC current is due to both positive ions and electrons. This current is a function of CIC physical dimension, gas pressure, applied voltage, electric field, mobility of positive ions and electrons in the gas, and density of positive ions and electrons in the sensitive volume of the detector. Thus, by using equation (2-95) the CIC current as a function of time is obtained.

2.3 The Effect of the Measuring System RC Network on the Detector Dynamic

The CIC current generated upon radiation must then be transmitted to a measuring system via a coaxial cable. The measuring system can

be: Pico ammeter, electrometer, current amplifier, or an oscilloscope. The cable itself can introduce error or dynamic change in the CIC current. Figure 2.9 shows the block diagram of the overall system.

2.3.1 Transmission Line

Transmitting the current from the source to the measurement system is done via a transmission line. The transmission line is modelled as a coaxial cable since a coaxial cable is typically used in a plant installation.

A coaxial cable can in general be modelled as distributed parameters (partial differential equation) as shown in Figure 2.10. Figure 2.11 shows an approximate model suitable for low frequencies in which the parallel conductance has been neglected.

If the length of cable is not too long, and frequency is not too high, the inductance can also be neglected. The cable model is shown in Figure 2.12 in which C and R are the total capacitance between the source and receiving end, and resistance of both conductors, respectively.

For coaxial cable the capacitance per foot can be calculated from either of the following equations.

$$C_1 = \frac{7.36 \epsilon_r}{\log_{10}(D/d)} \quad (2-96)$$

$$C_2 = 1016 \frac{\epsilon_r}{Z_o} = \frac{1016}{V_p Z_o} \quad (2-97)$$

Figure 2.9: Block Diagram of overall System

Where: C' = Capacitance/Cable Length
 L' = Inductance/Cable Length
 R' = Resistance/Cable Length
 g' = Conductance/Cable Length

Small Cable Length

Figure 2.10: Equivalent Circuit of a Coaxial Cable

Figure 2.11: Cable Model for Low Frequencies

Figure 2.12: Cable Model for short cable length
at low Frequencies

where:

ϵ_r = dielectric constant of transmission line insulation

V_p = Propagation velocity

Z_0 = source impedance of transmission line in ohms

C_1, C_2 = line capacitance in pF/ft

D = diameter of the inner surface of outer coaxial conductor

d = diameter of center conductor

Table 2.3 shows the specifications for different coaxial cables.

In the above table (2.3) ϵ_r , dielectric constant was calculated by knowing the manufacturer's specification on propagation velocity as (see Table 2.4)

$$V_p = \frac{100}{\sqrt{\epsilon_r}} \quad . \quad (2-98)$$

Thus, the total capacitance of the cable used using equations (2-96), (2-97), and (2-98) can be calculated. The result is shown in Table 2.5.

For the solid and tubular copper conductors used in the coaxial cables the series resistance can be calculated from

$$R = 0.1 \sqrt{f} \left(\frac{1}{d} + \frac{1}{D} \right) , \quad (2-99)$$

TABLE 2.3

Cable Capacitance(per ft)

Coaxial Cable Type	Z_o (ohm)	ϵ_r	D (inches)	d (inches)	C_1 (pF)	C_2 (pF)	C_3 (pF)
RG 71B/U	93	1.42	0.146	0.0253	13.73	13.01	13.5
RG 58A/U	50	2.30	0.120	0.0375	33.51	30.79	29.5
RG 62A/U	93	1.42	0.151	0.025	13.38	13.01	13.5

where: C_1 = Capacitance using Equation (2-96)

C_2 = Capacitance using Equation (2-97)

C_3 = Capacitance from cable specification

Table 2.4: Parameters of Different Cables

Cable type	V_p (%C)	$\sqrt{\epsilon_r}$	ϵ_r
RG 71B/U	84	1.19	1.42
RG 58A/U	66	1.52	2.30
RG 62A/U	84	1.19	1.42

Table 2.5: Total Cable Capacitance

Cable Type	Cable Length Used (ft)	Capacitance Per ft. (pF)	Total Capacitance (pF)
RG 71B	60.	13.5	810.
RG 58A	20.*	29.5	590.
RG 62A	20.*	13.5	270.

*Estimated

where:

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f: frequency in MHz

d and D: as defined previously in ft

R: cable resistance/100 ft .

For 60 ft of cable and frequency of 60 HZ, R is calculated and shown in Table 2.6.

TABLE 2.6

CABLE RESISTANCE

Coaxial Cable Type	D (inches)	d (inches)	R/100 ft (ohm)	R/60 ft (ohm)
RG				
71 B/V	0.146	0.0253	0.431	0.259
RG				
58 A/V	0.120	0.0375	0.325	0.195
RG				
62 A/V	0.151	0.025	0.433	0.260

Since the cable resistance is very small for the 60 ft of cable used, it can be neglected.

The Bandwidth of the Tektronics model (R 7912 A-D) Transient Waveform Digitizer (with 7813 A plug-in) used for X-ray experiments in the LINAC, and the Hewlett-Packard Oscilloscope Model (1741 A) used for other experiments at the OSU Research Reactor are both approximately 100 MHz. This frequency Bandwidth corresponds to a rise time estimated from the following

$$tr_{\max} = \frac{1.1 \text{ sec}}{\pi f_o} \quad (2-100)$$

$$tr_{\max} = \frac{1.1 \text{ sec}}{(\pi) (10^9)} = 3.5 \times 10^{-9} \text{ sec} = 3.5 \text{ nsec}$$

This is almost instantaneous compared with the CIC and associated cables.

2.3.3 Equivalent Electrical Circuit of the Detector with Associated Instrumentation

The equivalent circuit of the CIC detector depends on the insulation used, the gas and the geometry of the detector. One electrical circuit based on the actual data supplied for the test detector (by the Reuter-Stokes) is shown in Fig. 2.13. The equivalent circuit for Fig. 2.13 is obtained by shorting the voltage and using a current source to model the detector as shown in Fig. 2.14. Combining the capacitors and resistors in Fig. 2.14 results in the equivalent circuit shown in Fig. 2.15.

Figure 2.13: Electrical Equivalent Circuit of the CIC

Figure 2.14: Equivalent Circuit of the CIC and associated Instrumentations

Figure 2.15: CIC Equivalent Circuit with Associated Electronics

The observed voltage at the oscilloscope is

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$$V = I \cdot Z \quad (2-101)$$

$$= I \cdot \left(R \parallel \frac{1}{sC} \right) = \frac{RI}{RCS + 1}$$

or

$$RC \frac{dV}{dt} + V = RI \quad (2-102)$$

The time dependent voltage is then

$$V(t) = e^{-t/RC} \left(\underset{\substack{\uparrow \\ 0}}{\cancel{V(0)}} + \frac{1}{C} \int_0^t e^{t_1/RC} I(t_1) dt_1 \right) \quad (2-103)$$

(RC non-zero)

Any cable degradation can be modeled by modifying the capacitor value C (C is the effective capacitance of the detector, cable, and measurement system).

2.4 Random Signal Analysis Techniques for Detector Response Measurement

The possibility of using random signal analysis techniques to determine the transfer function (magnitude plot only) of a reactor system was first suggested by Moore [18] and verified experimentally by Cohn [19]. In this method, the power spectral densities (PSD) of the input and output of a system were measured.

The general relation between the PSD's of the input (random) and output of any linear, constant coefficient system is [20]

$$\Phi_y(\omega) = |W(j\omega)|^2 \Phi_x(\omega), \quad (2-104)$$

where $\phi_y(\omega)$ and $\phi_x(\omega)$ are the PSD's of the output and input respectively, and $|W(j\omega)|$ is the magnitude of the transfer function with the Laplace variable replaced by $j\omega$.

The PSD's of a system with more than one input can be treated as linear functions and superimposed as

$$\phi_x(\omega) = \sum_{i=1}^N \phi_{x_i}(\omega), \quad (2-105)$$

$$\text{where } x(t) = \sum_{i=1}^N x_i(t).$$

In the following paragraphs, the application of the above relations to determine the frequency response will be demonstrated.

In the neutron detection system, there are three sources of noise as shown in Fig. 2.16 (these sources can be either random or deterministic). Let $W(j\omega)$ represent the transfer function of the reactor (including vibrations, feedback, etc.), and $W_d(j\omega)$ represent the dynamic characteristics of the instrumentation system (detector, FFT analyzer, etc.). Assume $x(t)$ is the reactor random disturbance in the fission rate, rod, source fluctuations, coolant movement rate, or any other random fluctuations within the reactor. Then define $y(t)$ as the observed current response from the CIC.

Because of the random nature of the absorption of neutrons in the detector, assume that the observed current response from the detector is affected by both $n(t)$, the input noise source of the instrumentation system, and $m(t)$, the random fluctuations of the detection process.

The block diagram of the system is shown in Figure 2.16.

Figure 2.16: Block Diagram of a Reactor and Neutron Detection Instrumentation System

Application of Equation 2.104 and 2.105 to the system in Figure 2.16 gives

$$\phi_{yy}(\omega) = \phi_{nn}(\omega) |W_d(j\omega)|^2 + \phi_{xx}(\omega) |W_d(j\omega)|^2 |W(j\omega)|^2 + \phi_{mm} \quad (2-106)$$

Since the fission and detection processes are both random, then $\phi_{nn}(\omega)$ and $\phi_{xx}(\omega)$ are constants in the frequency range of interest (less than 100 kHz). However, ϕ_{mm} is not constant, and sometimes appears as spikes in the frequency range of interest (e.g., EM pickup or 60 Hz and its harmonics).

Let $\phi_{nn}(\omega) = A$, and $\phi_{xx}(\omega) = B$, then

$$\phi_{yy}(\omega) = A |W_d(j\omega)|^2 + B |W_d(j\omega)|^2 |W(j\omega)|^2 + \phi_{mm}(\omega). \quad (2-107)$$

Factoring $|W_d(j\omega)|^2$ results in

$$\phi_{yy}(\omega) = |W_d(j\omega)|^2 (A + B |W(j\omega)|^2) + \phi_{mm}(\omega). \quad (2-108)$$

Solving for $|W_d(j\omega)|$

$$W_d(j\omega) = \left[\frac{\phi_{yy}(\omega) - \phi_{mm}(\omega)}{A + B |W(j\omega)|^2} \right]^{1/2}. \quad (2-109)$$

Since the unknown sources usually appear as spikes in the PSD,

$$\phi_{yy}^*(\omega) = \phi_{yy}(\omega) - \phi_{mm}(\omega) \quad (2-110)$$

can be defined as the modified PSD. It is basically the PSD without spikes. The spikes can be detected by recording the PSD without any input to the FFT.

Since there are no more "break points" in the frequency response of the reactor after 15 Hz, any break point in the modified PSD is due to the detector and associated instrumentation.

In the experiments performed using noise analysis technique (see Chapter 3), since the power spectrum (PS) and PSD are only different in magnitude (PSD = PS/frequency), only the PS is recorded and investigated for the instrumentation break points.

2.5 Mathematical Simulation Using CSMP

2.5.1 Difference Equations and CSMP Solutions to the Space Charge Transport Equations

In system modelling, the charge transport equation (2-42, and 2-43) which is a parabolic equation, was solved simultaneously by a technique developed by Cheng [14]. In this method the space dependence of the equations are written as difference equations (Explicit method) and are solved simultaneously using CSMP (Continuous System Modelling Program III). In CSMP, the method of RKXFS (Fourth-order Runge-Kutta with Fixed Interval) is used.

Using the central difference for the first and second derivative with respect to r :

$$\left. \frac{\partial f}{\partial r} \right|_i = \frac{f_{i-1} - f_{i+1}}{2\Delta r} + O(\Delta r)^2 \quad (2-111)$$

$$\left. \frac{\partial^2 f}{\partial r^2} \right|_i = \frac{f_{i-1} - 2f_i + f_{i+1}}{(\Delta r)^2} + O(\Delta r)^2 \quad (2-112)$$

By referring to Fig. 2.17 we can assume that the number of Positive ions on the signal Electrode ($r=a$) to be maximum and to be zero (or negligible) on the H.V. Electrode ($r=b$). We can assume that the number of electrons on the signal Electrode ($r=a$) to be zero (or negligible) and to maximum on the H.V. Electrode ($r=b$). These assumptions determine our initial conditions and boundary conditions

$$\underline{\text{I.C.:}} \quad n_1^+ \Big|_{t=0} = n_1^- \Big|_{t=0} = 0.0 \quad (2-113)$$

$$\underline{\text{B.C.:}} \quad \frac{\partial n_1^+}{\partial r} \Big|_{r=a} = 0. \quad \frac{\partial n_1^-}{\partial r} \Big|_{r=b} = 0. \quad (2-114)$$

or

or

$$\frac{\partial n_1^+}{\partial r} \Big|_{i=1} = 0. \quad \frac{\partial n_1^-}{\partial r} \Big|_{i=10} = 0.$$

Applying the Difference equation results in

$$\frac{n_1^+ - n_2^+}{\Delta r} = 0 \quad \Rightarrow \quad n_1^+ = n_2^+ \quad (2-115)$$

$$\frac{n_{10}^- - n_9^-}{\Delta r} = 0 \quad \Rightarrow \quad n_9^- = n_{10}^- \quad (2-116)$$

Figure 2.17: Boundary Conditions of the Charge Transport Equations

Also:

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$$n_{10}^+ = n_1^- = 0.0.$$

The charge transport equations becomes of ordinary differential equations as follows:

$$\begin{aligned} \frac{dn_i^-}{dt} = & D^- \left(\frac{n_{i-1}^- - 2n_i^- + n_{i+1}^-}{(\Delta r)^2} \right) + \\ & + \left(\frac{-\mu^-}{p} \frac{v(t)}{\ln(b/a)} + D^- \right) \left(\frac{1}{a+(i-1)(\Delta r)} \right) \left(\frac{n_{i+1}^- - n_{i-1}^-}{2\Delta r} \right) \\ & - \alpha(n_i^-)(n_i^+) + N_o(t) \end{aligned} \quad (2-117)$$

$$\begin{aligned} \frac{dn_i^+}{dt} = & D^+ \left(\frac{n_{i-1}^+ - 2n_i^+ + n_{i+1}^+}{(\Delta r)^2} \right) + \\ & + \left(\frac{-\mu^+}{p} \frac{v(t)}{\ln(b/a)} + D^+ \right) \left(\frac{1}{a+(i-1)(\Delta r)} \right) \left(\frac{n_{i-1}^+ - n_{i+1}^+}{2\Delta r} \right) \\ & - \alpha(n_i^-)(n_i^+) + N_o(t) \end{aligned} \quad (2-118)$$

where $2 \leq i \leq 9$

The value of i defines the number of grids (the number of equations). The maximum value of i can be chosen to be any number, depending on the accuracy desired; the larger i , the more accurate the results and the more computer time (\$).

In this simulation i was chosen to be 10 nodes, two of which were boundary conditions.

For those cases, where the electron drift velocity in the gas is not a linear function of electron mobility it is best to use the experimental values of the electron drift velocity. The charge transport equation for positive ions is the same as before but for electrons the equation is

$$\frac{\partial n^-}{\partial t} = N_0 - \left[\left(\frac{\partial n^-}{\partial r} w^- + \frac{\partial w^-}{\partial r} n \right) + \frac{n^- w^-}{r} \right] + D^- \left[\frac{\partial^2 n^-}{\partial r^2} + \frac{1}{r} \frac{\partial n^-}{\partial r} \right] - \alpha n^- n^+, \quad (2-119)$$

or equivalently

$$\begin{aligned} \frac{\partial n^-}{\partial t} = D^- \left(\frac{\partial^2 n^-}{\partial r^2} \right) + (-w^- + D^-/r) \frac{\partial n^-}{\partial r} - n^- \left(\frac{w^-}{r} + \frac{\partial w^-}{\partial r} \right) - \alpha(n^+)(n^-) \\ + N_0. \end{aligned} \quad (2-120)$$

Using the central difference for first and second derivatives with respect to r results in

$$\begin{aligned} \frac{dn_i^-}{dt} = D^- \left(\frac{n_{i-1}^- - 2n_i^- + n_{i+1}^-}{(\Delta r)^2} \right) + (-w_i^- + D^-/(a + (i-1)\Delta r)) \left(\frac{n_{i+1}^- - n_{i-1}^-}{2\Delta r} \right) \\ - n_i^- \left((w_i^-/(a + (i+1)\Delta r)) + \left(\frac{w_{i+1}^- - w_{i-1}^-}{2\Delta r} \right) \right) \\ - \alpha(n_i^-)(n_i^+) + N_0(t). \end{aligned} \quad (2-121)$$

2.5.2 Verification of Different Constants in the Theoretical Model for Different CIC Fill Gases

In the model, several constants are necessary and important for computer simulation. In order to compare the theoretical model with the experimental results, one must use the most accurate constants.

The purpose in evaluating these data is to eliminate the discrepancy that exists from different sources and to use the most common values.

Heavy Ion Diffusion Coefficients and Mobilities for Different CIC Gas-fill

For the heavy ions of different gases, the mobility and diffusion coefficients will be evaluated from different sources [9, 23, 11]

Generally, the drift velocity of the heavy ions can be evaluated using the relation

$$\omega_+ = \mu_+(E/p), \quad (2-122)$$

where ω_+ is the drift velocity of positive ions in cm/sec, μ_+ is mobility of positive ions in $\text{cm}^2\text{-mm Hg/volt-sec}$ (similar equation for negative ions), E is the electric field in volt/cm, and p is the gas pressure in mm Hg.

However, in ANL-5800 [9], the drift velocity is evaluated using a different definition of mobility, which is

$$\omega_+ = \mu'_+(E/p') \quad (2-123)$$

where p' is the gas pressure in atmospheres and μ'_+ is the mobility in $\text{cm}^2/(\text{volt-sec-mm Hg})$, and the other terms are the same as before. The values for mobility using the above definition are shown in ANL-5800. To compare the two values of mobility, one must multiply the values of mobilities shown in ANL-5800 by 760.

Table 2.7 lists the mobilities and diffusion coefficients from different sources. The values of the mobilities presented by von Engel [23] are used in the model. It should be noted here that the formation of negative ions for the pure gases such as Nitrogen and Xenon is a rare process [23], and if they form, their mobility is approximately the same as the mobility of positive ions [9,23].

The mobility of the ion itself is the function of (E/p) . This is shown in Figure 2.18. For the E/p of interest, it is a constant.

The diffusion coefficient for the positive ions can be evaluated using the mobility and Equation 2-18 in Section 2.2.3.

The Electron Drift Velocity and Diffusion Coefficient for Different CIC Fill Gases

The electron drift velocity, just like the ion drift velocity, can be evaluated by [11]

$$W_{e-} = \mu_{e-}(E/p) \quad (2-124)$$

where μ_{e-} is the mobility and W_{e-} is the drift velocity of the electrons. The quantity μ_{e-} varies with the type of gas; in addition, it depends strongly on both the electric field strength and gas pressure. The above relation does not strictly hold for a constant μ_{e-} . The author believes there is a better general expression for the drift velocity. This expression is

$$W_{e-} = \mu_{e-}(E/p)^m \quad (2-125)$$

where m (m is usually about $\frac{1}{2}$ in the range of weak electric field) and μ_{e-} can be evaluated for different gases using a curve fitting technique.

Table 2.7: Comparison of the Diffusion Coefficients and Mobility of Heavy Ions at NTP

		ANL-5800 (p.690), 1959				Ionized Gases, von Engelm 1965		International Critical Tables, Vol.VI, 1929	
		cm ² /sec		cm ² /volt (sec)(mm Hg)		cm ² -mm Hg /volt-sec		cm ² -mm Hg /volt-sec	
				μ ₊ [']	μ ₋ [']				
GAS	ION	D ₊	D ₋	(μ ₊ /760)	(μ ₋ /760)	μ ₊	μ ₋	μ ₊	μ ₋
	N ₂								
N ₂	or	0.030	0.041	2.6	-	2000	-	980	1380
	N ₄			(μ ₊ =1976)					
Xe	Xe	0.016	-	0.58	-	440	-	-	-
				(μ ₊ =440)

Figure 2.18: Mobility of gas ions as a function of the reduced field X/p at 1 atm and 0°C [23]

Due to the flexibility in computer simulation in CSMP (using an arbitrary function generator), the experimental data for the drift velocity as a function of E/p were used for the purpose of simulation.

Figures 2.19 through 2.21 show the experimental values for the electron drift velocity in Nitrogen as a function of X/p (defined previously E/p). Figure 2.22 shows the electron drift velocity in Xenon as a function of X/p . Figure 2.23 shows the drift velocity of electrons as a function of reduced electric field for different gases. The comparison of the electron drift velocities in different gases is shown in Table 2.8.

The electron diffusion coefficient for different fill gases was not found in the literature. Therefore, it was decided to calculate it using the equation suggested by Engel [23]. The diffusion coefficient for electrons can be obtained by using the equation (for mostly molecular gases)

$$D_e = \left(\frac{K T_e}{e} \right) K_e , \quad (2-126)$$

where: T_e = electron temperature

K = Boltzman constant = 8.61707×10^{-5} eV/°K

and K_e = mobility coefficient

Referring to table 2.8, the value of X/P is between 1.95 and 2.20 V/cm-mm Hg for the N_2 -filled CIC. Now using Figure 2.24, T_e is estimated to be about one eV or equivalently 7740 °K.

The electron drift velocity for N_2 can be estimated to be approximately:

Figure 2.19: Drift velocity of electrons in Nitrogen as a function of X/p . Theoretical curves are shown for comparison [25]

Figure 2.20: Drift velocity of electrons as a function of E/p in H_2 and N_2 [15]

Figure 2.21: Drift velocity of electrons measured at $p_0 = 653$ mm Hg. Comparison is made with measurements of Nielsen and of Bortner et al. All data in this figure and subsequent figures are normalized to 0°C . Space-charge distortion of the electric field is estimated to be greater than 1% for values of E/p_0 smaller than that indicated by the vertical line in this figure [27].

Figure 2.22: Drift velocity of electrons measured at $p_0 = 267$ mm Hg. Comparison is made with measurements (open circles) of English and Hanna [27].

Figure 2.23: Drift velocity v_d of electrons as a function of the reduced field X/p for different gases [23].

Table 2.8: Comparison of the Electron Drift Velocities for Different CIC fill gases [25]

Detector Gas Filling	Gas Pressure (atm)	X/P V/cm-mm Hg		Drift Velocity (V/cm)	Drift Velocity
				at	Under
		at	at	X/P = 2	Pressure
		$R_A = 1''$	$R_B = 1.125''$	(V/cm-mm Hg)	Conditions
N_2	1	2.2	1.95	1.3×10^6	1.3×10^6
Xe	1	0.55	0.49	3.57×10^5	1.79×10^5

Figure 2.24: Electron temperature T_e as a function of the reduced field X/p in various molecular gases at large values of X/p in swarm experiments (low current)(180). 1 eV corresponds here to 7740° K [23].

$$W_e = \mu_e (E/p) = (\mu_e/p) E = K_e E, \quad (2-127)$$

where K_e is the mobility coefficient. For the range of interest of X/p and 760 mm Hg pressure, $K_e \approx 5 \times 10^5 / 760 = 657.89 \text{ cm}^2/\text{volt}$.

The electron diffusion coefficient in Nitrogen gas is

$$\begin{aligned} D_e &= \frac{(8.61707 \times 10^{-5} \text{ eV/}^\circ\text{K})(7740^\circ\text{K})}{e} (657.89 \text{ cm}^2/\text{volt-sec}) \\ &= 438.79 \text{ cm}^2/\text{sec} \end{aligned}$$

The diffusion coefficients for Xenon gas can be calculated from the equation suggested by von Engel [23] which is

$$D_e \approx 2 \times 10^5 \lambda_e \sqrt{T_e} \quad (2-128)$$

where λ_e is the mean free electronic path and T_e is the electron temperature.

The electron temperature for X/p from 0.49 to 0.55 is not available. However, from Figure 2.24, one can conclude that at low values of X/p , the electron energies are almost the same. It is estimated that the Xenon temperature is in the same order of 0.7 eV which corresponds to 5418°K (1 eV corresponds here to 7740°K).

The collision cross-section, Q_e , of electrons for Xenon gas of low energies ($3 \times 10^{-2} \text{ eV}$) is about 130 cm^{-1} (at 1 mm Hg and 0°C) [23]. The mean free electronic path is then calculated from

$$\lambda_e = \frac{1}{Q_e} = \frac{1}{130} = 7.69 \times 10^{-3} \text{ cm}. \quad (2-129)$$

The electron coefficient for diffusion (at 1 mm Hg) is therefore:

$$D_e \approx 2 \times 10^5 (7.69 \times 10^{-3}) (\sqrt{5418}) \approx 1.13 \times 10^5 \text{ cm}^2/\text{sec at 1 mm Hg}.$$

For four atmospheres pressure ($4 \times 760 = 3040$ mm Hg), the coefficient is then

$$D_e \approx 1.13 \times 10^5 / 3040 = 37.251 \text{ cm}^2/\text{sec}.$$

Recombination Coefficients

One of the most common loss mechanisms for ions is the recombination of negative ions and electrons with positive ions. The recombination coefficient for different fill gases is listed in Table 2.9.

The data shown are not very reliable. Generally, the recombination coefficient for different gases decreases with increase in pressure. This reduction is inversely proportional to the square root of pressure for pressures above 1 or 2 atm. Langevin recombination theory [26] also predicts the inverse relationship between pressure and recombination coefficients.

2.5.3 O.S.U. Reactor Scram Response Simulation Using CSMP

In order to simulate the detector response to a reactor scram, the behavior of the neutron flux is simulated using point kinetics. The theoretical flux transient due to a reactor scram is then used as input to the detector model to simulate the detector response. Point kinetics uses a time-dependent reactivity input and predicts the reactor response. The time-dependent reactivity insertion was modeled as free falling rods (gravitational acceleration) opposed by a frictional force proportional to the rod velocity. The

Table 2.9: Recombination Coefficients

Gas	Gas Pressure (atm.)	α in 1 atm. Pressure	α in Appropriate Pressure
N ₂	1	1.5×10^{-6}	1.5×10^{-6}
Xe	4	1.4×10^{-6}	0.7×10^{-6}

$$m \frac{dv}{dt} = -mg - bv \quad (2-130)$$

Solving for $v(t)$:

$$v(t) = -\frac{mg}{b} (1 - e^{-bt/m}) \quad (2-131)$$

Integrating both sides of the above equations results in:

$$X(t) = X_0 + \frac{m^2 g}{b^2} \left(1 - \frac{b}{m} t - e^{-bt/m} \right), \quad (2-132)$$

where:

$$g = 980 \text{ cm/sec}^2$$

$$X_0 = 51 \text{ cm} = \text{Initial position of the control rods}$$

$$m = \text{mass of rods, gm}$$

$$b = \text{friction factor}$$

Defining K as

$$\frac{b}{m} \triangleq K \quad \text{constant} \quad (\text{sec}^{-1})$$

Thus, the position of the control rods as a function of time is

$$X(t) = X_0 + \frac{g}{K^2} (1 - e^{-Kt}) - \frac{g}{K} t. \quad (2-133)$$

From known rod insertion times (OSU Nuclear Reactor Laboratory, control rod system data (see Table 2.10)), K was found. The value of K is found to be 4.88 sec^{-1} .

Table 2.10: OSU Nuclear Reactor Lab Control Rod System data

OSU NUCLEAR REACTOR LAB CONTROL ROD SYSTEM DATA

Operator: Joel M. HatchDate: June 18, 1982Pool Temperature (Pos. 6) 85 °F

A. Magnet Release Time (msec)

T.S. Limit 50 msec

Current Drop	Shim-1	Shim-2	Shim-3
From 60 ma to 20 ma	21.9	32.9	12.8
Notes Adjusted Σ bus to 45 V on safety monitor. This corresponds with approximately 20 ma.			

B. Rod Insertion Times (msec)

T.S. Limit 600 msec

Rod Position (cm)	Shim-1	Shim-2	Shim-3
5	181.4	180.4	180.5
10	230.3	240.4	229.2
30	350.7	362.0	353.8
Upper Limit	489.6	501.9	494.8
Notes Adjusted for 30msec release time			
Adjusted for 35 ms			

C. Minimum Magnet Currents (ma)

Current Measured	Shim-1	Shim-2	Shim-3
Min. Holding	19	21	26
Min. Withdrawal	22	21	28
Min. Pickup	30	28	30.5
Notes (Shim-2): Min. holding and min. withdrawal were at lowest point before safety fault caused a scram ($I_m=0.$).			

D. Rod Drive Time

T.S. Limit 12.7 cm/min

Rod	Direction of Travel	Time (sec)	Speed (cm/min)
Shim-1	Lower Limit to Upper Limit (<u>61.5</u> cm)	333.5	10.98
	Upper Limit to Lower Limit	331.8	11.04
Shim-2	Lower Limit to Upper Limit (<u>61.16</u> cm)	336.3	10.91
	Upper Limit to Lower Limit	333.3	11.01
Shim-3	Lower Limit to Upper Limit (<u>61.02</u> cm)	333.3	10.98
	Upper Limit to Lower Limit	331.9	11.03
Reg. Rod	Lower Limit to Upper Limit (<u>61.15</u> cm)	333.7	10.99
	Upper Limit to Lower Limit	332.5	11.03

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With rod position as a function of time known, reactivity insertion as a function of rod position was modeled. Since the control rod calibration curves shown in Figure 2.25 are plotted on ~~8~~line paper, a quasi-linear equation was used.

Thus,

$$\rho(t) = \rho_{\text{total}} \left[\frac{X(t)}{H} - \frac{\sin \frac{2\pi X(t)}{H}}{2\pi} \right] - \rho_o \text{ total} \quad (2-134)$$

$$\text{where: } \rho_{\text{total}} = 6.29 \% \frac{\Delta K}{K}$$

$$H = 51 \text{ cm}$$

$X(t)$ = position of rods as a function of time
previously defined, cm.

The above equation will give the negative reactivity inserted into the cone as a function of time in the Rod Drop experiment.

Now, using the above reactivity equation in the point kinetic equations, the neutron flux as a function of time can be predicted. The point kinetic equations used to simulate the reactor neutron density are [58]:

$$\frac{dn}{dt} = \frac{\rho - \beta}{\ell} n + \sum_1^6 \lambda_i C_i, \quad (2-135)$$

and

$$\frac{dC_i}{dt} = \frac{\beta_i}{\ell} n - \lambda_i C_i \quad (2-136)$$

O.S.U. REACTOR CONTROL ROD CALIBRATION

Figure 2.25: O.S.U. Reactor Control Rod Calibration

where:

n = neutron density, n/cm^3

t = time, sec

$\beta = \sum_{i=1}^6 \beta_i$ = total delayed neutron fraction

= 0.0076 for the OSU Reactor

ℓ = neutron lifetime = 7×10^{-5} sec for the OSU Reactor

λ_1 = decay constant of the precursor, sec^{-1}

C_1 = precursor density, n/cm^3

Values of λ can be obtained from Reference [58] for the OSU Reactor (U^{235} fuel).

$\lambda_1 = 0.0124 \quad \text{sec}^{-1} \quad \triangleq \quad \text{AL } 1$

$\lambda_2 = 0.0305 \quad \text{sec}^{-1} \quad \triangleq \quad \text{AL } 2$

$\lambda_3 = 0.111 \quad \text{sec}^{-1} \quad \triangleq \quad \text{AL } 3$

$\lambda_4 = 0.301 \quad \text{sec}^{-1} \quad \triangleq \quad \text{AL } 4$

$\lambda_5 = 1.14 \quad \text{sec}^{-1} \quad \triangleq \quad \text{AL } 5$

$\lambda_6 = 3.01 \quad \text{sec}^{-1} \quad \triangleq \quad \text{AL } 6$

Since $\beta_i = \beta \cdot \lambda_i$, the CSMP program can calculate the values of β_i 's. For the CSMP code the β_i 's are defined as

B1, B2, B3, B4, B5, and B6.

Knowing the steady-state reactor power, detector sensitivity, and the measured detector output current one can find the initial

value of the neutron density, n_o . For example, to simulate the rod drop experiment, the initial value of neutron density for the Nitrogen-filled detector is:

$$n_o = \frac{I \text{ amp}}{(6.9 \times 10^{-14} \text{ amp/n/cm}^2\text{-sec})(2.2 \times 10^5 \text{ cm/sec})} \quad (2-137)$$

If we operate the reactor at 10 watts, the value of n_o is calculated to be approximately 159.75 n/cm^3 . The initial values of the precursor densities can then be calculated by having the initial value of the neutron density be:

$$C_{i0} = \frac{\beta_i n_o}{\lambda_i \ell} = C10 \quad (2-138)$$

Integration of the point kinetics equations can easily be done using CSMP. The complete listing of the CSMP program for the OSU reactor scram response (excluding the detector system which was modeled previously) is shown in Appendix F. Notice that the variable names for the program have been changed. The variables and equivalent CSMP are:

$$\beta_1 = B1, \dots$$

$$\lambda_1 = AL1, \dots$$

$$n = AN$$

$$n_o = AN\phi$$

$$C_1 = C1, \dots$$

$$\frac{dC_1}{dt} = C1D, \dots$$

$$C1_o = C1\phi$$

$$x = XP$$

$$\rho = RR$$

$$\rho_{\text{net}} = PP = (PR + PFB)/100$$

$$\rho_{\text{pos. feed back}} = PFB$$

$$\frac{\rho - \beta}{\ell} = AK$$

Notice also that the positive reactivity feed back for the OSU reactor is considered in the programming, even though its contribution is very small.

2.5.4 Simulation Results

In this section, some of the theoretical techniques used to find the CIC detector response time are presented.

One such technique is a step change in flux. In this technique, the flux is suddenly (approximately 20 nsec rise time) changed and the CIC response is obtained. A second technique to obtain the CIC response is a step change in the high voltage power supply. As will be shown later, the step change in flux and high voltage give identical response times. This is due to the fact that the CIC has only one characteristic equation.

The CIC detector is a system with three possible inputs. These inputs are neutrons, Gamma or X-rays, and High Voltage bias. The system output is the CIC current (see Figure 2.26). Since the system has three inputs, the system has three transfer functions. The denominators of all the transfer functions are identical polynomials in s called the Characteristic Polynomial (when set to zero, the system characteristic equation is obtained). Irrespective of which input/output

Transfer Function S : $W_1 = I/A$, $W_2 = I/B$, $W_3 = I/C$

Figure 2.26: General CIC System Block Diagram

pair is considered, we get the same characteristic equation. The CIC response is related to the system characteristic equation in the time domain. Thus, no matter what input/output is chosen, one fundamental response, which is related to the system characteristic equation, is obtained.

In the following sections, the theoretical step change in flux and high voltage bias are simulated using the CSMP program based on the solution of the coupled partial differential equations explained previously (Equations (2-118) and (2-121) and using equations (2-95) and (2-103).

Step Flux Response

In the computer simulation, the system response was obtained using a sudden increase in the neutron flux. The increase in flux was assumed to be a first order system with a response time of less than 20 nsec (the time constant of the first order system was 4 nsec).

Two simulations were performed for the nitrogen-filled CIC; one for a short simulation time (1.5 microseconds) and the other for a longer time (0.5 msec). Figures 2.27 and 2.28 show the two components of the nitrogen-filled CIC response. The first (or fast) component of the response is due to the collection of electrons, and the second (slow) component is due to the collection of positive ions. From the CIC current response, the electron collection time for nitrogen-filled CIC is 320 nsec and the positive ion collection time is 88.5 μ sec (collection time is the time that the response reaches its maximum value). Figures 2.29 and 2.30 show the simulation results for the xenon-filled CIC. The current response shows two break points. The first break point (change in slope) is due to electron collection time and is 4.35 μ sec,

Figure 2.27: Nitrogen-filled CIC response for step change in neutron flux (short simulation time)

Figure 2.28: Nitrogen-filled CIC response for step change in neutron flux (long simulation time)

Figure 2.29: Xenon-filled CIC response for step change in neutron flux (short simulation time)

Figure 2.30: Xenon-filled CIC response for step change in neutron flux (long simulation time)

and the second break point is due to positive ion collection time and is 1.593 msec. It is concluded from these results that xenon-filled CIC has a longer collection time for electrons (the electron and ion collection time in the nitrogen-filled CIC is approximately 14 times faster than in the xenon-filled CIC). The reason is due to the higher drift velocity of electrons in nitrogen-filled CIC as compared to the xenon-filled CIC. The drift velocity of electrons in nitrogen gas (with $E/p \approx 2$ V/cm-mm Hg) is approximately 1.14×10^6 cm/sec; whereas, the drift velocity of electrons in xenon gas (with $E/p \approx 0.52$ V/cm-mm Hg, the difference in E/p is due to change in gas-fill pressure) is approximately 1.34×10^5 cm/sec.

It is also concluded that xenon-filled CIC has a longer positive ion collection time (the positive ion collection time in nitrogen-filled CIC is approximately 18 times faster than in xenon-filled CIC). The principal reason is the higher mobility of the nitrogen positive ions in the nitrogen gas.

Step High Voltage

Similarly, Instead of changing the neutron flux, a CIC response was obtained using a step high voltage input. The high voltage was changed from zero to +500 Volts in less than 20 nsec. However, this time the neutron flux stayed constant. The nitrogen-filled CIC response was obtained using a step high voltage input as is shown in Figures 2.31 and 2.32. From the CIC current response, two break points due to electron and positive ions, similar to those observed in the step flux, were observed. The electron collection time is 315 nsec. This is almost equal to the results obtained by the step flux. The positive ion

Figure 2.31: Nitrogen-filled CIC for step change in High Voltage Bias (short simulation time)

Figure 2.32: Nitrogen-filled CIC for step change in High Voltage Bias (long simulation time)

collection time is 88.5 μsec . This result is identical to the step flux response.

Comparison of the CIC Response for Different Step High Voltage and Neutron Flux

Two other simulations were performed using the CIC model in this section. First, the CIC response was obtained using three different flux levels (see Figure 2.33): 4×10^7 , 2×10^7 , and 1×10^7 nV. The corresponding values of the CIC current were: 5.0211×10^{-6} , 2.5106×10^{-6} , and 1.2553×10^{-6} Amp. This indicates that there is a linear relationship between neutron flux and current. The electron collection time was at 320 nsec for all the cases. This is an indication that the electron collection time does not change with changes in the neutron flux level. Similar results (see Figure 2.34) were obtained using the Xenon-filled CIC. Nevertheless, the Xenon-filled CIC at 500 volt bias voltage is not exactly linear (see Section 4.7). However, since in both detectors, similar partial differential equations were used, the results should be linear.

The effect of high voltage on the CIC response time was studied using different high voltages to the CIC. Figure 2.35 shows this effect. The electron collection time changes with the changes in high voltage bias. This is due to the fact that the drift velocity of electrons changes with the applied electric field (and High Voltage). For 500, 300, and 100 Volt high voltage, the corresponding electron collection times were calculated from corresponding simulations to be 320, 460, and 815 nsec respectively.

Figure 2.33: Effect of neutron flux changes in the Nitrogen-filled CIC response time (short simulation time)

Figure 2.34: Effect of neutron flux changes in the Xenon-filled CIC response time (short simulation time)

Figure 2.35: Effect of High Voltage bias changes on the Nitrogen-filled CIC response time (short simulation time)

The value of the current due to electrons did not change. We conclude here that the CIC rise time changes with high voltage bias.

CHAPTER III

EXPERIMENTAL PROCEDURE

3.1 Introduction

The objectives of the experimental investigation were three-fold. The first objective was to measure the response time of a normal (nitrogen filled) compensated ionization chamber (CIC) using different methods. Experimentally determined response times are necessary to evaluate the dynamic properties of the detector which depend on electrostatic field strength, space charge distributions, electrical properties, and other factors. This objective was accomplished by the methods that are described in the following paragraph.

The second objective was to evaluate and compare different experimental techniques and select a suitable in-situ method to measure and/or monitor the CIC response time. The experimental techniques used to measure the CIC response time are also correlated with the physical and mathematical transient response model.

The third objective was to experimentally evaluate the degradation of CIC response time resulting from changes in detector gas, cable and measurement system. The third objective was accomplished by changing the detector gas from nitrogen at one atmosphere pressure to xenon at four atmospheres pressure, by insertion of a delay box between the CIC and the measurement system, or changing the

characteristic of the measurement system (termination of the measurement system with different capacitors or resistors.

There are several methods commonly used for measuring the transient response of a system. These methods deal with the nature of the time variation of external deterministic and random input signals. The system behavior is investigated by measuring the response in both the time and frequency domain.

The methods utilized in this research were:

- 1) step and impulse response using X-rays generated by a pulsed electron beam from a Varian V-7715A Linear Accelerator (LINAC) and a "target" material.
- 2) Noise analysis using the OSU research reactor and a dual channel Fast Fourier Transform (FFT) analyzer.
- 3) Ramp response (scram) using the OSU research reactor.
- 4) High voltage step response using a mercury-wetted contact relay high voltage switch and the OSU research reactor.
- 5) Sinusoidal frequency response using the OSU research reactor.

The above methods were used with the following detector configurations:

- 1) a normal CIC filled with nitrogen at one atmosphere pressure and standard signal cable;
- 2) a simulated degraded CIC filled with xenon gas pressurized to four atmospheres and standard signal cable;
- 3) a CIC (normal and degraded), a delay box (with a known delay and response time to simulate a degraded signal cable), and signal cable;
- 4) and a CIC (normal and degraded) and a signal cable with different termination resistances and capacitances.

Each method and its respective experimental procedures are described in this Chapter.

3.2 Pulsed X-Ray Experiments: Impulse and Step Response

There are several ways to measure neutron detector transient response time. One method uses pulsed X-rays. The results of this method are used as a comparison with theory and to calibrate other methods.

In order to obtain the step and impulse response of the detector, a controllable neutron, gamma or X-ray source that can be turned on and off very fast (faster than detector response) is required. At OSU an X-ray source generated from high energy electrons is the only source available that can be perturbed fast enough to obtain neutron detector step and impulse response.

Using pulsed X-rays generated by a Linear Accelerator (LINAC) discussed in detail in Appendix A.2, the CIC response time was measured. The CIC was covered by a lead target to convert, via Bremstrahlung, pulsed high energy electrons from the LINAC to pulsed X-rays.

There were two sets of experiments completed using pulsed X-rays. One used the shortest available electron pulse (20 nsec width, measured at half-maximum height of the pulse) and the other used a longer pulse (1 microsecond pulse measured as before). The short pulse was used as an impulse response test, and the long pulse as a step response test. Before performing the pulsed X-ray experiments, predictions were made of the magnitude of the CIC response (using a theoretical model and computer simulations shown in Appendix F).

The impulse and step response experiments were performed for both the normal (nitrogen filled CIC) and degraded (xenon-filled CIC) detector configurations for several different termination circuits and a delay box both introduced to simulate detector and/or cable degradation.

The block diagram of the pulsed X-ray experiments is shown in Fig. 3.1. Photograph of the shielded CIC is shown in Fig. 3.2.

3.3 Noise Analysis Techniques for Reactor Experiments

Another means of testing and monitoring the sensitivity and response time of a neutron detector is analysis of the random nature of the signal from the detector itself, often referred to as noise analysis.

Noise analysis techniques use signal current fluctuations coming from the neutron-sensors output. Since noise analysis can be performed during normal reactor operation, it does not interfere with reactor operation. Therefore, it has potential for in-site detection of gross changes in response time.

The current fluctuations coming from the detector processes can be divided into four categories: zero-power noise, reactivity induced noise, geometric noise, and detector noise [21,22]. Since the detector is within, or reasonably close to, the reactor core, the input to the detector is not white noise, and one must consider the effect of the reactor transfer function with its associated feedbacks [29]. Because the OSU research reactor has a relatively low power (≤ 10 kilowatts), the reactor is essentially a "zero-power reactor", and its dynamic behavior can be characterized by neutron point kinetics

Figure 3.1: Block diagram for Pulsed X-ray Experiments

Figure 3.2: Photograph of the Shielded CIC with Lead in Front of LINAC

equations and detector dynamics [35,36]. This is due to the fact that the power is insufficient to cause significant reactivity feedback effects from changes in temperature, pressure, density, motion etc. The experimental evaluation of the OSU reactor transfer function was made by Walker [35] and Maki [36]. Therefore, the detector dynamics (with associated electronics) can be experimentally determined.

In using noise analysis, the power spectrum (which is related to power spectral density) of discretely sampled current fluctuations from the detector was measured using a Nicolet Model 660A analyzer. The measurement is based on techniques employing the Fast Fourier Transform (FFT) computed by the Nicolet 660 analyzer. The OSU reactor transfer function is known from several sources [35,36], therefore its frequency spectrum (break points) is known. By analyzing only a portion of the power spectrum of the CIC current, the dynamics of the detector systems can be evaluated.

Fig. 3.3 shows a block diagram of the instrumentation used for noise analysis. In these experiments, the CIC was placed in the "dry tube" (see Fig. 3.4) beside the core of the OSU Research Reactor. Several experiments were completed for different frequency ranges of interest, and at different reactor power levels. In addition, many experiments were completed using terminating resistors and capacitors, and a delay box, between the detector and FFT analyzer.

Several experiments were also performed using a Keithley 427 current amplifier, with and without a Krohn-Hite model 3202 variable filter (used as a band pass filter before connecting to the FFT analyzer). The purpose of current amplifier was to study the effect of current

Figure 3.3: Experimental Setup for Noise Analysis Experiments

A - CIF
 B - SOURCE DRIVE
 C - GRAPHITE ELEMENT
 D - FUEL ELEMENT
 E - CONTROL ROD DRIVE
 F - DRY TUBE
 G - RABBIT TUBE
 H - BEAM PORT NO.2
 EXTENSION

I - BEAM PORT NO.1
 EXTENSION
 J - FISSION CHAMBER
 DRIVE
 K - THERMAL COLUMN
 EXTENSION
 L - IONIZATION CHAMBER
 HOUSING

Figure 3.4: OSU Reactor Core Showing Dry Tube

to voltage conversion and amplifying the signal before analysis.

The variable band pass filter was used to investigate only the frequency range of interest. Fig. 3.5 shows the Nicolet FFT 660A analyzer.

3.4 OSU Reactor Ramp (Scram) Response Experiment

One way for determining neutron sensor dynamic behavior is to change the neutron source. This was accomplished by measuring the detector response to a reactor "scram". The neutron flux transient resulting from a "scram" actually appears to the CIC as a ramp change rather than a step change (for detectors whose response is slow compared with the scram transient, it appears as step change).

The experimental set-up shown in Fig. 3.6 was used to obtain the results. The scram response was performed at 10 kw reactor power. The experiment involved externally triggering a transient HP 1741A storage oscilloscope with a logic pulse from a Rod Drop Timer model 71 generated from the scram command of the OSU research reactor. The experiment was repeated for the xenon-filled CIC.

3.5 High Voltage Perturbation Experiments

There were two types of high voltage perturbation experiments completed. The first was a step response using a high voltage mercury wetted relay switch, and the second was a sinusoidal high voltage frequency response. These two different types of experiments are described in this section.

Figure 3.5: Photograph of the Nicolet FFT Analyzer Model 660A

Figure 3.6: Experimental Setup for Ramp (Scram) Response

One method of measuring the detector response time is by perturbing the high voltage power supply to the detector with a rise time faster than the detector response time. In this method, the input high voltage jumps from zero to a constant voltage (in less than 20 nsec), which is then maintained for some time until the detector response reaches a steady-state value. The detector response to such a dynamic input is called the "step" response. The design of the switch to perturb the high voltage bias input to the detector is described in Appendix A.3.

Fig. 3.7 shows the block diagram of the apparatus for the high voltage step response measurements at non-zero reactor power levels. In these experiments, the CIC was placed in the dry tube (see Fig. 3.4) beside the core of the OSU research reactor. To assure uniform irradiation, all the sensitive length of the CIC was placed beside the core by resting the detector on a plastic spacer inside the dry tube. All zero power measurements were completed either with the detector away from the core in the corner of the reactor pool or out of the pool, to assure zero neutron and gamma flux (for the case of the xenon-filled CIC, zero flux was not possible due to the radioactivity of the detector itself).

In the majority of the studies the high voltage was perturbed from zero to 500 volts D.C. The measurements can be made at different repetition rates, by changing the frequency of the sine wave voltage applied to the relay coil, for different detectors. If the response of the detector is slow, a slower repetition rate is chosen to assure that the steady-state is reached before switching the high

Figure 3.7: Experimental Setup for the High Voltage Step Response Measurements Using High Voltage Mercury-Wetted Contact Relay Switch

voltage to zero (the high voltage must stay constant until the detector response reaches steady-state value). Most of the measurements for the CIC were made at 60 Hz (period is about 16.6 m sec). Sometimes, to assure minimum "bouncing" of the mercury relay, the lowest possible frequency is desirable.

The signal from the CIC was tested with different termination resistors and capacitors to study their effect on the response. Cable degradation was investigated by placing a delay box between the CIC and oscilloscope. The above measurements were completed for both a nitrogen and xenon-filled CIC to study detector degradation.

3.5.2 Sinusoidal High Voltage Frequency Response Experiment

One method of obtaining the detector low frequency transfer function is by measuring its sinusoidal frequency response. The response to a sinusoidal input is particularly useful, since different frequencies (of interest) can be selected to investigate the system dynamic behavior at those frequencies. The lower frequencies are selected to investigate slower response and higher frequencies for faster response. The oscillation frequency of the input sine wave is limited by the apparatus used in the experiment. In this investigation the highest frequency that could be achieved was 20 KHZ.

The response to sinusoidal input is called the frequency response and is completely described by the amplitude ratio of the output to input high voltage and the phase angles between these two sine waves for all frequencies.

As is explained in the previous chapters, the detector has two inputs: high voltage, and radiation. Sinusoidal frequency response can be measured in two ways: one using a sinusoidal high voltage input and the other, using a sinusoidal radiation source. In this study only the sinusoidal high voltage response was investigated.

In order to understand the sinusoidal high voltage frequency response, one must understand the operation of the detector. For example, a CIC detector has a different plateau bias curve for different neutron flux levels. This is shown in Appendix B. As the power increases, the "knee" of the plateau increases. This implies that the higher the reactor power, the higher the operating high voltage bias. Stultz [5] measured the frequency response using small high voltage perturbations for the same type of CIC. He used a sine wave from a Wavetek sine wave generator with a maximum of 30 volts peak-to-peak (V P-P). However, in this present research, the frequency response was investigated using a larger sine wave amplitude to assure that the detector would operate above the recombination regions (and the charge transport would take place in the detector). This causes the detector to operate below and above the knee of the bias curve. Three separate sine wave amplitudes were chosen: one a high voltage sine wave 70 V P-P with a 35 volt D.C. value (the minimum high voltage would be zero and the maximum +70 volts) at 10 watts reactor power. The other was 80 V P-P with 100 v D.C. and 100 V P-P with no D.C. value both at 10 k watt reactor power. To generate such a large sine wave an Audio Oscillator and power amplifier, type 1308-A was used. The block diagram of the set-up is shown in Fig. 3.8.

Figure 3.8: Experimental Setup for Sinusoidal High Voltage Frequency Response Analysis

3.6 Summary

In this chapter different experimental techniques were described. In order to facilitate an understanding of the experimental objectives, a detailed description of the experimental apparatus and its design are presented in Appendix A.

The experimental results to meet the objectives along with the theoretical computer simulation are analyzed in Chapter IV. The most promising in-situ technique is discussed further in Chapter V.

CHAPTER IV

EXPERIMENTAL AND THEORETICAL RESULTS AND ANALYSIS

In this chapter the results of each method used to obtain or evaluate the CIC response time are presented and analyzed in detail. After experimental analysis and results of each method a summary is presented. Finally, at the end of the chapter the theoretical results obtained by computer simulation of the CIC model (with identical experimental condition), are compared with the experimental results.

4.1 X-Ray Pulse Experimental Results and Analysis

Two sets of experiments were performed using X-ray pulses generated by electrons from the LINAC. The width of the pulse was set to 20 nsec and 1 μ sec. In both sets of experiments the rise time of the X-ray pulse was less than 20 nsec. This rise time was well below the CIC response time. The experimental results for each pulse width are analyzed separately in the following paragraphs.

4.1.1 Step Response (Long X-Ray Pulse)

This section will discuss the results of the experiments described in chapter 3. The LINAC was adjusted to obtain the maximum possible pulse duration (one microsecond measured from the full-width at half-maximum). Calibration of the pulse was done with a Ferro electric (Pyroelectric) [59] detector. The response time of this detector is

less than 5 nanoseconds (which is less than the CIC response time). Thus the Ferroelectric detector response is assumed to be instantaneous compared with the CIC response.

The Ferroelectric detector response to a long pulse is shown in Fig. 4.1. From this figure, the rise time of the Ferroelectric detector is about 20 nsec (see Fig. 4.2). However the LINAC operating specifications list an electron pulse rise time of 6-10 nsec. The increased rise time probably results from the combination of the Ferroelectric detector response, coaxial cable response and a degraded LINAC performance. Note there are several "valleys" in the pulse structure, one near the beginning of the pulse, and several others after it reaches steady-state. Digitization of the signal may mask some of the fine structure of the pulse.

The nitrogen gas filled CIC response to a one microsecond duration pulse is shown in Fig. 4.3. The increase in rise time compared to the input pulse is readily apparent. The leading and trailing edge of the CIC response are shown in Figs. 4.4 and 4.5. Note that the "valley" observed at the beginning of the pulse by the Ferroelectric detector is observed. The second valley (at approximately 350 nsec) may be due to one of the following: the end of electron collection (and continuation of positive ion collection), input pulse itself, or, oscillatory response of the CIC detector. This kind of oscillatory behavior can be observed for any system having order two or more. The CIC output pulse continues to increase in amplitude until the input pulse drops to zero. This may be due to the somewhat slower collection time for positive ions. The oscillation or decrease (valley) in the flat section of the pulse was also observed in the computer simulation of the CIC response. (re: Section 4.6.1).

FIG. 4.1 Ferroelectric Detector Response (The entire pulse used for testing N_2 filled detector)

Fig. 4.2 Ferroelectric Detector Response, Leading Edge

Fig. 4.3 CIC Output Response, Entire Pulse
 (N_2 Filled CIC)

Fig. 4.4. CIC Output Response, Leading Edge (N_2 Filled CIC)

Fig. 4.5. CIC Response, Trailing Edge (N_2 Filled CIC)

The leading edge of the CIC response shows distinct break points (apparent change in the slope of the input pulse rise), one at 60 nsec and the other at 140 nsec after the initial rise of the output pulse. It is believed that the 140 nsec break point is related to the electron collection time in the CIC detector. It is thought that the first break point is either due to the RC response of the circuit or from the structure of the input X-ray pulse. The calculation of the RC time constant is as follows:

$$R = 50 \, \Omega, \text{ terminator resistance}$$

$$C = C_{\text{detector}} + C_{\text{Cable}} + C_{\text{Scope}}$$

$$= 344.8 + 810 + 12$$

$$= 1166 \text{ P F}$$

$$T = RC = (50 \times 1166 \times 10^{-12}) \approx 58.34 \text{ nsec}$$

$$\approx 60 \text{ nsec.}$$

The CIC trailing edge measurement shows that the fall time is much slower than the rise time. This may result from the fact that the positive ions are still being collected when the input X-ray flux drops to zero. This delay effect is shown in Fig. 4.6.

One break point is observed at 1070 nsec from the start of the pulse (or about 140 nsec from the steady state or "flat top value". The second break point is at 1170 nsec from the start of the pulse (or about 240 nsec from the steady state value).

The CIC was placed closer to the electron source to observe any effects of solid angle change. The CIC response amplitude increased,

Fig. 4.6. Behavior of the CIC Fall Time Response (Not Experimental Data)

as expected. The entire pulse along with leading and trailing edges are shown in Fig. 4.7 through 4.9. The same break points are observed at the same approximate times. However, the valleys at the beginning and in the flat top region of the pulse are not as pronounced as before. This may be due to effects of digitization of the pulse or X-ray source itself.

A similar series of experiments was performed with the CIC detector filled with xenon gas instead of nitrogen. This simulated a degraded CIC detector response. Once again, a one microsecond pulse was used. The Ferroelectric detector was used to calibrate and measure the pulse duration. The pulse obtained was similar to that used before, and is shown in Fig. 4.10. Notice that the flat top of the pulse is smoother than before, and the pulse height is still approximately 2 volts (measured by the Ferroelectric detector).

The xenon-filled CIC response is shown in Fig. 4.11 through 4.13. Note that the CIC in this case was operated at 500 V.D.C. which is below the "knee" of the plateau (I-V) curve. From the leading edge of the pulse, three break points are observed: 60 nsec, 140 nsec, and 230 nsec. The time it takes to reach the maximum is increased to 480 nsec. This is related to difference in charge mobility in xenon. From the trailing edge, four break points are observed. These are at 960 nsec, 1045 nsec, 1100 nsec, 1145 nsec. A comparison of the CIC response time with different fill gases is shown in Fig. 4.14. In the case of the xenon-filled CIC, the one microsecond pulse acts more like an impulse than a step. This is because a one-microsecond pulse is too short, (compared with electron and positive ion collection times in the xenon-filled CIC) to be considered a step input. This was also clearly illustrated by the computer simulation. (See Section 4.6).

Fig. 4.7. CIC Output Response, the Entire Pulse (N_2 Filled CIC)

Fig. 4.8. CIC Output Response, Leading Edge (N_2 Filled CIC)

Fig. 4.9. CIC Output Response, Trailing Edge (N_2 Filled CIC)

Fig. 4.10. Ferroelectric Detector Response, Entire Pulse, (used for testing Xenon Filled CIC).

Fig. 4.11. CIC Response, the Entire Pulse (Xe-Filled CIC)

Fig. 4.12. CIC Response, Leading Edge (Xe-Filled Detector)

Fig. 4.13. CIC Response, Trailing Edge (Xe-Filled CIC)

Fig. 4.14. Comparison of the Response of the CIC with Different Gases.

For the case of the xenon-filled CIC detector, the effect of high voltage bias on the response was studied. Fig. 4.15 and 4.16 show the xenon-filled CIC detector response to the one-microsecond pulse with 200 VDC high voltage bias. In the previous cases the high voltage bias was 500 VDC.

Comparison of the effect of high voltage change on the response of the xenon-filled CIC is shown in Fig. 4.17. The changes result from more ion-pairs being collected at 500 VDC than at 200 VDC. At 200-volts there is more recombination of ion-pairs. As expected, the amplitude of the signal is higher for a 500 volt bias than at 200 volts. The second "hump" in the CIC response, which is related to electron collection time, is reached faster (960 nsec versus 1008 nsec) for the CIC with higher bias voltage.

Fig. 4.15. CIC Response for Different High Voltage Setting (Xe-Filled CIC)

Fig. 4.16. CIC Response Time, Leading Edge for Different High Voltage Setting (Xe-Filled CIC)

Fig. 4.17. Comparison of the Xenon-Filled CIC Response for Different High Voltage Bias.

Summary

From the analysis of the step (long X-ray) response the following can be observed and concluded:

- (1) Step (one μ sec pulse) from the LINAC is a good evaluation method for CIC response time.
- (2) Degradation in the CIC gas can be observed. It is also expected that the degradation in cable and other electrical properties of the CIC cable, and associated measurement system can be observed using the step response method.
- (3) Response time (due to electron collection) is not possible for detectors which have an electron collection time greater than (or equal to) the long pulse width (1 microsecond).
- (4) Measurement of the response time due to positive ions for the CIC is not possible using the step response method.
- (5) Increasing the high voltage bias will decrease the response time.

4.1.2 Impulse Response

Several impulse response experiments were performed as described in Chapter 3. In these experiments, the input X-ray pulse to the CIC was chosen to be as narrow as possible (20 nsec) to obtain the CIC impulse response. While the data analysis of the system response to the long pulse was fairly straightforward, the analysis of the impulse response data method is more complex.

The CIC impulse response is the response of the detector to an impulse flux input. An impulse input can be thought of as a driving function that increases from zero to some steady state in an infinitesimal time when compared to the overall system response. Practically, in the frequency domain, if the impulses have a characteristic cutoff frequency equal to or greater than the cutoff frequency of the system being tested, the system response is a "perfect" impulse response (faster response implies higher cutoff frequency and vice-versa). A primary concern in impulse response analysis is the area and duration of the input pulse. In the experiments done to measure the response of the CIC the input pulse was a quasi-Gaussian X-ray pulse with the minimum possible duration (20 nsec pulse width measured from full width of half-maximum). The height of the impulse was constant and could not be changed.

The input pulse to the CIC, as measured with the Ferroelectric detector, (< 10 nsec response time), is shown in Fig. 4.18. The rise time of the impulse input, measured by Ferroelectric detector, is 20 nsec.

The response of the nitrogen-filled CIC with an operating voltage of 500 VDC to the impulse input is shown in Fig. 4.19. Note that the response is inverted by the oscilloscope. The undershoot at the beginning of the CIC impulse response is not fully understood. It is believed

Fig. 4.18. Ferroelectric Detector Response for Impulse Experiment
(used for Nitrogen-filled Detector)

Fig. 4.19. CIC Impulse Response (for Nitrogen-filled CIC)
For 500 Volt Bias Voltage

to be either a characteristic of the impulse input or the system behavior itself.

Calculation of Frequency Response from Impulse Response

An accurate analysis of the CIC impulse response (denoted $h(t)$) and resultant CIC dynamic behavior was done using the relation [38]

$$W(i\omega) = L[h(t)] = \int_0^{\infty} h(t)e^{-i\omega t} dt,$$

where, $W(i\omega)$ is system transfer function,

and, L is the Laplace transform.

By using a computer program which utilizes the fast Fourier Transform (FFT), the system transfer function can be calculated from the impulse response data obtained by experiments (see Appendix F). The transfer function of the system defines the frequency space data (or dynamic behavior) of the system. The results of this transformation are shown in Figs. 4.20 and 4.21. From these results one can conclude that the cutoff frequency for N_2 - filled CIC is below one MHz.

Calculation of Step Response from Impulse Response

Once the impulse response is obtained, the step response can be calculated by integrating the impulse response as follows:

$$Y(t) = \int_0^t X(t) dT,$$

where, $Y(t)$ = step response

and $X(t)$ = impulse response

Calculation of the step response can be performed either by a simple trapezoidal integration scheme using the sample points from digitized impulse response, or by CSMP using the Runge-Kutta method. In this study,

Fig. 4.20: Magnitude Plot of the CIC Frequency Response from Impulse Response

Fig. 4.21: Phase Plot of the CIC Frequency Response
From Impulse Response

CSMP was used to evaluate the integral and obtain the step response. Calculated step responses from experimental impulse response data for both nitrogen and xenon filled detector are shown in Figs. 4.22 and 4.23. The results indicate that the nitrogen filled CIC is faster than the xenon-filled CIC. Only the response of electron collection time is observed here. From the calculated step response, the electron collection time is approximately 350 nsec for the nitrogen filled CIC.

For the xenon-filled CIC, the electron collection time is approximately 0.9 microseconds (or maybe slightly greater). From these calculations, it is believed that the entire impulse response was not observed. If the entire impulse response were observed, one could also obtain the positive ion collection time.

High Voltage Effects on the Impulse Response

The CIC impulse response was studied for different D.C. bias voltages. The impulse response of the nitrogen-filled CIC for bias voltages of 100, 300, 700 and 1000 VDC are shown in Fig. 4.24 through 4.27. Table 4.1 compares the CIC impulse response for different operating bias voltages. Comparison of the CIC impulse response for different operating bias voltages yields the following conclusions:

- (1) Total impulse response duration is less for higher operating voltages.
- (2) The time between maximum and minimum amplitude remains constant.
- (3) Increasing the bias voltage increases the maximum and minimum amplitude.

Fig. 4.22: CIC (N₂ filled) Step Response from Impulse Response

Fig. 4.23: CIC (Xe-Filled) Step Response From Impulse Response

Fig. 4.24. CIC Impulse Response (for Nitrogen-filled CIC), 100 VDC HV.

Fig. 4.25. CIC Impulse Response (for Nitrogen-filled CIC)
300 VDC HV.

Fig. 4. 26. CIC Impulse Response (for Nitrogen-filled CIC)
300 VDC HV

Fig. 4.27. CIC Impulse Response (for Nitrogen-filled CIC)
for 1000 VDC HV.

Table 4.1 Comparison of the CIC Impulse Response for Different Operating High Voltage
(Nitrogen Filled CIC)

Operating Voltage Volt D.C.	Max. Amplitude (Volt)	Min. Amplitude (Volt)	Pulse Duration (MSEC)	Max. Plus Min. Amplitude (Volt)
100	0.29	0.16	0.82	0.45
300	0.43	0.13	0.46	0.56
500	0.554	0.206	0.35	0.76
700	0.73	0.25	0.3	0.98
1000	0.92	0.32	0.25	1.24

- (4) The maximum amplitude increases more than the minimum amplitude when the bias voltage is increased.
- (5) The signal increases after oscillations have ceased (which is believed to be due to the continuation of positive ion collection) occurs at the same time for different bias voltages.
- (6) The duration of observed impulse response decreases with increase in the bias voltage from the above.

One can conclude that points (2) and (5) indicate an intrinsic time response property of the CIC which is independent of the electric field. Point (1) may be due to faster detector response for higher detector bias voltage (this has to be proven by the computer simulation). If one looks at the pulse duration and the computer calculations for the step response discussed earlier, it can be concluded that the pulse duration is directly proportional to the detector response time. Using the impulse response duration data (which is related to response time), it is also observed that the high voltage and response time is approximately related by the following:

$$\text{Response Time} \propto \frac{1}{\sqrt{\text{High Voltage}}}$$

Point (3) may be due to less recombination effect of the ion-pairs at the higher bias voltage. The cause of point (4) is not understood. Point (6) has also been proven by the computer simulation. This is due to reduction in the drift velocity in the chamber.

The effects of the fill gas on the impulse response were studied. In these experiments the impulse response of the CIC was measured for a xenon-filled detector with an RG 62 B/U (93 Ω) cable terminated with a 93 Ω resistor at the oscilloscope input.

Fig. 4.28 shows the Ferroelectric detector output, and Fig. 4.29 shows the xenon-filled CIC impulse response. Comparison of the experimental impulse response and their numerical data for the nitrogen and xenon-filled CIC are shown in Fig. 4.30 and Table 4.2 respectively. As these data show, the duration and the amplitude of the impulse response is increased for the xenon-filled CIC.

It also appears that longer response duration means lower cutoff frequency and slower response for xenon-(than nitrogen) filled CIC. The xenon-filled CIC has a better sensitivity than the nitrogen-filled CIC.

Some oscillations are observed for the xenon-filled CIC impulse response. These oscillations are believed to be caused by the cable. From this oscillation one can calculate the cable lengths from the CIC to the measurement system. The propagation of the electromagnetic wave in a coaxial cable depends on the relative permittivity of the dielectric medium. The speed of propagation in the coaxial cable is:

$$v_p = \frac{c}{\sqrt{\epsilon_r}} ,$$

Where, c is the speed of light (3×10^8 m/sec), and

ϵ_r is the relative permittivity of the dielectric medium (ϵ_r for polyethylene is between 2.25 to 2.34).

Fig. 4.28 Ferroelectric Detector Response
(Input of the Xenon-Filled CIC)

Fig. 4.29. CIC Impulse Response for Xenon-Filled Detector

Fig. 4.30. Comparison of the Nitrogen and Xenon-Filled CIC Impulse Response

TABLE 4.2 Comparison of the Impulse Response
of the Nitrogen and Xenon-Filled CIC

	Nitrogen Filled CIC (1 atm)	Xenon-Filled CIC (4 atm)
Maximum Amplitude (Volt)	0.63	1.5
Minimum Amplitude (Volt)	0.2	0.08
Pulse Duration (μ sec)	0.3	0.85

V_p in the coaxial cable is then about 66% of the speed of light.

The wave length, λ , from the measured data can be calculated from the relation:

$$\lambda = V_p T,$$

where: V_p speed of propagation in the cable,

and, T period of the oscillation.

From which λ is

$$\begin{aligned}\lambda &= (.66 \times 3 \times 10^8 \text{ m/s})(66.6 \times 10^{-9} \text{ s}) \\ &= 13.19 \text{ meter} \\ &= 43.25 \text{ ft}\end{aligned}$$

This shows that the cable length is approximately a wavelength.

Cable Degradation Effect on the CIC Impulse Response

The effects of cable degradation were investigated using a delay box to add an artificial delay to the cable response. The CIC impulse response with this added delay for both nitrogen and xenon-filled CIC are shown in Fig. 4.31 and 4.32.

The results indicate a definite change in the response. First, the shape of the response as well as the response duration are changed substantially. Second, the response of the nitrogen and xenon-filled CIC are not similar, when such a delay is added. Notice the oscillatory zero response ("delay time") at the beginning for the case of the xenon-filled CIC only. The delay time is about 0.475 μsec .

For the xenon-filled CIC, this delay time is approximately 0.475 μsec . In the case of the nitrogen-filled CIC only, an oscillatory response of about 20 μsec is observed. The reasons for the difference in response between nitrogen and xenon-filled CIC is not clear. But the delay in the xenon-filled CIC was expected. Thus, by adding a delay box in the system the CIC response is altered.

Fig. 4.31. CIC Impulse Response With a Delay Box (nitrogen filled CIC)

Fig. 4.32. CIC Impulse Response with a Delay Box (Xenon-filled CIC)

Non-Terminating Effects on the CIC Impulse Response

Fig. 4.33 through 4.35 show the xenon-filled CIC impulse response with different time scales using no termination at the oscilloscope input. The results indicate that the amplitude of the response is larger when termination is not used (this was expected). The amplitude is approximately 15 volts. There are two components to the impulse response rise time. First, the response rises to 8 volts in about 0.8 μ sec. Then, it rises to 15 volts in about 0.2 msec (after the first break point). It is believed that the first rise in the response is related to electron collection and the second is related to positive ion collection.

Other Termination Effects on the CIC Response

Next, the CIC impulse response was studied for various terminations and cables. The impulse response of the nitrogen filled CIC for 500 VDC bias voltage, using the RG 62 B/U (93 Ω) cable (instead of RG 58 A/U 150 Ω) with a 93 Ω terminator (instead of 50 Ω) is shown in Fig. 4.36. The maximum amplitude of the signal increases, but the minimum amplitude decreases. This may indicate that minimum amplitude (undershoot) at the beginning of the pulse is due to mismatch in impedance that causes reflection of the signal in the cable.

Fig. 4.37 shows the effect of termination at both ends of the cable with a 93 Ω terminator. The amplitude is reduced as expected. It is concluded that different terminations can not be the cause of all the oscillations observed in the impulse response, and it is caused primarily by the CIC characteristics. However, no oscillation is observed by the CIC when an open termination is used (1 M Ω oscilloscope only).

Fig. 4.33. CIC Impulse Response (Xenon-filled CIC) With no Termination.

Fig. 4.34 CIC Impulse Response (Xenon-Filled CIC) with No Termination.

Fig. 4.35. CIC Impulse Response (Xenon-Filled CIC) with no Termination.

Fig. 4.36. CIC Impulse Response (Nitrogen-Filled CIC) for 93 Ω Cable and Terminator.

Fig. 4.37. CIC Impulse Response for Nitrogen-Filled Detector

It is further concluded that the time constant due to the input impedance and capacitance of the measuring system, cable, and detector play an important role in CIC response time measurements.

Summary

From the experimental analysis of the impulse response the following can be concluded:

- (1) From the impulse response both the "step and "frequency" (only part of it depending on response duration) response can be obtained.
- (2) Increasing high voltage bias will decrease the CIC response time.
- (3) Any degradations in the detector including change in the detector gas, change in cable or detector electrical properties can be easily detected using the impulse response.

4.2.1 Introduction

Several experiments were performed using noise analysis techniques. In these experiments, the Power Spectrum (PS) of the CIC output signal was recorded by a Nicolet 660A Fast Fourier Transform (FFT) analyzer. In some experiments the signal from the CIC was connected directly to the FFT analyzer. Many experiments were performed under the same conditions to assure that the results show repeatability.

The experimental results that are described here involve two identical CICs, one with nitrogen fill gas at one atmosphere pressure and the other with xenon fill gas at four atmospheres pressure. Measurements were made at different reactor power levels. Beside the gas change, the effect of the CIC degradation on the PS (and response time) was studied in two other experiments. One involved the use of a delay box between the CIC and FFT (to simulate cable degradation), and the other involved the use of different terminating capacitors at the FFT input (to simulate cable degradation and the RC effect of the measurement system on the response).

In order to maintain consistent experimental conditions, several parameters that affect the PS were held constant for comparable experiments. These conditions are noted on PS graphs that are presented later in this section. These parameters can be summarized as follows:

- (1) H.V. input to the CIC (500 VDC). As will be explained in the recommendations, the effect in PS or malfunction of the high voltage should be evaluated.
- (2) Coupling (AC or DC)
- (3) Use of Keithley 427, current amplifier (yes or no) between CIC and FFT.

- (4) Cable type and length (RG 71 B/U, 60 ft length) 176
- (5) Frequency range
- (6) Reactor power level (no power, source only, 10W, 100W, 1 KW, 10 KW Power)
- (7) Number of averages (512)
- (8) Method of averaging (summation)
- (9) Location of the CIC in the reactor (dry tube)
- (10) Amplitude units (db/Lin, V/EU, ABS/Rel, or per Hz)

In Table 4.3, a summary of the experiments performed with their objectives are presented.

4.2.2 Analysis of the Data from FFT (Nicolet 660A) Analyzer

In using noise analysis techniques, the power spectrum (PS) of an input signal is recorded. Most unusual peaks or changes in the PS can be located by moving the cursor of the FFT analyzer to the desired location and specifying the frequency and magnitude. In some cases it is desired to specify a peak or break point on a recorded PS. The following procedure was used to specify a desired frequency (X) on a PS Logarithm plot (see Fig. 4.38).

- (1) Draw two parallel lines (call them A and B)
at the nearest decade points around a desired
frequency
- (2) Insert a decade of a semi-log paper (in any
angle between lines A and B in a manner that

Experimental Summary

Experimental Conditions	Objective, Comparison
1) No connection made to FFT analyzer	Determination of background noise and other Electro-magnetic peaks by FFT
2) No gamma or neutron flux present, CIC connected to FFT	Electrical effect of CIC AC/N ₂
3) Small radiation effect (neutron source), CIC connected	Charge transport and electrical effect, DC/N ₂ /Xe Xe/AC/DC
4) 10 W Reactor Power, CIC connected	Same as above DC/N ₂ /Xe
5) Different reactor power, CIC connected current amplifier effect	Same as above 10W/1KW/N ₂ /Current amp/no current amp
6) Power level change, CIC connected	Same as above 10KW/1KW/100 W/10W/N ₂ /Xe
7) 1KW reactor power, CIC connected different detector	Same as above N ₂ /Xe
8) 10KW reactor power, CIC connected different detector	Same as above N ₂ /Xe
9) 10KW reactor power, CIC connected different detector, delay box	Same as above Delay box/N ₂ /Xe
10) 10KW reactor power, CIC connected different detector, external capacitance	Same as above C ₁ /C ₂ /N ₂ /Xe

Figure 4.38: Specifying an unknown frequency on the Power Spectrum(PS)

the lowest frequency point of the semi-log paper touches a point (C) on lines A and the highest frequency touches a point (D) on line B.

- (3) Draw a line between "C" and "D" (call it "Z")
- (4) Mark the log divisions of the semi-log paper between points C and D (or if desired, leave the log paper where it is).
- (5) Draw a line (Y) parallel to point A (or B) that passes from the desired frequency point (X) on the PS (using two right-angled triangle instruments if desired)
- (6) Read the intersection of line Z and Y using the division of semi-log paper to specify the frequency point at point X.

4.2.3 Analysis of Power Spectrum of the Nitrogen and Xenon Filled CIC at Different Power Levels

The FFT analyzer can calculate the PS of noise picked up by its input, which acts as an antenna. Thus, in the first experiment, the peaks were studied when no input is connected to it. The objective of this experiment was to determine the background peaks. The source of these peaks are; the electromagnetically-picked-up radio frequencies from sparks, digitizing noise, etc.

As expected, several peaks were observed in the PS. These peaks are shown for different frequency ranges in Figs 4.39(a) through 4.39(c). A peak at 60 HZ and its harmonics are prominent. Notice the three peaks at 39750, 53750, and 65250 HZ in the PS. The source of these peaks are probably a radio station and radar source nearby.

512 #AVG 518.-12 V2 VLG
180.0000 HZ C

Figure 4.39 (a): PS of the FFT when no input signal is connected.

512 #AVG 11.4-12 V2 VLG
2600.000 HZ C

Figure 4.39 (b): PS of the FFT when no input signal is connected.

Figure 4.39 (c): PS of the FFT when no input signal is connected.

A second experiment involved recording the PS of the nitrogen filled CIC when exposed to no neutron or gamma flux. The high voltage was set at 500 VDC. The objective of this experiment was to determine the PS of the CIC (electrical effect) with the associated cable connections and the high voltage bias supply. The length of the cable from CIC to FFT was 60 ft. This length of cable acts as an antenna and certain frequencies that are more dominant than the others are observed in the PS. Fig. 4.40 shows a sharp drop in the PS starting at about 500 Hz. The slope of this is about -32.3 db/decade. A peak appears at about 27750 Hz. The two peaks at 53750 and 65250 Hz that were also observed before (Fig. 4.39) are due to electromagnetic pick up. The other smaller peaks are due to the power line frequency passed by the high voltage supply.

Following these experiments, the PS of the CIC output when exposed to the flux from the start-up source of the O.S.U. research reactor (OSURR) was measured. The PS of the nitrogen-filled CIC is shown in Fig. 4.41 and the PS of the xenon-filled CIC are shown in Fig. 4.42(a) and 4.42(b). Notice the 60 Hz harmonics in the PS of both CICs. No noticeable difference is observed except the sensitivity of the xenon-filled CIC is higher than the nitrogen-filled CIC (because overall magnitude of the PS of this xenon-filled CIC is larger than the nitrogen-filled CIC).

Up until now the PS was obtained when CIC was connected to the FFT analyzer by "DC coupling". This was done simply by setting a switch on the FFT to "DC coupling". This time the PS was obtained under the same conditions using "AC coupling". The experimental results for the xenon-filled detector with the neutron source present are shown in Fig. 4.43(a) and 4.43(b). Notice the lower frequency portion (less than 1000Hz) of the PS.

Figure 4.40: PS of the CIC Output Signal (N₂ filled)

Figure 4.41: PS of the CIC Output Signal
(N₂ filled)

512 #AVG 758.-15 V2 VLG
3100.000 HZ C

Figure 4.42 (a): PS of the CIC Output Signal (Xe-filled)

512 #AVG 66.2-12 V2 VLG
2125.000 HZ C

Figure 4.42 (b): PS of the CIC Output Signal (Xe-filled)

Figure 4.43 (a): PS of the CIC Output Signal (Xe-filled)

Figure 4.43 (b): PS of the CIC Output Signal (Xe-filled)

The amplitude of the power line peaks (60 Hz and its harmonics) are more prominent in the DC coupling than in the AC coupling. There is a structural difference in the PS observed at the 100K Hz range. The slope of the PS changes suddenly at about 375 Hz.

Next, the reactor power was increased to 10 watts and a comparison of the PS from the nitrogen-and xenon-filled CICs was made. The experimental results for both detectors are shown in Fig. 4.44(a,b) through 4.45 (a,b). The 10 KHz range of PS for both N_2 -and Xe-filled CIC are redrawn in Fig. 4.46(a). Two break points between 1 and 2 KHz are observed. It is also noted that the break points for N_2 -filled CIC is at a higher frequency than the Xe-filled CIC. Differences in positive ion collection properties could account for the observed differences.

Different break points are clearly shown in Fig. 4.46(b) in the 100 KHz range. The break point for xenon is at about 1125 Hz and for nitrogen is about 2000 Hz. This is an indication that the random noise technique will show any changes in detector response (such as fill gas in this case). Notice also the slope difference between the two CIC at their break frequencies. The slope of the xenon-filled detector is greater than the nitrogen-filled detector. The cause of this slope difference may be due to lower ion (or electron) velocity.

A break point in the PS could result from the total RC value of the CIC, cable, and FFT. To eliminate this possibility, a current amplifier (Keithly 427) was placed between the CIC and the FFT. In these experiments, the Keithly 427 current amplifier was used to convert the CIC current to voltage to be analyzed by the FFT. The experimental results for the nitrogen-filled CIC at 10 watts are shown in Fig. 4.47(a) and (b).

Figure 4.44 (a): PS of the CIC Output Signal (N₂-Filled)

512 #AVG 1.01-09 V2 VLG
18250.00 HZ C

Figure 4.44 (b): PS of the CIC Output Signal (N_2 -Filled)

512 #AVG
187.5000 HZ

16.7-09 V2

VLG
C

Figure 4.45 (a): PS of the CIC Output Signal (Xe-Filled)

Figure 4.45 (b): PS of the CIC Output Signal (Xe-Filled)

Figure 4.46 (a): Comparison of the PS of the Xenon and Nitrogen Filled CIC at 10 Watts Reactor Power and 10 KHZ Frequency Range.

Figure 4.46 (b): Comparison of the Xenon and Nitrogen-Filled CIC at 10 Watts Reactor Power and 100K HZ Frequency Range.

Figure 4.47 (a): PS of the CIC Output Signal (N_2 -Filled)

Figure 4.47 (b): PS of the CIC Output Signal (N₂-Filled)

Since the cut off frequency of the Keithly 427 current amplifier is about 30 KHz, there is a sudden drop in the PS at this frequency. Results using the current amplifier show a more constant amplitude in the PS (up to 30 KHz), but the PS breaks at about 800 Hz for the case where no current amplifier is used (see Fig. 4.48). This break point could be related to the RC value of the FFT and CIC.

The effect of Keithly 427 current amplifier was also evaluated for higher power levels. Fig. 4.49(a) and (b) show the effect of the current amplifier on the PS at one kilowatt for the nitrogen-filled CIC. The 30 KHz cut off frequency of the current amplifier is also observed here. The 5 KHz break point is in both PS (with and without current amplifier). This break point (5 KHz) may be due to detector characteristics. Notice that the break point (at 5 KHz) is not as obvious as in the case with the current amplifier. The comparison of the PS with and without current amplifier for the nitrogen-filled CIC at one kilowatt is made in Fig. 4.50. A break point at about 1500 Hz is observed when the current amplifier is not used. However, such a break point is not observed, except at about 5 KHz.

The next experiments involved the xenon-filled detector when the power level was changed. Fig. 4.51 and 4.52 (a,b) show the PS for 10 and 100 watts. In order to compare the effect of power, the PS for 10W, 100W, 1KW, and 10KW were redrawn and superimposed in Figs. 4.53(a) and (b). Two different ways of superimposing the PSs are shown. In order to compare the PS, the magnitude of the entire spectrum are normalized (since we only want to compare the structural difference, not amplitude). The break points at all powers are nearly identical. Notice that the slopes below 1 KHz are not the same. No reason can be given regarding this difference. For 10W the PS between 70-100 KHz is higher than the other power levels due to lower S/N.

Figure 4.48: Comparison of the PS for Nitrogen-Filled CIC With and Without Current Amplifier at 10 Watt Reactor Power.

512 #AVG 2.90-09 V2 VLG
1375.000 HZ C

Figure 4.49 (a): PS of the CIC Output Signal (N_2 -Filled)

512 #AVG 3.96-09 V2 VLG
31000.00 HZ C

Figure 4.49 (b): PS of the CIC Output Signal (N_2 -Filled)

Figure 4.50: Comparison of the PS for the Nitrogen-Filled CIC With and Without Current Amplifier at 1K Watt Reactor Power.

512 #AVG 98.7-12 V2 VLG
21500.00 HZ C

Figure 4.51: PS of the CIC Output Signal (Xe-Filled)

Figure 4.52 (a): PS of the CIC Output Signal (Xe-Filled)

Figure 4.52 (b): PS of the CIC Output Signal (Xe-Filled)

Figure 4.53 (a): Comparison of the Normalized PS of the Xenon-Filled CIC at Different Reactor Power Levels.

Figure 4.53 (b): Comparison of the Normalized PS of the Xenon-Filled CIC at Different Reactor Power Levels.

The comparison of the nitrogen filled and xenon-filled CIC was made at one kilowatt reactor power. The experimental results of the PS are shown in Figs. 4.54 and 4.55. The comparison of the 10 KHz range gives the clear indication of the break point differences for the nitrogen and xenon-filled CIC. Defining the exact break point is not possible, but it definitely shows that the break point for xenon is lower than nitrogen filled CIC. One can draw lines to define the break points. Using this technique, the break point is at about 3100 Hz for the nitrogen-filled CIC and is about 1200 Hz for the xenon-filled CIC.

In the 100 KHz range, several break points are observed in the PS (shown by arrows). The comparison between the xenon and nitrogen detector shows the first break point and the third and fourth break points are the same. However, the second break point (top arrow) is at a lower frequency for the xenon than the nitrogen-filled detector. It is believed that this is due to the detector difference.

Figs. 4.56 and 4.57 show the experimental results of the PS for the nitrogen and xenon-filled CIC at 10 kilowatt reactor power. The PS is much smoother than at lower power levels. The comparison of the 10 KHz range of the PS indicates a break point difference. For the xenon-filled detector, the break point is lower than the nitrogen-filled detector. The other break points are marked by arrows. The same kind of conclusion can also be obtained from the 100 KHz range (shown in Fig. 4.58). As is shown in Fig. 4.58, a definite difference in the break point is observed. The break point for the Xe-filled is at lower frequency than the N_2 -filled CIC.

Figure 4.54 (a): PS of the CIC Output Signal (N_2 -Filled)

Figure 4.54 (b): PS of the CIC Output Signal (N_2 - Filled)

Figure 4.55 (a): PS of the CIC Output Signal (Xe-Filled)

Figure 4.55(b): PS of the CIC Output Signal (Xe-Filled)

512 #AVG 451.-09 V2 VLG
3325.000 HZ C

Figure 4.56 (a): PS of the CIC Output Signal (N_2 -Filled)

512 #AVG 6.92-09 V2 VLG
88000.00 HZ C

Figure 4.56 (b): PS of the CIC Output Signal (N_2 -Filled)

Figure 4.57 (a): PS of the CIC Output Signal (Xe-Filled)

Figure 4.57 (b):

PS of the CIC Output Signal (Xe-Filled)

Figure 4.58: Comparison of the PS of the Xenon and Nitrogen-Filled CIC at 10K Watt Reactor Power.

4.2.4 Analysis of Power Spectrum of the Degraded Nitrogen and Xenon-Filled CIC

Figs. 4.59 and 4.60 show the effects of a delay box which simulates a cable degradation in the PS. One comparison is made between two normal N_2 -filled detectors one with and the other without a delay box. The other comparison is between xenon-filled CIC's with and without a delay box. There are great differences in the PS between the N_2 -filled CIC with and without a delay box. The results are clearly indicated in the graphs. The comparison of the PS of the N_2 -filled and Xe-filled CIC with delay box shown in Fig. 4.61 and 4.62 indicate that there is a definite change in the shape and structure of the PS.

These changes are different for the two types of nitrogen and xenon-filled CIC. For the xenon-filled CIC, the amplitude of the PS decreases as the frequency increases (an effect similar to an external capacitance). However, for the nitrogen-filled CIC the PS is completely different for low and high frequencies. From these experiments we can conclude that, any degradation (such as delay effect) in the CIC can be detected using the noise analysis technique.

4.2.5 Effect of Capacitance in the Power Spectrum of the Nitrogen and Xenon-Filled CIC

To simulate the cable for the CIC degradation, an external capacitance was placed from CIC signal to ground. The experimental results are shown in Figs. 4.63 through 4.66. Several comparisons were made between different terminating capacitors at the oscilloscope input. Fig. 4.67 of using an external capacitance at the output of a xenon-filled CIC. The comparison indicates that the use of an external capacitor decreases the PS

Figure 4.59(a): PS of the CIC Output Signal (N_2 -Filled)

Figure 4.59 (b): PS of the CIC Output Signal (N_2 -Filled)

Figure 4.60 (a): PS of the CIC Output Signal (Xe-Filled)

Figure 4.60 (b): PS of the CIC Output Signal (X_e - Filled)

Figure 4.61: Comparison of the PS (Normalized) of a Nitrogen-Filled CIC With and Without a Delay Box.

Figure 4.62: Comparison of the PS (Normalized) of a Xenon-Filled CIC with and without a Delay Box.

512 #AVG
750.0000 HZ

-51.4 dBV

VLG
C

Figure 4.63: PS of the CIC Output Signal (N_2 -Filled)

Figure 4.64: PS of the CIC Output Signal (N_2 -Filled)

Figure 4.65: PS of the CIC Output Signal (Xe-Filled)

Figure 4.66: PS of the CIC Output Signal (Xe -Filled)

Figure 4.67: Comparison of the Normalized PS with Addition of an External Capacitance at the CIC Output Signal (Xe-filled CIC)

while increasing the frequency. It also indicates that the cutoff frequency decreases (or response time increases) with the addition of a capacitor. We conclude that any degradation in the cable that results in the capacitance change in the cable can be detected in the PS.

Comparison of the CIC degradation using the delay box, which was discussed previously, and 0.001 μF capacitance indicates that the PS for 100KHz range are nearly identical. The reason for this is not clear.

4.2.6 Summary of the Noise Analysis Experimental Results

A summary of the experimental results using the noise analysis technique is presented here.

- (1) The Power Spectrum (PS) is different for different detectors. (Ref. Fig. 4.54(a), 4.55(b), and 4.58.
- (2) The difference in the PS can be observed best at lower power levels.
- (3) There is no break point difference in the PS at different reactor power levels.
- (4) Detector degradation can be detected using noise analysis techniques (both in the spectrum amplitude and the spectrum structure).
- (5) Any capacitance change in the cable or detector can be observed by the noise analysis technique.
- (6) The experimental setup including the cables and power supplies should be the same to detect any degradation in the system.
- (7) The CIC response time verification can be made best

when the CIC signal is terminated. However, terminating (93 ohms) the signal for the OSU Research Reactor causes the output signal voltage to drop to the noise level, and makes it impossible to measure the CIC response time. It is expected, however, that for power reactors, the level of the CIC signal would be higher than it is for the OSU Reactor, and that terminating the signal still makes it possible to check the CIC response time.

- (8) Due to the frequency limitation of the present FFT Analyzer (< 100 KHz) the electron collection response cannot be observed even when a terminator is used.

4.3 Experimental Results from the O.S.U. Research Reactor Scram Response

Two separate experiments were performed on the CIC detector as discussed in Chapter 3. One experiment used a nitrogen filled detector to establish baseline performance and the other used a degraded (xenon-filled) detector.

The scram response was investigated by dropping all the three control rods simultaneously, with the reactor power at a steady state. Due to gravity and friction, the rods do not drop instantaneously, thus producing a fast ramp transient (also because of the prompt neutron lifetime which is approximately 10^{-4} sec) when compared with other possible reactor transients. However, this transient is slow when compared with the detector response time.

To be able to compare the results for the normal and degraded detectors, scram responses were made from a steady state power of 10 watts. Oscilloscope photographs of the scram response for both the nitrogen-filled (one atm. pressure) and xenon-filled (four atm. pressure) detectors are shown in Figs. 4.68 and 4.69.

The comparison of the experimental data for the normal and degraded detector is shown in Table 4.4.

The following conclusions can be obtained for the two cases:

1. The response time did not change significantly.
2. The sensitivity is better for the xenon-filled CIC.

The first conclusion implies that although the detector response time is degraded for such a slow transient (compared with detector responses), the detector still follows the transient. It is important to mention that scram is the fastest reactor transient.

$I_{ss}=2.5 \mu\text{Amp}$
 50 mSec/Div
 0.5 V/Div
 1 M Ω Oscilloscope Input
 500 Volt DC Bias

Figure 4.68: Scram Response for Nitrogen-Filled CIC at 10 W Reactor Power

$I_{ss}=4.8 \mu\text{Amp}$
 50 mSec/Div
 1 V/Div
 1 M Ω Oscilloscope Input
 500 Volt DC Bias

Figure 4.69: Scram Response for Xenon-Filled CIC at 10 W Reactor Power

$I_{ss}=2.8 \text{ mAmp}$
 50 mSec/Div
 0.02 V/Div
 50 Ω Terminator
 500 Volt DC Bias

Figure 4.70: Scram Response for Xenon-Filled CIC at 10 KW Reactor Power

Table 4.4
Comparison of the Scram Response Data
for Normal and Degraded CIC

Variables	N ₂ -Filled CIC	Xe-filled CIC
Max. Current Microamp	2.5	4.8
Max. Osc. Voltage (volts)	2.5	4.8
Response Time (msec)	375	375
Transient Slope (V/sec)	10.42	19.13

The rod drop scram response was also performed for the xenon-filled detector at 10 kilowatts. Figure 4.70 shows one oscilloscope photograph of the results of this test. The response time is roughly 375 msec, the same as for nitrogen-and xenon-filled detectors at 10 watts. But, the maximum current observed at 10 kilowatts is 2.8 milliamps. This shows a non-linearity with reactor power at 10 kilowatts for the xenon filled detector. It is suspected that since the high voltage applied to the CIC was 500 volts D.C., the voltage was not high enough to be in the flat portion of the plateau bias curve. However, such non-linearity was not observed for the normal nitrogen filled detector. More detailed bias curves for the two detectors are shown in Appendix B.

It is expected that a difference in the scram response would be observed if the data were digitized prior to examination. Further discussion of this possible experiment is included in the recommendations section.

Comparison of those experiments with the LINAC x-ray experiments reveals that for fast transients (such as LINAC experiments) a difference is observed in the time response between the baseline and degraded detectors. However, no such difference is observed for slow transients.

4.4 High Voltage Perturbation Experimental Analysis of the Mercury Wetted Contact Relay Switch

4.4.1 Introduction

One in-situ method to determine the dynamic response of a neutron sensor is to rapidly perturb the high voltage bias and evaluate the response. The perturbation is performed using the mercury-wetted contact relay switch explained in Appendix A-3.

In this section, the high voltage perturbation is performed at different reactor power levels with different detector fill gases. In addition, cable degradation is simulated using external resistors and capacitors termination and a delay box.

4.4.2 High Voltage Perturbation Switch

The first experiment with the high voltage perturbation using the switch analyzed the perturbed high voltage input to the CIC. The experimental results for a perturbed voltage of 100 volts DC are shown in Figs. 4.71 (a) through 4.71 (c). A rise time of less than 10 nanoseconds is observed. The rise time of the high voltage switch changes slightly with the cable length. The fall time is about 200 microseconds. The length of time that the high voltage is kept "on" can be adjusted by changing the frequency of the sinusoidal input to the mercury wetted relay switch (see Appendix A).

4.4.3 High Voltage Perturbation Analysis for Nitrogen and Xenon-Filled CIC's Different Reactor Power Levels

The electrical effect of the CIC on the response was studied using a CIC at zero reactor power. Fig. 4.72 (a) through 4.72 (c) show the xenon-filled CIC response at zero reactor power. A similar response is also observed for the Nitrogen-filled CIC. The rise time at the beginning of the

20 V/Div
5 nSec/Div
100 Volt DC Input
Rise Time

Figure 4.71 (a)

20 V/Div
1 mSec/Div
100 Volt DC Input
Entire "ON" and "OFF" of HV

Figure 4.71 (b)

20 V/Div
20 μ Sec/Div
100 Volt DC Input
Fall Time

Figure 4.71 (c)

Figure 4.71: Mercury-Wetted Contact Relay Switch Output
Using a 100 Volt DC Input

Zero Power, Xenon-Filled CIC
 0.2 V/Div
 20 nSec/Div
 500 Volt DC Bias Perturbation
 1 M Ω Oscilloscope Input

Figure 4.72 (a)

Zero Power, Xenon-Filled CIC
 0.2 V/Div
 0.5 μ Sec/Div
 500 Volt DC Bias Perturbation
 1 M Ω Oscilloscope Input

Figure 4.72 (b)

Zero Power, Xenon-Filled CIC
 0.1 V/Div
 2 mSec/Div
 500 Volt DC Bias Perturbation
 1 M Ω Oscilloscope Input

Figure 4.72 (c)

Figure 4.72 : Xenon-Filled CIC Response at Zero Reactor Power Using High Voltage Perturbation

response is 20 nsec for both the xenon and nitrogen-filled CIC. The increase in the rise time from 10 nsec to 20 nsec may be due to cable effects. Some ringing that can be attributed to independance mismatch is also observed. The frequency of the oscillations is approximately 5.5 MHz. The frequency of oscillations can also be estimated using the equation

$$f = \frac{V_p}{2\ell} = \frac{c}{2\ell \epsilon_r},$$

where: c = speed of light
 V_p = propagation velocity
 ℓ = length of cable from detector
to the oscilloscope

$$\text{Thus, } f = (3 \times 10^8 \text{ m/sec}) / (2 \times 60 \text{ ft} / 3.28 \text{ ft/m})(2.25) = 5.47 \text{ MHz}$$

The decay time of the response is increased from approximately 200 microsecond (for high voltage input) to approximately 4 msec. for both nitrogen and xenon-filled CIC. The increase in the decay time can be attributed to an increase in the capacitance (detector and cable). The starting decay at about 8.2 msec is due to the relay contact break point in which further discharge of the 2 μ f capacitor in the high voltage pertubation switch is halted. To insure that the ringing in the response is due to cable, an experiment was performed using a xenon-filled CIC at zero reactor power with a very short cable. Fig. 4.73 (a) through 4.73 (d) shows the results. As expected, the frequency of the ringing was increased and made the response better. However, in the experiments discussed later a cable length of 60 ft. from the high voltage power supply to the CIC and from the CIC to the oscilloscope was used.

Since the xenon-filled detector becomes internally radioactive (estimated activity of 0.01 Ci at the connector (about 5 Mr/hr)), a small current of approximately 0.115 microamp is measured by a picoammeter.

Zero Power, Xenon-Filled CIC
 0.2 V/Div
 20 nSec/Div
 Ground: 4/5 Div Up
 500 Volt DC Bias Perturbation
 1 M Ω Oscilloscope Input

Figure 4.73 (a)

Zero Power, Xenon-Filled CIC
 0.2 V/Div
 0.2 μ Sec/Div
 Ground: 1 Div Up
 500 Volt DC Bias Perturbation
 1 M Ω Oscilloscope Input

Figure 4.73 (b)

Zero Power, Xenon-Filled CIC
 0.2 V/Div
 0.2 mSec/Div
 Ground: 9/10 Div Up
 500 Volt DC Bias Perturbation
 1 M Ω Oscilloscope Input

Figure 4.73 (c)

Zero Power, Xenon-Filled CIC
 0.2 V/Div
 2 mSec/Div
 Ground: 1 Div Up
 500 Volt DC Bias Perturbation
 1 M Ω Oscilloscope Input

Figure 4.73 (d)

Figure 4.73: Xenon-Filled CIC Response at Zero Power
 Using High Voltage Perturbation with Short
 Cables

The CIC response after ringing settles to a steady state and starts to decay down until it reaches another steady-state value. The cause of this decay is due to the leakage of charge from the capacitance through the resistance of the entire neutron sensor. After a steady state is reached, the signal starts to decay again. The second decay is due to the break in the contact relay (the relay is for D, Break-before-make). This time the CIC response reaches zero when the high voltage is turned on again by the relay (the "on" and "off" of the switch is controlled by the input sine wave to the relay).

The next experiment is the high voltage perturbation at 10.W reactor power. Results similar to zero power are observed except the amplitude of the signal is increased. It is believed that for the nitrogen-filled CIC we must expect to see a "hump" before the response reaches the steady state value (in the first decay). However, due to the lack of data, this was not observed. This hump can be related to the positive ion collection time. Due to the much slower response of the xenon-filled CIC than the nitrogen filled CIC, no such hump was observed. This is because the positive ion collection time is approximately equal to the RC time constraint of the system. The reconstruction of the entire response for both the xenon and nitrogen-filled CIC are shown in Fig. 4.74.

Fig. 4.74 also shows the CIC response for other reactor powers. Generally, the CIC response, using the high voltage perturbation, has three components. First is the fast component at the beginning. It is a 20 nsec rise time oscillating at about 5.5 MHz. It is believed that this is due to the characteristics of the high voltage reaching the CIC (cable effects). In both CIC's at different reactor power levels, these oscillations at the beginning of the CIC response are nearly identical. The oscillations could be due to the cable effect at the high voltage input or output.

Figure 4.74: Reconstruction of the CIC Response Due to High Voltage (Bias) Perturbation at Various Reactor Power Levels (not to scale, time scale varies)

Second is the slowest component of the response. This component depends on both the detector and its termination value. The CIC response after the fast oscillatory component either increases or decreases exponentially until it reaches a steady-state value (depending on the magnitude of the signal and its termination value). The time that it takes to reach the steady state value is believed to be related to the CIC response. Any change in the capacitance or termination can be detected at this component. Theoretically, the value of the steady state is the product of the measured CIC current (measured by a Picoammeter) and the input impedance of the oscilloscope (which is about 1 megohm, if no termination is used). However, practically achieving 2750 volts (2.75×10^{-3} amp $\times 10^6$ ohm) for the xenon-filled CIC at 10K watts is impossible for two reasons: One, achieving this kind of voltage at the input of the oscilloscope is not possible. Second, the voltage at the output of the detector cannot exceed the input high voltage of 500 volts. Therefore, using 10K watts reactor power, the xenon-filled CIC signal cannot be observed (or be valid) for the input impedance of 1 megohm, and therefore, it has to be terminated to be able to observe the response.

Figs. 4.75 and 4.76 show the high voltage response for the nitrogen and xenon-filled CIC at 1 KW reactor power, respectively. Comparison of the responses is shown in Fig. 4.77. A clear "hump" at the beginning for the nitrogen-filled CIC is apparent. The hump is related to the positive ion collection time. However, there is no such hump for the xenon-filled CIC.

After the steady value is reached, the current from the CIC decreases slowly to zero (this is the third component). The time taken to decay from the steady state value to ground level is roughly half the total of the first and second components.

1 KW Power, Nitrogen-Filled CIC
 >20 V/Div
 0.5 mSec/Div
 Ground: 1 Div Up
 500 Volt DC Bias Perturbation
 DC Coupling
 1 M Ω Oscilloscope Input
 $I_{ss} = 0.24$ mAmp

Figure 4.75: Nitrogen-Filled CIC Response at 1 KW Reactor Power Using High Voltage Perturbation

1 KW Power, Xenon-Filled CIC
 >20 V/Div
 0.5 mSec/Div
 Ground: 1 Div Up
 500 Volt DC Bias Perturbation
 1 M Ω Oscilloscope Input
 DC Coupling
 $I_{ss} = 0.42$ mAmp

Figure 4.76: Xenon-Filled CIC Response at 1 KW Reactor Power Using High Voltage Perturbation

Fig. 4.77: Comparison of the Nitrogen and Xenon-filled CIC Response Using the High Voltage Perturbation Experiment.

The high voltage perturbation experiments at different power levels show that changes in the detector and cable can be detected. These observations will be explained in more detail in the following sections.

4.4.4. Delay Effect on High Voltage Perturbation Analysis

The effect of delay due to cable or detector malfunction was simulated using a delay box. The delay box was placed between the CIC and the oscilloscope.

Fig. 4.78 shows the experimental results for a xenon-filled CIC at 1 KW reactor power. The results indicate that the fast (first) component was slowed from 20 nsec rise time to approximately 100 nsec. The second component seems to change considerably. The voltage signal from the CIC increases more slowly to a steady state value when the delay box is used. The third component seems to be also affected by the delay box. When the delay box is used, the CIC voltage signal reaches zero slower than when not used. A comparison of the CIC response with and without delay box is shown in Fig. 4.79.

Figs. 4.80 and 4.81 show the nitrogen-filled CIC high voltage perturbation response with and without the delay box. Fig. 4.82 shows the comparison of the two responses. Notice that the response is slowed by using a delay box.

4.4.5 The Effect of High Voltage Changes in the CIC High Voltage Perturbation Response

The effect of high voltage on the CIC response using the high voltage perturbations switch was studied next. Fig. 4.83 shows this result for

1 KW Power, Xenon-Filled CIC
 >20 V/Div
 0.1 μ Sec/Div
 500 Volt DC Bias Perturbation
 1 M Ω Oscilloscope Input

Figure 4.78 (a)

1 KW Power, Xenon-Filled CIC
 20 V/Div
 5 μ Sec/Div
 500 Volt DC Bias Perturbation
 1 M Ω Oscilloscope Input

Figure 4.78 (b)

1 KW Power, Xenon-Filled CIC
 >20 V/Div
 0.5 mSec/Div
 500 Volt DC Bias Perturbation
 1 M Ω Oscilloscope Input

Figure 4.78 (c)

1 KW Power, Xenon-Filled CIC
 >20 V/Div
 1 mSec/Div
 500 Volt DC Bias Perturbation
 1 M Ω Oscilloscope Input

Figure 4.78 (d)

Figure 4.78 : Delay Box Effect on the Xenon-Filled CIC Response to High Voltage Perturbation

Figure 4.79: Comparison of the Xenon-Filled CIC Response at 1 KW Reactor Power With and Without Delay Box Using High Voltage Perturbation

10 KW Power, Nitrogen-Filled CIC
20 V/Div
10 mSec/Div
500 Volt DC Bias Perturbation
1 M Ω Oscilloscope Input

Figure 4.80: Nitrogen-Filled CIC Response at 10 KW Reactor Power Using High Voltage Perturbation Without Delay Box

10 KW Power, Nitrogen-Filled CIC
20 V/Div
10 mSec/Div
500 Volt DC Bias Perturbation
1 M Ω Oscilloscope Input

Figure 4.81: Nitrogen-Filled CIC Response at 10 KW Reactor Power Using High Voltage Perturbation with Delay Box (A)

Figure 4.82 : Comparison of the Nitrogen-Filled
CIC Response at 10 KW Reactor
Power Using High Voltage Perturbation
With and without Delay Box

1 KW, Xenon-filled CIC
 >20 V/Div
 .02 μ sec/Div
 1 M Ω Oscilloscope input
 from Top to Bottom:
 500,400,300,200
 Volt DC Bias Perturbation

Figure 4.83 (a)

1 KW, Xenon-filled CIC
 >20 V/Div
 0.5 μ sec/Div
 1 M Ω Oscilloscope input
 from Top to Bottom:
 500,400,300,200
 Volt DC Bias Perturbation

Figure 4.83 (b)

1 KW, Xenon-filled CIC
 >20 V/Div
 0.2 msec/Div
 1 M Ω Oscilloscope input
 from Top to Bottom:
 500,400,300,200,100
 Volt DC Bias Perturbation

Figure 4.83 (c)

1 KW, Xenon-filled CIC
 >20 V/Div
 2 msec/Div
 1 M Ω Oscilloscope input
 from Top to Bottom:
 500,400,300,200,100
 Volt DC Bias Perturbation

Figure 4.83 (d)

Figure 4.83: Comparison of the Xenon-filled CIC Response for Different High Voltage Perturbations at 1 KW Reactor Power (Multi-exposure)

for the Xenon-filled CIC at 1K watt reactor power. It is observed that the speed of the first (fast) component does not change with the changes in high voltage. Only its amplitude increases with an increase in the high voltage. It is also observed that the time to reach the steady state value seems to increase with an increase in the high voltage. However, the initial slope of the CIC response (at the beginning of the response) is steeper for a higher bias voltage. This is an indication that the positive ion collection time is less for higher voltages. This was also proven by computer simulation. The steady state value is also different for different high voltages. This was expected based on the CIC plateau curves. This is because there is more recombination of positive ions and electrons at lower bias voltages (operating below the "knee" of the plateau curve).

4.4.6 Effect of Terminating Resistance on the CIC (Xe) High Voltage Perturbation Response

93 Ohm Terminator

In this section, the effect of a 93-ohm terminator on the CIC response is investigated using the high voltage perturbation method. The purpose of these experiments was to reduce the initial oscillatory behavior of the response.

It is believed that the oscillations at the beginning are due to cable impedance mismatch.

93 ohms first seems to be the best termination for the RG 71 B/U (nominal impedance of 93 ohms) used in the CIC cables. But as will be explained later 93 ohms is not a good choice to observe the response for the 10 KW O.S.U. reactors.

Fig. 4.84 shows the 93 Ω termination effects on the Xe-filled CIC response using high voltage perturbation at 10 KW reactor power.

10 KW Power, Xenon-Filled CIC
20 V/Div
0.2 μ Sec/Div
Ground: 1 Div Up
500 Volt DC Bias Perturbation
93 Ω Terminator
Break Points: 170 nSec
 320 nSec
 900 nSec

Figure 4.84: High Voltage Perturbed Response of Xenon-Filled
CIC. Reactor Power=10 KW, 93 Ω Termination

Two humps, one at approximately 170 nsec, and the other at 320 nsec are observed. The source of these humps is believed to be due to the cable and high voltage switch (they are also observed at zero reactor power). The amplitude of the occurrence of the first hump increases with an increase in the reactor power level. The rise time in all cases remains at about 20 nanoseconds. The amplitude of the response increases with an increase in the reactor power. It is observed that at about 0.9 μ sec the CIC response at 10 KWatts reaches a very small value. Nevertheless, the oscillations in the high voltage perturbation response were eliminated, no other conclusions regarding response can be obtained using the 93 ohm terminator.

Thus, there is a trade-off between using a 93 ohm and the other terminators. 93 ohm terminator which matches the impedance of the cable, eliminates the oscillation, but it reduces the amplitude of the signal significantly that the CIC response could not be observed.

Other Terminators

Since measuring the CIC high voltage perturbation response is not possible when using a 93 ohms terminator, it was decided to observe the CIC response at other termination values.

Fig. 4.85 shows the CIC (xenon-filled) response at 1 KW reactor power using a 10 K Ω termination. The result indicates that the amplitude of the steady state response decreases as expected when compared with no termination. Also, the response is much faster for the lower terminating resistance. The amplitude of the steady-state level increases with increase in the terminating resistor.

Fig. 4.86 shows the effect of changing terminating resistance on the xenon-filled CIC response for high voltage perturbation switch at

1 KW Power, Xenon-Filled CIC
20 V/Div
0.2 μ Sec/Div
10 K Ω Terminator
500 Volt DC Bias Perturbation

Figure 4.85 (a)

1 KW Power, Xenon-Filled CIC
20 V/Div
10 μ Sec/Div
10 K Ω Terminator
500 Volt DC Bias Perturbation

Figure 4.85 (b)

1 KW Power, Xenon-Filled CIC
20 V/Div
2 mSec/Div
10 K Ω Terminator
500 Volt DC Bias Perturbation

Figure 4.85 (c)

Figure 4.85 : Xenon-Filled CIC Response to High Voltage Perturbation
Perturbation at 10 KW Reactor Power Using
10K Ω Terminator

10 KW, Xenon-filled CIC
 >20 V/Div
 20 nsec/Div
 500 Volt DC Bias Perturbation
 R Terminator from Bottom to Top:
 500, 1K, 2K, 5K, 10K, 20K, 32K, 51K, 100K Ω

Figure 4.86 (a)

10 KW, Xenon-filled CIC
 20 V/Div
 0.5 μ sec/Div
 R Terminator from Bottom to Top:
 500, 1K, 2K, 5K, 10K, 20K, 32K, 51K, 100K Ω

Figure 4.86 (b)

10 KW, Xenon-filled CIC
 >20 V/Div
 10 μ sec/Div
 R Terminator from Bottom to Top:
 500, 1K, 2K, 5K, 10K, 20K, 32K, 51K, 100K Ω

Figure 4.86 (c)

10KW, Xenon-filled CIC
 >20 V/Div
 1 msec/Div
 R Terminator from Bottom to Top:
 1K, 2K, 5K, 10K, 20K, 32K, 51K, 100K Ω

Figure 4.86 (d)

Figure 4.86: Xenon-filled CIC Response to High Voltage Perturbation at 10 KW Reactor Power Using Different Terminators (Multi-Exposure)

10 KWatt reactor power. The same types of observations as before can be made.

4.4.7 The Effect of a Capacitance Terminator on the High Voltage Perturbation Response

Next the effect of capacitance on the CIC high voltage perturbation response was observed.

Fig. 4.87 (a) through (c) show the experimental results when a different terminating capacitor is used at the oscilloscope input (at the end of cable connected to CIC). The amplitude of the highest frequency component (fastest part of response) was reduced considerably. It also caused the second and third component to change slightly.

Fig. 4.88 shows the Xenon-filled CIC response at 1KW reactor power using high voltage perturbation. The comparison of the response with and without a 0.001 μ F capacitor is shown in fig. 4.89.

From these experiments one can conclude that one way to reduce the oscillation at the higher frequency relative to the low frequency component is to use a capacitance at the input of the oscilloscope. Using a terminating capacitor will change the CIC response. But, nevertheless, it could be used to observe the modified CIC response to monitor any degradations in the CIC and/or cable.

1 KW Power, Xenon-Filled CIC
10 V/Div
5 nSec/Div
500 Volt DC Bias Perturbation
1 M Ω Oscilloscope Input

Figure 4.87 (a)

1 KW Power, Xenon-Filled CIC
20 V/Div
0.5 μ Sec/Div
500 Volt DC Bias Perturbation
1 M Ω Oscilloscope Input

Figure 4.87 (b)

1 KW Power, Xenon-Filled CIC
>20 V/Div
0.5 mSec/Div
500 Volt DC Bias Perturbation
1 M Ω Oscilloscope Input

Figure 4.87 (c)

Figure 4.87: : Xenon- Filled CIC Response to High Voltage Perturbation at 1 KW Reactor Power for Different Terminating Capacitors (Multi-Exposure)

1 KW Power, Xenon-Filled CIC
 >20 V/Div
 1 mSec/Div
 500 Volt DC Bias Perturbation
 1 MΩ Oscilloscope Input
 $C_{ext} = 0.001 \mu F$

Figure 4.88 : Xenon-Filled CIC Response at 1 KW Reactor Power Using High Voltage Perturbation with an External Capacitor (0.001 μF)

1 KW Power, Xenon-Filled CIC
 >20 V/Div
 1 mSec/Div
 500 Volt DC Bias Perturbation
 1 MΩ Oscilloscope Input

Figure 4.89 : Comparison of the Xenon-Filled CIC Response with and without an External Capacitor Using High Voltage Perturbation

4.4.8 SUMMARY

The high voltage perturbation switch can be used to monitor the detector dynamics. As was shown, any degradation in the signal cable and/or detector which adds a capacitance, a resistance or a delay can be detected. Terminating the signal and observing the response can be the best way to monitor the CIC dynamics. However, the response of the terminated CIC is difficult to observe. It is expected that by modifying the mercury switch the magnitude of the CIC response at the beginning (first component) will be reduced and this will enable the experimenter to observe the response at lower oscilloscope sensitivity.

4.5 Sinusoidal High Voltage Perturbation Experimental Results

A traditional method used to study the dynamic behavior of a linear (or non-linear) system is to determine its frequency response. One method to experimentally determine the frequency response of the CIC is to sinusoidally perturb the high voltage input and observe the output voltage. The CIC output voltage is then a sine wave with the same frequency as the input with magnitude change and phase shift. These data are used to complete a Bode plot.

However, since the CIC normally operates in the plateau region of the bias curve (see Appendix B), various perturbations of the high voltage bias may be chosen. One method utilized a high voltage DC plus a small sinusoidal voltage. A second method utilized a large sine wave with no DC term. (In either method, the value of the DC and/or sinusoidal high voltage was dependent on the neutron flux level.)

The magnitude and phase plots of the CIC for both the nitrogen and xenon-filled CIC's using a sinusoidal high voltage perturbation, are shown in Fig. 4.90 and 4.91. The experimental results used to plot the frequency response are shown in Table C.1 and C.2 in Appendix C. The magnitude plots are almost identical. A least squares fit of the data indicates the "corner" frequency of 180 Hz for the xenon-filled CIC and 190 Hz for the nitrogen-filled CIC.

Fig. 4.92 and 4.93 show the magnitude and phase plots for the nitrogen and xenon-filled CIC at zero reactor power (when the detector bias voltage is perturbed at 35VDC + 70 VPP). The experimental result used to plot Fig. 4.92 and 4.93 are shown in Appendix C (Table C.3 and C.4) No appreciable difference is observed for both Xe and N₂-filled

Fig. 4.90 Magnitude Plots of the CIC Frequency Response at Zero Reactor Power

Fig. 4.91 Phase Plots of the CIC Frequency Response at Zero Reactor Power

Fig. 4.92 . Magnitude Plot of the CIC Frequency Response at no Reactor Power

Fig. 4.93 Phase Plot of the CIC Frequency Response at No Reactor Power.

in the frequency response. The corner frequency is about 155 HZ for both detectors. The roll-off slope is about +20db/decade. As is seen in Fig. 4.92 the CIC acts as a differentiator.

Fig. 4.94 shows the magnitude plots for the nitrogen and xenon-filled CIC at 10 KW reactor power (when there is a 100 VDC superposed on the sine wave). The corner frequency for the xenon-filled CIC is about 1500 HZ, whereas for the nitrogen-filled CIC is about 1400 HZ. The roll-off slope for xenon-filled CIC is higher than the nitrogen-filled CIC. This result indicates that xenon-filled CIC responds faster than nitrogen-filled CIC, which is not what is expected. The discrepancy is due to two reasons. One, the xenon-filled CIC was not operated at the plateau region of the bias curve (the bias curve for nitrogen and xenon-filled CIC are shown in Appendix B). Second, the experimental conditions were not quite the same for the two detectors. In testing the nitrogen filled CIC, it was noticed that the high voltage amplitude (CIC input) from the audio oscillator decreases with increasing frequency (due to frequency response of the amplifier of the audio oscillator). The decrease in the high voltage amplitude at high frequencies is clearly seen in Fig. 4.94 by further asymptote separation of the magnitude plots of the two detectors.

It is believed that if 1) the input high voltage stayed constant at all frequencies for both xenon and nitrogen-filled CIC, and 2) the D.C. portion of the CIC's high voltage were chosen in the plateau regions of both detectors, a higher cutoff frequency for nitrogen than the xenon-filled CIC would be observed.

Fig. 4.95 shows the phase plots for both CIC at 10KW reactor power. A higher phase shift for xenon-filled CIC (after 500HZ) than nitrogen CIC is observed.

Fig. 4.94 . Magnitude Plot of the CIC Frequency Response at 10KW Reactor Power.

Fig. 4.95. Phase Plot of the CIC Frequency Response at 10KW Reactor Power.

Fig. 4.96 and 4.97 show the magnitude and phase plot of the CIC frequency response at 10K Watt reactor power. The cutoff frequencies of 1300 HZ for Xe and 740 HZ for N_2 filled CIC are observed. This is an indication of faster response for xenon and N_2 -filled CIC. This, again contradicts the results obtained by other methods. The false result came from the fact that the 1) Xenon was operated at higher input high voltage, and high voltage would change the drift velocity of both ions and electrons and as the result would change the response time and cutoff frequency.

The effect of high voltage on the response time is discussed in detail in the computer simulation, 2) the plateau curve of xenon and nitrogen filled are different and with such a low operating bias voltage we are actually operating the detector in the recombination region for the Xenon-filled CIC and this may be the determining factor in giving the false result.

As in shown in Fig. 4.98 and 4.99, the magnitude and the phase plot of the frequency response for both xenon and nitrogen-filled CIC for 10 watt reactor operations are very similar for the frequencies above 500 HZ and below 20KHZ. However, the corner frequency for nitrogen-filled CIC is higher than for the Xe-filled CIC. The corner frequency for Xe-filled CIC is about 300 HZ, whereas, for nitrogen-filled CIC is about 400 HZ, (the cutoff frequency at zero power is 155 HZ). This value translates to the response times of

$$\text{for Xe: } t = \frac{1}{2\pi(300)} = 0.531 \text{ msec}$$

$$\text{for } N_2: t = \frac{1}{2\pi(400)} = 0.398 \text{ msec}$$

Fig. 4.96 . Magnitude Plot of the CIC Response at 10K Watt Reactor Power.

Fig. 4.97 . Phase Plot of the CIC Frequency Response at 10K Watt Reactor Power.

Fig. 4.98. Magnitude Plot of the CIC Frequency Response at 10 Watt Reactor Power.

Fig. 4.99 Phase Plot of the CIC Frequency Response for 10 Watt Reactor Power.

One cannot conclude from the results that xenon-filled CIC is slower than nitrogen-filled CIC due to statistical and measurement error. However, if the phase shift is analyzed, a similar conclusion is obtained. This is because the nitrogen-filled detector starts to reach zero phase shift at a faster rate.

Since the CIC response time depends on high voltage bias, a different value of response time is observed here.

Fig. 4.100 shows the magnitude plot of the xenon-filled CIC at zero power and 10 watts with the perturbed high voltage input of 35 VPC + 70 VPP. Increasing the reactor power from zero to 10 watts changes the CIC cutoff frequency from 180 to 300 HZ. The reason for this change is due to the change in dynamic behavior of the CIC. At 10 watt there is some charge transport inside the chamber. The change in the cutoff frequency can be related to the ion collection time. The 180 HZ cutoff at no reactor power can be due to the RC effect of the CIC.

Fig. 4.101 and 4.102 show the comparison of the magnitude and phase plot for the xenon-filled CIC at different high voltage inputs and reactor power. There are several observations and conclusions one can obtain from the comparison. These are:

- (1) The magnitude and phase plots are different for different high voltage inputs.
- (2) The phase shift is positive at zero (and low) power and frequencies and negative at high power and frequencies.

Fig. 4.100 Comparison of the Magnitude Plots of the Xenon-Filled CIC at No Reactor Power and 10 Watts.

Fig. 4.101 - Magnitude Plot of the Xenon-Filled CIC at Different Reactor Power Levels and High Voltage Input.

Fig. 4.102 Phase Plots of the Xenon-Filled CIC Frequency Response for Different Reactor Power Levels and High Voltage.

- (3) and the frequency response indicates that the
CIC at low and zero power acts as a differentiator
and at the higher power acts as an integrator.

The cause of the first two, is due to the fact that the overall CIC transfer function changes with alteration in high voltage bias and reactor power. There are also slight changes in the CIC capacitance and resistance due to the charge transport at different power levels.

At zero reactor power level the detector transfer function is

$$H(S) = \frac{S}{(S + T_0) \dots}$$

(The three dots indicate that there might be other terms that were not observed.)

At low reactor power level, the detector transfer functions changes to

$$G(S) = \frac{S^m}{(S + T_1) \dots}$$

Where $T_1 > T_0$, and $m < 1$

At higher power levels the detector transfer function changes to

$$O(S) = \frac{1}{(S + T_2) \dots}$$

Where $T_2 > T_1 > T_0$.

There is one final conclusion that can be obtained from sinusoidal frequency response experiments. This is due to the fact that

xenon-filled CIC is a non-linear system. This nonlinearity can be quite pronounced, especially when the CIC is operated at a high power level (10 KW). This nonlinearity is observed by looking at the sine wave output at the very low frequencies. One such nonlinearity is shown in Fig. 4.103. Notice that the input is a 22 HZ sine wave and the CIC output is distorted. It is important to recall that analysis of frequency response is not quite valid for non-linear systems.

CIC output vs output
22 Hz sine wave input

Input bias voltage 35
VDC + 80 VPP 1V/div
10 msec/div

Fig 4.103: Comparison of the CIC sine wave input and its distorted sine wave output

4.6 Comparison of the Experimental Results with the Computer Simulation

4.6.1 Step (Long X-ray) Response

Figures 4.104 and 4.105 show the computer simulation results for nitrogen and xenon-filled CIC response for a one-microsecond input pulse. The data (total detected Bremsstrahlung energy) to simulate the step response was obtained using the results shown in Tables 4.5 and 4.6 calculated from the computer program to predict the steady state value of the CIC response. The computer programs are presented in Appendix F. The shape of the input pulse was simulated using a first order "step" with approximately a 20 nsec response time (4 nsec time constant).

Comparison of the experimental and theoretical computer simulation of the CIC response for nitrogen and xenon-filled CICs are shown in Figures 4.106 and 4.107. Notice the "dip" observed in the experimental response of the long pulse from nitrogen-filled CIC. This may be due to either reflection in the cable or a charge recombination effect. This dip is not observed in the theoretical response. In the theoretical model, signal reflection is not considered. Some difference is also observed in the rise time of the theoretical and experimental response time. This difference in the response (theoretical vs. experimental) may be due to one or a combination of the following. First, the input data used in the CIC model, especially drift velocity of electrons and mobility of positive ions is somewhat uncertain and may not be accurate. The drift velocity of electrons from one source [25] was reported to be 1.30×10^6 cm/sec, while another source [15] was reported to be 1.15×10^6 cm/sec at the $\frac{X}{P}$ (the ratio of electric field to gas pressure) value of 2 V/cm-mm Hg. The mobility of positive ions in nitrogen gas from one source [11] was reported

Table 4.5 Computer results of the steady state response of a Nitrogen-filled CIC for a one microsecond input pulse

*** LEAD TARGET/NITROGEN FILLED DETECTOR ***

E	UM1	UM2	UM3	DETATT	TARATT	DETEFF	EX	EXX	EDD
0.800E-02	0.511E+02	0.706E+01	0.236E+03	0.908E-30	0.144E-03	0.291E-02	0.327E+00	0.262E-02	0.174E-47
0.100E-01	0.265E+02	0.354E+01	0.134E+03	0.195E-19	0.667E-02	0.146E-02	0.327E+00	0.655E-03	0.199E-28
0.150E-01	0.794E+01	0.110E+01	0.108E+03	0.123E-05	0.173E-01	0.454E-03	0.327E+00	0.163E-02	0.252E-14
0.200E-01	0.341E+01	0.555E+00	0.859E+02	0.209E-02	0.402E-01	0.229E-03	0.326E+00	0.163E-02	0.694E-11
0.300E-01	0.111E+01	0.287E+00	0.299E+02	0.148E+00	0.327E+00	0.119E-03	0.326E+00	0.326E-02	0.299E-08
0.400E-01	0.565E+00	0.221E+00	0.141E+02	0.380E+00	0.589E+00	0.912E-04	0.325E+00	0.325E-02	0.106E-07
0.500E-01	0.369E+00	0.194E+00	0.791E+01	0.531E+00	0.744E+00	0.802E-04	0.324E+00	0.324E-02	0.164E-07
0.600E-01	0.281E+00	0.189E+00	0.494E+01	0.618E+00	0.831E+00	0.741E-04	0.323E+00	0.323E-02	0.197E-07
0.800E-01	0.204E+00	0.163E+00	0.236E+01	0.705E+00	0.915E+00	0.673E-04	0.321E+00	0.645E-02	0.447E-07
0.100E+00	0.172E+00	0.153E+00	0.508E+01	0.744E+00	0.827E+00	0.630E-04	0.320E+00	0.641E-02	0.397E-07
0.150E+00	0.139E+00	0.135E+00	0.200E+01	0.788E+00	0.928E+00	0.558E-04	0.316E+00	0.159E-01	0.104E-06
0.200E+00	0.123E+00	0.123E+00	0.101E+01	0.810E+00	0.963E+00	0.509E-04	0.312E+00	0.157E-01	0.995E-07
0.300E+00	0.104E+00	0.107E+00	0.401E+00	0.836E+00	0.985E+00	0.440E-04	0.303E+00	0.307E-01	0.178E-06
0.400E+00	0.929E-01	0.955E-01	0.226E+00	0.853E+00	0.992E+00	0.394E-04	0.295E+00	0.299E-01	0.159E-06
0.500E+00	0.846E-01	0.872E-01	0.155E+00	0.865E+00	0.994E+00	0.360E-04	0.287E+00	0.291E-01	0.144E-06
0.600E+00	0.781E-01	0.806E-01	0.119E+00	0.875E+00	0.996E+00	0.333E-04	0.279E+00	0.283E-01	0.131E-06
0.800E+00	0.684E-01	0.708E-01	0.845E-01	0.889E+00	0.997E+00	0.292E-04	0.262E+00	0.541E-01	0.224E-06
0.100E+01	0.615E-01	0.636E-01	0.682E-01	0.900E+00	0.997E+00	0.262E-04	0.246E+00	0.508E-01	0.191E-06
0.102E+01	0.608E-01	0.629E-01	0.669E-01	0.901E+00	0.997E+00	0.260E-04	0.244E+00	0.539E-02	0.201E-07
0.150E+01	0.500E-01	0.518E-01	0.509E-01	0.918E+00	0.998E+00	0.213E-04	0.205E+00	0.107E+00	0.336E-06
0.200E+01	0.432E-01	0.444E-01	0.448E-01	0.929E+00	0.998E+00	0.184E-04	0.164E+00	0.922E-01	0.251E-06
0.204E+01	0.427E-01	0.439E-01	0.444E-01	0.929E+00	0.998E+00	0.181E-04	0.160E+00	0.714E-02	0.192E-07
0.300E+01	0.354E-01	0.358E-01	0.415E-01	0.941E+00	0.998E+00	0.147E-04	0.820E-01	0.116E+00	0.256E-06
0.400E+01	0.309E-01	0.306E-01	0.408E-01	0.948E+00	0.998E+00	0.126E-04	0.0	0.410E-01	0.784E-07

AVERAGE DETECTOR ATTENUATION----- 0.64629E+00
 AVERAGE TARGET ATTENUATION----- 0.75573E+00
 AVERAGE DETECTOR EFFICIENCY----- 0.24881E-03
 GEOMETRICAL FACTOR----- 0.15988E+00
 TOTAL BREMSSTRAHLUNG ENERGY----- 0.65600E+09 MEV/ABSORBED ELECTRON
 TOTAL BREMSSTRAHLUNG ENERGY(DEF)--- 0.23262E-05 MEV/ABSORBED ELECTRON
 TOTAL ABSORBED ENERGY----- 0.46463E+07 MEV/PULSE
 CIC CHARGE FOR EACH PULSE----- 0.21268E-07 COULOMBS
 THEORETICAL CIC CURRENT----- 0.21268E-01 AMPS
 OSC VOLTAGE WITH 50-OHM TERMINATOR- 0.10634E+01 VOLTS
 OSC VOLTAGE WITH 93-OHM TERMINATOR- 0.19779E+01 VOLTS

Table 4.6 Computer results of the steady state response of a Xenon-filled CIC for a one microsecond input pulse

*** LEAD TARGET/XENON FILLED DETECTOR ***

E	UM1	UM2	UM3	DETATT	TARATT	DETEFF	EX	EXX	EDD
0.800E-02	0.511E+02	0.313E+03	0.236E+03	0.988E-38	0.144E-03	0.444E+00	0.327E+00	0.262E-02	0.265E-45
0.100E-01	0.265E+02	0.173E+03	0.134E+03	0.195E-19	0.667E-02	0.277E+00	0.327E+00	0.655E-03	0.377E-26
0.150E-01	0.794E+01	0.581E+02	0.108E+03	0.123E-05	0.173E-01	0.103E+00	0.327E+00	0.163E-02	0.573E-12
0.200E-01	0.341E+01	0.266E+02	0.859E+02	0.289E-02	0.402E-01	0.485E-01	0.326E+00	0.163E-02	0.147E-08
0.300E-01	0.111E+01	0.875E+01	0.299E+02	0.148E+00	0.327E+00	0.162E-01	0.326E+00	0.326E-02	0.409E-06
0.400E-01	0.565E+00	0.229E+02	0.141E+02	0.380E+00	0.589E+00	0.419E-01	0.325E+00	0.325E-02	0.487E-05
0.500E-01	0.369E+00	0.128E+02	0.791E+01	0.531E+00	0.744E+00	0.237E-01	0.324E+00	0.324E-02	0.485E-05
0.600E-01	0.281E+00	0.789E+01	0.494E+01	0.618E+00	0.831E+00	0.147E-01	0.323E+00	0.323E-02	0.389E-05
0.800E-01	0.204E+00	0.364E+01	0.236E+01	0.705E+00	0.915E+00	0.679E-02	0.321E+00	0.645E-02	0.452E-05
0.100E+00	0.172E+00	0.201E+01	0.508E+01	0.744E+00	0.827E+00	0.375E-02	0.320E+00	0.641E-02	0.236E-05
0.150E+00	0.139E+00	0.713E+00	0.200E+01	0.788E+00	0.928E+00	0.133E-02	0.316E+00	0.159E-01	0.248E-05
0.200E+00	0.123E+00	0.371E+00	0.101E+01	0.810E+00	0.963E+00	0.694E-03	0.312E+00	0.157E-01	0.136E-05
0.300E+00	0.104E+00	0.177E+00	0.401E+00	0.836E+00	0.985E+00	0.332E-03	0.303E+00	0.307E-01	0.134E-05
0.400E+00	0.929E-01	0.121E+00	0.226E+00	0.853E+00	0.992E+00	0.226E-03	0.295E+00	0.299E-01	0.914E-06
0.500E+00	0.846E-01	0.957E-01	0.155E+00	0.865E+00	0.994E+00	0.179E-03	0.287E+00	0.291E-01	0.717E-06
0.600E+00	0.781E-01	0.817E-01	0.119E+00	0.875E+00	0.996E+00	0.153E-03	0.279E+00	0.283E-01	0.602E-06
0.800E+00	0.684E-01	0.661E-01	0.845E-01	0.889E+00	0.997E+00	0.124E-03	0.262E+00	0.541E-01	0.950E-06
0.100E+01	0.615E-01	0.572E-01	0.682E-01	0.900E+00	0.997E+00	0.107E-03	0.246E+00	0.508E-01	0.781E-06
0.102E+01	0.608E-01	0.564E-01	0.669E-01	0.901E+00	0.997E+00	0.106E-03	0.244E+00	0.539E-02	0.819E-07
0.150E+01	0.500E-01	0.457E-01	0.509E-01	0.918E+00	0.998E+00	0.855E-04	0.205E+00	0.107E+00	0.134E-05
0.200E+01	0.432E-01	0.405E-01	0.448E-01	0.929E+00	0.998E+00	0.758E-04	0.164E+00	0.922E-01	0.104E-05
0.204E+01	0.427E-01	0.402E-01	0.444E-01	0.929E+00	0.998E+00	0.752E-04	0.160E+00	0.714E-02	0.796E-07
0.300E+01	0.354E-01	0.366E-01	0.415E-01	0.941E+00	0.998E+00	0.684E-04	0.820E-01	0.116E+00	0.119E-05
0.400E+01	0.309E-01	0.352E-01	0.408E-01	0.948E+00	0.998E+00	0.658E-04	0.0	0.410E-01	0.408E-06

AVERAGE DETECTOR ATTENUATION----- 0.64629E+00
 AVERAGE TARGET ATTENUATION----- 0.75573E+00
 AVERAGE DETECTOR EFFICIENCY----- 0.40959E-01
 GEOMETRICAL FACTOR----- 0.15988E+00
 TOTAL BREMSSTRAHLUNG ENERGY----- 0.65600E+00 MEV/ABSORBED ELECTRON
 TOTAL BREMSSTRAHLUNG ENERGY(DET)--- 0.34183E-04 MEV/ABSORBED ELECTRON
 TOTAL ABSORBED ENERGY----- 0.68276E+08 MEV/PULSE
 CIC CHARGE FOR EACH PULSE----- 0.49495E-06 COULOMBS
 THEORETICAL CIC CURRENT----- 0.49495E+00 AMPS
 OSC VOLTAGE WITH 50-OHM TERMINATOR- 0.24748E+02 VOLTS
 OSC VOLTAGE WITH 93-OHM TERMINATOR- 0.46030E+02 VOLTS

Figure 4.104 Computer simulation of a Nitrogen-filled CIC response for a one-microsecond input pulse

Figure 4.105 Computer simulation of a Xenon-filled CIC response for a one-microsecond input pulse

Figure 4.106 Comparison of the experimental and theoretical Nitrogen-filled CIC response to a one-microsecond input pulse (normalized)

Figure 4.107 Comparison of the experimental and theoretical Xenon-filled CIC response to a one-microsecond input pulse (normalized)

to be $980 \text{ cm}^2\text{-mm Hg/volt-sec}$ and from another source [23] was reported to be $2000 \text{ cm}^2\text{-mm Hg/volt-sec}$. Two, the capacitance and resistance of the CIC with associated instrumentation were obtained using the manufacturer specifications and an estimate of the cable length, thus possibly resulting in an incorrect RC time constant. Third, the recombination modeling may be inadequate. Fourth, the electron attachment, which was ignored here, should be included in future theoretical analysis.

4.6.2 Impulse Response

The impulse response was simulated using half a sine wave. The impulse width and rise time were similar to the experiments. Figures 4.108 and 4.109 show the computer simulation results for both nitrogen and xenon-filled CIC. The inputs of the modeling (total detected Bremsstrahlung energy) to obtain the X-ray impulse response shown in Tables 4.7 and 4.8 were calculated using the prediction programs presented in Appendix F. Figures 4.110 and 4.111 show the comparison between the theoretical and experimental results. These results match closely. Again, a "dip" is observed in the experimental results for the Nitrogen-filled CIC. No such dip was observed in the theoretical results. The reason again may be due to recombination or reflection in the cable. The impulse response duration of both experimental and theoretical response are approximately identical. The comparison between the theoretical and experimental values of the xenon-filled CIC impulse response indicate that they are very similar except that some oscillations are observed in the experimental response. These oscillations may be due to signal reflection in the cable (from CIC to oscilloscope) resulting from an impedance mismatch.

Figure 4.108 Computer simulation of impulse response of a Nitrogen-filled CIC

Figure 4.109 Computer simulation of impulse response of a Xenon-filled CIC

Table 4.7 Computer results of the steady state response of a Nitrogen-filled CIC for a 20 nsec pulse

*** LEAD TARGET/NITROGEN FILLED DETECTOR/20 NSEC PULSE ***

E	UM1	UM2	UM3	DETATT	TARATT	DETEFF	EX	EXX	EDD
0.800E-02	0.511E+02	0.706E+01	0.236E+03	0.988E-38	0.144E-03	0.291E-02	0.327E+00	0.262E-02	0.174E-47
0.100E-01	0.265E+02	0.334E+01	0.134E+03	0.195E-19	0.667E-02	0.146E-02	0.327E+00	0.655E-03	0.199E-28
0.150E-01	0.794E+01	0.110E+01	0.108E+03	0.123E-05	0.173E-01	0.454E-03	0.327E+00	0.163E-02	0.252E-14
0.200E-01	0.341E+01	0.555E+00	0.859E+02	0.289E-02	0.402E-01	0.229E-03	0.326E+00	0.163E-02	0.694E-11
0.300E-01	0.111E+01	0.287E+00	0.299E+02	0.148E+00	0.327E+00	0.119E-03	0.326E+00	0.326E-02	0.299E-08
0.400E-01	0.565E+00	0.221E+00	0.141E+02	0.380E+00	0.589E+00	0.912E-04	0.325E+00	0.325E-02	0.106E-07
0.500E-01	0.369E+00	0.194E+00	0.791E+01	0.531E+00	0.744E+00	0.802E-04	0.324E+00	0.324E-02	0.164E-07
0.600E-01	0.281E+00	0.180E+00	0.494E+01	0.618E+00	0.831E+00	0.741E-04	0.323E+00	0.323E-02	0.197E-07
0.800E-01	0.204E+00	0.163E+00	0.236E+01	0.705E+00	0.915E+00	0.673E-04	0.321E+00	0.645E-02	0.447E-07
0.100E+00	0.172E+00	0.153E+00	0.508E+01	0.744E+00	0.827E+00	0.630E-04	0.320E+00	0.641E-02	0.397E-07
0.150E+00	0.139E+00	0.135E+00	0.200E+01	0.788E+00	0.928E+00	0.558E-04	0.316E+00	0.159E-01	0.104E-06
0.200E+00	0.123E+00	0.123E+00	0.101E+01	0.810E+00	0.963E+00	0.509E-04	0.312E+00	0.157E-01	0.995E-07
0.300E+00	0.104E+00	0.107E+00	0.401E+00	0.836E+00	0.985E+00	0.440E-04	0.303E+00	0.307E-01	0.178E-06
0.400E+00	0.929E-01	0.955E-01	0.226E+00	0.853E+00	0.992E+00	0.394E-04	0.295E+00	0.299E-01	0.159E-06
0.500E+00	0.846E-01	0.872E-01	0.155E+00	0.865E+00	0.994E+00	0.360E-04	0.287E+00	0.291E-01	0.144E-06
0.600E+00	0.781E-01	0.806E-01	0.119E+00	0.875E+00	0.996E+00	0.333E-04	0.279E+00	0.283E-01	0.131E-06
0.800E+00	0.684E-01	0.708E-01	0.845E-01	0.889E+00	0.997E+00	0.292E-04	0.262E+00	0.541E-01	0.224E-06
0.100E+01	0.615E-01	0.636E-01	0.682E-01	0.900E+00	0.997E+00	0.262E-04	0.246E+00	0.508E-01	0.191E-06
0.102E+01	0.608E-01	0.629E-01	0.669E-01	0.901E+00	0.997E+00	0.260E-04	0.244E+00	0.539E-02	0.201E-07
0.150E+01	0.500E-01	0.518E-01	0.509E-01	0.918E+00	0.998E+00	0.213E-04	0.205E+00	0.107E+00	0.336E-06
0.200E+01	0.432E-01	0.444E-01	0.448E-01	0.929E+00	0.998E+00	0.184E-04	0.164E+00	0.922E-01	0.251E-06
0.204E+01	0.427E-01	0.439E-01	0.444E-01	0.929E+00	0.998E+00	0.181E-04	0.160E+00	0.714E-02	0.192E-07
0.300E+01	0.354E-01	0.358E-01	0.415E-01	0.941E+00	0.998E+00	0.147E-04	0.820E-01	0.116E+00	0.256E-06
0.400E+01	0.309E-01	0.306E-01	0.408E-01	0.948E+00	0.998E+00	0.126E-04	0.0	0.410E-01	0.784E-07

AVERAGE DETECTOR ATTENUATION----- 0.64629E+00
 AVERAGE TARGET ATTENUATION----- 0.75573E+00
 AVERAGE DETECTOR EFFICIENCY----- 0.24881E-03
 GEOMETRICAL FACTOR----- 0.15988E+00
 TOTAL BREMSSTRAHLUNG ENERGY----- 0.65600E+00 MEV/ABSORBED ELECTRON
 TOTAL BREMSSTRAHLUNG ENERGY(DET)--- 0.23262E-03 MEV/ABSORBED ELECTRON
 TOTAL ABSORBED ENERGY----- 0.17423E+06 MEV/PULSE
 CIC CHARGE FOR EACH PULSE----- 0.79755E-09 COULOMBS
 THEORETICAL CIC CURRENT----- 0.39877E-01 AMPS
 OSC VOLTAGE WITH 50-OHM TERMINATOR- 0.19939E+01 VOLTS
 OSC VOLTAGE WITH 93-OHM TERMINATOR- 0.37086E+01 VOLTS

Table 4.8 Computer results of the steady state response of a Xenon-filled CIC for a 20 nsec pulse

*** LEAD TARGET/XENON FILLED DETECTOR20 NSEC PULSE ***

E	UM1	UM2	UM3	DETATT	TARATT	DETEFF	EX	EXX	EDD
0.800E-02	0.511E+02	0.313E+03	0.236E+03	0.988E-38	0.144E-03	0.444E+00	0.327E+00	0.262E-02	0.265E-45
0.100E-01	0.265E+02	0.173E+03	0.134E+03	0.195E-19	0.667E-02	0.277E+00	0.327E+00	0.655E-03	0.377E-26
0.150E-01	0.794E+01	0.581E+02	0.108E+03	0.123E-05	0.173E-01	0.103E+00	0.327E+00	0.163E-02	0.573E-12
0.200E-01	0.341E+01	0.266E+02	0.859E+02	0.289E-02	0.402E-01	0.485E-01	0.326E+00	0.163E-02	0.147E-08
0.300E-01	0.111E+01	0.875E+01	0.299E+02	0.148E+00	0.327E+00	0.162E-01	0.326E+00	0.326E-02	0.409E-06
0.400E-01	0.565E+00	0.229E+02	0.141E+02	0.380E+00	0.589E+00	0.419E-01	0.325E+00	0.325E-02	0.487E-05
0.500E-01	0.369E+00	0.128E+02	0.791E+01	0.531E+00	0.744E+00	0.237E-01	0.324E+00	0.324E-02	0.485E-05
0.600E-01	0.281E+00	0.789E+01	0.494E+01	0.618E+00	0.831E+00	0.147E-01	0.323E+00	0.323E-02	0.389E-05
0.800E-01	0.204E+00	0.364E+01	0.236E+01	0.705E+00	0.915E+00	0.679E-02	0.321E+00	0.645E-02	0.452E-05
0.100E+00	0.172E+00	0.201E+01	0.508E+01	0.744E+00	0.827E+00	0.375E-02	0.320E+00	0.641E-02	0.236E-05
0.150E+00	0.139E+00	0.713E+00	0.200E+01	0.788E+00	0.928E+00	0.133E-02	0.316E+00	0.159E-01	0.248E-05
0.200E+00	0.123E+00	0.371E+00	0.101E+01	0.810E+00	0.963E+00	0.694E-03	0.312E+00	0.157E-01	0.136E-05
0.300E+00	0.104E+00	0.177E+00	0.401E+00	0.836E+00	0.985E+00	0.332E-03	0.303E+00	0.307E-01	0.134E-05
0.400E+00	0.929E-01	0.121E+00	0.226E+00	0.853E+00	0.992E+00	0.226E-03	0.295E+00	0.299E-01	0.914E-06
0.500E+00	0.846E-01	0.957E-01	0.155E+00	0.865E+00	0.994E+00	0.179E-03	0.287E+00	0.291E-01	0.717E-06
0.600E+00	0.781E-01	0.817E-01	0.119E+00	0.875E+00	0.996E+00	0.153E-03	0.279E+00	0.283E-01	0.602E-06
0.800E+00	0.684E-01	0.661E-01	0.845E-01	0.889E+00	0.997E+00	0.124E-03	0.262E+00	0.541E-01	0.950E-06
0.100E+01	0.615E-01	0.572E-01	0.682E-01	0.900E+00	0.997E+00	0.107E-03	0.246E+00	0.508E-01	0.781E-06
0.102E+01	0.608E-01	0.564E-01	0.669E-01	0.901E+00	0.997E+00	0.106E-03	0.244E+00	0.539E-02	0.819E-07
0.150E+01	0.500E-01	0.457E-01	0.509E-01	0.918E+00	0.998E+00	0.855E-04	0.205E+00	0.107E+00	0.134E-05
0.200E+01	0.432E-01	0.405E-01	0.448E-01	0.929E+00	0.998E+00	0.758E-04	0.164E+00	0.922E-01	0.104E-05
0.204E+01	0.427E-01	0.402E-01	0.444E-01	0.929E+00	0.998E+00	0.752E-04	0.160E+00	0.714E-02	0.796E-07
0.300E+01	0.354E-01	0.366E-01	0.415E-01	0.941E+00	0.998E+00	0.684E-04	0.820E-01	0.116E+00	0.119E-05
0.400E+01	0.309E-01	0.352E-01	0.408E-01	0.948E+00	0.998E+00	0.658E-04	0.0	0.410E-01	0.408E-06

AVERAGE DETECTOR ATTENUATION----- 0.64629E+00
 AVERAGE TARGET ATTENUATION----- 0.75573E+00
 AVERAGE DETECTOR EFFICIENCY----- 0.40959E-01
 GEOMETRICAL FACTOR----- 0.15988E+00
 TOTAL BREMSSTRAHLUNG ENERGY----- 0.65600E+00 MEV/ABSORBED ELECTRON
 TOTAL BREMSSTRAHLUNG ENERGY(DET)--- 0.34183E-04 MEV/ABSORBED ELECTRON
 TOTAL ABSORBED ENERGY----- 0.25603E+07 MEV/PULSE
 CIC CHARGE FOR EACH PULSE----- 0.18561E-07 COULOMBS
 THEORETICAL CIC CURRENT----- 0.92803E+00 AMPS
 OSC VOLTAGE WITH 50-OHM TERMINATOR- 0.46402E+02 VOLTS
 OSC VOLTAGE WITH 93-OHM TERMINATOR- 0.86307E+02 VOLTS

Figure 4.110 Comparison of the theoretical and experimental impulse response of a Nitrogen-filled CIC

Figure 4.111 Comparison of the theoretical and experimental impulse response of a Xenon-filled CIC

4.6.3 High Voltage Perturbation

High voltage perturbation experiments were simulated for both the nitrogen and xenon-filled CIC. The computer results are plotted in Figures 4.112 to 4.114. In the experimental high voltage perturbation, the CIC signal cable was not terminated. This was necessary to be able to observe the signal on the oscilloscope. A comparison between the response of the terminated and non-terminated cable are shown (see Figures 4.112 through 4.114). Notice that the response time and the signal amplitude were increased by not terminating the cable. Comparison of the nitrogen and xenon-filled CIC responses(theoretical) to high voltage perturbation for the non-terminated case ($1\text{ M}\Omega$) is shown in Figure 4.115. It is apparent that the nitrogen-filled CIC response is faster than the xenon-filled CIC. A comparison between the theoretical and measured CIC response (normalized) is shown in Figure 4.116. Some differences are observed. These differences are more noticeable at the beginning of the response. The measured response rises much faster at the beginning. This may be due to the transients of the high voltage switch and/or incorrect theoretical data. The fast transient of the switch raises the response voltage very quickly and then the response due to the positive ions causes a further increase in the response until it reaches a steady state value.

Figure 4.112 Computer simulation of the Nitrogen-filled CIC response to a high voltage perturbation at 1 kW reactor power

Figure 4.113 Computer simulation of the Nitrogen-filled CIC response to high voltage perturbation at 1 kW reactor power

Figure 4.114 : Xenon-filled CIC response to high voltage perturbation at 1 kW reactor power

Figure 4.115: Comparison of the computer simulation of the Nitrogen and Xenon-filled CIC response to high voltage perturbation at 1 kW reactor power

Figure 4.116 : Comparison of the experimental and theoretical Nitrogen and Xenon-filled CIC response (normalized) to high voltage perturbation

4.6.4 Scram (Ramp) Response

Computer simulation of the O.S.U. reactor scram response can be divided into three sections. First is the Rods Drop modeling, second is the Point Kinetics, and third is the CIC detector modeling. The computer simulation of the O.S.U. reactor scram response, excluding the CIC detector, is shown in Figure 4.117. Examination of the Rods Drop and Point Kinetics indicate that the response is very slow. Since the response of both Xenon and Nitrogen-filled CIC is much faster than the results shown, there is no need for simulating the scram response to include the CIC detector modeling because a similar response should be observed. Due to expensive computer time, this was verified for a short time by running the complete model (Rods Drop, Point Kinetics, and CIC detector).

A comparison of the experimental Xenon and Nitrogen-filled CIC scram response with the theoretical O.S.U. reactor scram response (excluding CIC) is shown in Figure 4.118 (normalized amplitudes). Some small difference is observed at the beginning of the response. This difference may be due to different triggering levels in the oscilloscope when the data were taken. The response duration however, is nearly identical for all of them.

Figure 4.117 O.S.U. Reactor Scram Response (excluding CIC detector response)

Figure 4.118: Comparison of the Nitrogen and Xenon Filled CIC Scram Response

4.6.5 Summary

It is concluded that the theoretical model is a good representation of the experimental CIC response. However, there are several improvements in the mathematical model which should be made to predict the experimental response more closely. These recommended changes are:

- Recombination of the electron and positive ions needs to be modeled more precisely.
- The cable reflection needs to be included in the CIC modeling.
- Electron attachment effects for both xenon and nitrogen gases are negligible. However, for other gases such as air, oxygen, etc., this may not be the case, and must be included in the model for future analysis.

4.7 Linearity of the Nitrogen and Xenon-filled CIC

Linearity of the CIC current relative to the reactor power level at 500 volt bias voltage is evaluated in this section. The nitrogen and xenon-filled CIC were measured at reactor power levels of 10 W, 100 W, 1 kilowatt, and 10 kilowatts with a Keithley 414S picoammeter. The results are tabulated in Table 4.9 and plotted in Figure 4.119. It is apparent that the nitrogen-filled CIC is linear with reactor power level at 500 volt bias voltage up to 10 kwatt reactor power. However, the xenon-filled CIC current is only linear with reactor power level up to 1 kilowatt, and it becomes nonlinear above that. This is due to the fact that Xenon-filled CIC at 500 volts bias voltage is operating below the "knee" of the plateau curve (see Appendix B).

An indication of the linearity of the CIC can be obtained by calculating the correlation coefficient for a least squares fit of the data. The correlation coefficient for the N_2 -filled CIC is 0.999, whereas, for the xenon-filled CIC it is 0.998.

Table 4.9: Comparison of the CIC current with different gas-filling

Reactor Power Level (watt)	CIC current (amp)	
	N ₂	Xe
10	2.425×10^{-6}	4.3×10^{-6}
100	2.2×10^{-5}	4.2×10^{-5}
1K	2.35×10^{-4}	4.15×10^{-4}
10K	2.35×10^{-3}	2.75×10^{-3}

Figure 4.119 Linearity Comparison Between Nitrogen and Xenon-filled CIC

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Several conclusions can be made as a result of the present work. These are as follows:

- 1) High voltage perturbation has definite potential for being effectively developed as an in-situ method to measure response time, or for diagnosing degradation in the CIC detector and its instrumentation. As was shown in Section 4.4, any degradation in the signal cable and/or detector which adds a capacitance, a resistance or a delay time can be detected using high voltage perturbation technique. However, a definitive conclusion regarding measurement of degradation resulting from detector fill gas change cannot be made.
- 2) The noise analysis technique has promise as a method to observe degradation in the CIC and its instrumentation (as was shown in Section 4.2). Specifically, the changes in the response caused by changes in fill gas were demonstrated in Section 4.2.3. The effects of delay time and capacitance changes used to simulate cable degradation were discussed in Sections 4.2.4 and 4.2.5 respectively. However, the noise analysis technique may not be used to measure absolute response time (at least in the low fluxes of a research reactor). In power reactors, it is believed that noise analysis may be a good technique to monitor

the response time when the detector signal cable is correctly terminated.

- 3) In neutron sensor response time measurement, one must pay particular attention to the cable and associated measurement system. As was shown in Chapter IV (see Sections 4.1, 4.2, and 4.4), change(s) in cable, detector, and/or measurement system input will alter the measured detector response time.
- 4) Positive ion and electron collection time are the primary components of neutron sensor response time (excluding the RC time constant of the detector, cable, and measurement system). This was concluded by the results of the analytical simulation discussed in Section 2.5.4 (see Figures 2.27 through 2.30).
- 5) When the neutron sensor degrades, the response time as well as sensitivity are altered. This conclusion was obtained both from the bias curves data shown in Appendix B and from the measurement of the response using different techniques discussed in Chapter IV.
- 6) Increasing the detector bias voltage decreases its response time. This was demonstrated in Figures 2.35 and 4.17, and in Section 4.1.2.
- 7) Step (one μ sec pulse) and impulse (20 nsec pulse) response using LINAC are the excellent laboratory methods to investigate the neutron sensor response time degradation. Both changes in fill gas and cable degradation were studied with an impulse response but degradation in the cable was not studied for a step response.

It is expected that the cable degradation can also be studied using step response.

- 8) Measurement of the positive ion response time (due to collection of positive ions) from the step response is not possible using a one μsec x-ray pulse (see Section 4.1.1).
- 9) Measurement of the electron response time (due to collection of electrons) is not possible for detectors which have an electron collection time greater than 1 μsec using a one μsec x-ray pulse (see Section 4.1.1).

5.2 Recommendations

- 1) In the theoretical model, the following improvements are recommended:
- . Due to expensive computer time using the CSMP package, the mathematical equation may be solved using the Crank-Nicolson or Weighted Residual method (using FORTRAN IV).
 - . Cable modelling must be improved. It should also include signal reflection in the coaxial cable.
 - . Recombination of positive ions and electrons must be modeled more precisely to include spatial distribution.
 - . Electron attachment is not included in the model. It must be included for detectors with fill gases that contain oxygen, air, or water vapor, etc.
- 2) In the high voltage perturbation using the mercury-wetted contact relay switch, the following improvements are recommended:
- . The frequency of the input sine waves to the switch may be increased to reduce the width of the high voltage pulse.

Thus, it may be possible to perform experiments similar to X-ray experiments.

- . The high voltage switch should be modified to eliminate or minimize the switch transients.

- . A current or voltage probe should be used to couple the CIC signal to the oscilloscope. This would eliminate or reduce the signal reflections in the cable caused by impedance mismatch.

3) In the noise analysis method, the following improvements are recommended:

- . Use a proper terminator at the input of the FFT analyzer (to decrease the RC time constant of the detector, cable, and measurement system) to be able to more clearly observe the response time related to the collection of positive ions.

- . Increase the upper frequency of the power spectrum to be able to observe the response time related to the collection of electrons (with the proper terminator).

4) Design a high voltage pulser to obtain CIC impulse response (using the high voltage perturbation method).

5) Sinusoidal frequency response of the CIC at higher frequencies can be obtained using a power amplifier (General Radio Company, Model 1308A) and a sinewave generator (Wavetek).

6) Study the effect of other fill gases on the CIC response.

7) Evaluate the feasibility of relating steady state response time measured by either high voltage perturbation or noise analysis.

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APPENDIX A

EXPERIMENTAL APPARATUS AND DESIGN

A.1 Test Detector Configuration

The detector used in all experiments was a modified Compensated Ion Chamber (CIC) manufactured by Reuter Stokes (Model No. RS - C1 - 2514 and equivalent to RSN - 15A, see Fig. A.1 through A.3). The modification made by Reuter Stokes provided the capability of changing the detector fill gas. Normally, the CIC chamber is filled with nitrogen gas at one atmosphere pressure. In this research program, experiments were performed using two detector configurations: one using a nitrogen-fill gas and one using a xenon-fill gas, both at one atmosphere pressure. Xenon was used to investigate its effect in the response time of the detector. Changing the detector gas simulates the detector degradation.

CIC's are typically used in the reactors for power monitoring purposes. The detector is an electrically compensated ionization chamber for measuring thermal neutron flux over the range of 2.5×10^2 to 2.5×10^{10} neutron/cm²-sec (designated as nv). The detector can also be used to measure gamma rays or x-rays. However, it is designed for use in mixed neutron and gamma flux ~~is~~ where the gamma radiation is a significant portion of the total radiation. Under these conditions, the gamma current is a large portion of the total ionization current

Figure A.1: Physical Dimension of the CIC detector

Figure A.2: Top cross-section of the CIC Model RS-C1-2514-115 (not to scale)

Figure A.3: Half of the cross-section of the CIC Model RS-C1-2514-115 (Not to scale)

produced in the chamber, and compensation is required. For simplicity however, since there are two separate chambers in the CIC, one sensitive to gamma (or X-ray) only, and the other sensitive to both neutron and gamma (or X-ray), only the chamber sensitive to both gamma and neutron was used to perform all the experiments. The chamber sensitive to gammas (or X-rays) and neutrons requires a high voltage source (bias voltage). The chamber sensitive to gammas only requires a negative compensating voltage. By capping the negative compensating voltage electrode and not supplying any negative voltage, the gamma chamber was made inactive. All the ion-pairs produced in that chamber will combine due to the lack of polarizing voltage. The comparison between the nitrogen and xenon-filled CIC's is shown in Table A.1.

A.2 Pulsed X-Ray Production

In this section the analysis necessary to design and produce x-ray pulses from the Varian Linear Electron Accelerator (LINAC) is presented.

Since x-rays and gammas are both photons, and the detector is sensitive to gammas, it is also sensitive to x-rays.

When high velocity electrons from the LINAC come close to and are deflected (accelerated) by positively charged nuclei in the target, the following fundamental processes occur. An electron experiences a force as a consequence of its near collision with a nucleus and is diverted from its straight line path (that is, it is accelerated). Classical electromagnetic theory predicts that accelerated electric charge will radiate electromagnetic energy. Quantum theory requires

TABLE A.1
SPECIFICATION

Compensated Ionization Chamber Model No. Modified RS-C1-2514-115 (former RSN-15), Serial No. 2-7810		
Test parameters	Nitrogen-fill gas (1 atmosphere pressure)	Xenon-fill gas (4 atmospheres pressure)
Neutron sensitivity (Amp/NV) (measured at 640 NV flux)	6.9×10^{-14}	1.3×10^{-13}
Gamma sensitivity (Amp/R/hr) uncompensated (tested by Co-60 source, traceable to NBS)	1.42×10^{-11} *Co-60 source intensity 63.3 R/hr, 1500 volt applied H.V.	1.14×10^{-10} Co-60 source intensity 61.7 R/hr, 1500 volts applied H.V.
Resistance, OHMS (25°C, 60%, relative humidity)	Signal to ground	5×10^{13}
	H.V. to ground	5×10^{13}
	Comp. to ground	5×10^{13}
Capacitance, p.f. (25°C, 60% relative humidity)	Signal to ground	320
	H.V. to ground	344.8
	Comp. to ground	174.8
	Signal to high voltage	24.8
Mechanical	Maximum diameter	3-5/32 inches (8.02 cm)
	Maximum overall length	23-3/4 inches (60.32 cm)
	Sensitive length connectors	13-13,16 inches (35.08 cm) Type HW
	Net weight	8 pounds (3.63 kg)
	Boron thickness	(1.739×10^{-5}) inches (1.739×10^{-4}) cm
Material	Outer shell & inner electrodes	1100 Aluminum
	Connectors	6061 Aluminum
	Detector insulation	Alumina ceramic
	Connectors insulation	Alumina ceramic
	Neutron sensitive materials	Boron enriched to >92% 8-10)
Maximum ratings	Inter-electrode voltage	1500 volts
	Temperature	300°C
	Thermal neutron flux	10 nv
	Burn-up for life	2×10^{19} nvt
	for 10% decrease in sensitivity	

* Boron areal density 0.4 mg/cm^2
Boron density 2.3 g/cm^3

that radiated electromagnetic energy consist of discrete quanta or photons. A deflected (and therefore accelerated) electron will radiate one or more photons and will leave the site of collision with less kinetic energy. The resulting radiation is called Bremstrahlung ("breaking radiation"). This is shown in Fig. A.4.

Classical electromagnetic theory predicts continuous radiation throughout the time that the electron is accelerated, whereas quantum theory predicts radiation in single, discrete photons of the Bremstrahlung process. Upon striking the target the fast electrons are decelerated and brought essentially to rest by collisions. Each electron loses its kinetic energy as a result of impact with the target material. Most of this energy appears as thermal energy in the target, but there is, in addition, the production of electromagnetic radiation through the Bremstrahlung process. Any electron striking the target may make a number of Bremstrahlung-producing collisions with atoms in the target, thereby producing a number of photons. The most energetic photon is produced, however, by an electron whose entire kinetic energy is converted into electromagnetic energy when the electron is brought to rest in a single collision.

The total Bremstrahlung radiation produced for a thick target, assuming a monoenergetic electron, can be obtained using the following equations [37].

$$\text{Total Bremstrahlung energy, } E_{\text{xx}} = KZE^2, \quad (\text{A-1})$$

where: E = initial kinetic energy of the electron (Mev)

Z = atomic number of the thick target

K = constant (1/Mev).

Figure A.4: Bremsstrahlung Radiation

The Spectral Distribution for thick-target Bremsstrahlung using the Sommerfeld Nonrelativistic Theory and semi-empirical relations [37]

$$\frac{d E_{xx}(\nu)}{d\nu} = CZ (\nu_{\max} - \nu) \quad (A-2)$$

where: C = a constant

$\nu_{\max}$ = maximum frequency of the x-ray photons produced

ν = frequency of x-ray

Since Energy (E) is related to frequency by the relation:

$$E = h\nu, \quad \text{or} \quad \nu = \frac{E}{h}, \quad (A-3)$$

where: h = Planck's constant

Therefore,

$$\frac{d E_{xx}}{d(E/h)} = CZ \frac{E_{\max}}{h} - \frac{E}{h} \quad (A-4)$$

or

$$\frac{d E_{xx}}{dE} (E) = \frac{C}{h^2} Z (E_{\max} - E). \quad (A-5)$$

Now integrating the above equation gives

$$E_{xx} = \int_0^{E_{\max}} \frac{C}{h^2} Z (E_{\max} - E) dE \quad (A-6)$$

$$E_{xx} = \left[\frac{C}{h^2} Z E_{\max} E - \frac{CZ}{h^2} \frac{E^2}{2} \right]_0^{E_{\max}} \quad (A-7)$$

$$E_{xx} = \frac{CZ}{2h^2} E_{\max}^2. \quad (A-8)$$

Comparing the above equation with Equation A-1 yields

$$K = \frac{C}{2h^2} \quad . \quad (A-9)$$

The theoretical value of K [37] for an electron energy of 0.5 to 4.6 Mev is 0.5×10^{-3} . In a computer analysis, the following form is used:

$$Ex(I) \approx \frac{dExx}{dE} (I) = 2KZ (E_{\max} - E(I)) \quad (A-10)$$

The total Bremstrahlung energy can be obtained by integrating Ex using numerical techniques. One of the simplest techniques is the trapezoidal rule, in which the integral is approximated by the sum of trapezoidal areas. Thus,

$$Exx = \int_0^{E_{\max}} \frac{dExx}{dE} (E) dE = \int_0^{E_{\max}} Ex dE \quad (A-11)$$

or

$$Exx = \sum_{I=2}^n 0.5(Ex(I-1) + Ex(I))(E(I) - E(I-1)) \quad (A-12)$$

A.2.1 Target Consideration

Several target materials are available, but due to various considerations (including price), lead was chosen. A comparison of different materials is shown in Table A.2.

Table A.2 Comparison of Different Target Materials for X-ray Production

Target Material	Z	ρ density g/cm ³	Range of electrons in the target, cm.	$I=KZE^2$ Mev	$I/E=KZE$ (%)
Tungsten, W	74	19.350	0.104	0.592	14.8
Copper Cu	29	8.954	0.225	0.232	5.8
Molybdenum Mo	42	10.220	0.197	0.330	8.4
Chromium Cr	24	7.2	0.280	0.192	4.8
Aluminum Al	13	2.707	0.744	0.104	2.6
Lead Pb	82	11.347	0.177	0.656	16.4

In Table A.2 it is assumed (see Reference [37]) that $K = 0.5 \times 10^{-3} \text{ Mev}^{-1}$, and the electron energy (E) is 4 Mev. The range of electrons in the target calculated using the range-energy empirical relation (assuming monoenergetic electron) described in Reference [37], as follows:

$$R_O(\text{mg/cm}^2) = 530 E - 106 ; \quad (\text{A-13})$$

substituting for E results in

$$R_O = 530(4) - 106,$$

or

$$R_O = 2014 \text{ mg/cm}^2.$$

Knowing the density of the target, the electron range may be calculated. Electron range was used in selecting proper thickness of target material.

Other considerations in choosing the target material included finding the amount of energy that would be converted into heat in the target and assuring that the target would not melt.

Lead was chosen as the target material because 1) lead is a soft metal. Thus it can be easily shaped around the detector with very little effort, 2) lead is available as a sheet and its price is less than other target materials under consideration, 3) its high Z value results in a high conversion factor.

A.2.2 Target and Detector Attenuation

X-rays generated in the target will be attenuated by the target itself and the detector walls. Lambert's attenuation law predicts the intensity of the x-ray flux emerging from the target or detector walls. Detector attenuation using Lambert's law is

$$\text{DET ATT} = \text{detector attenuation} = e^{-\left(\frac{\mu_1}{\rho_1}\right) x_1 \rho_1} \quad (\text{A-14})$$

where: $\left(\frac{\mu_1}{\rho_1}\right)$ is the mass attenuation coefficient of Al walls of the detector

$x_1 = 0.25$ in total Al thickness of the wall

$\rho_1 = 2.699 \text{ g/cm}^3$, Al density.

Target attenuation using Lambert's law is

$$\text{TAR ATT} = \text{target attenuation} = e^{-\left(\frac{\mu_3}{\rho_3}\right) x_3 \rho_3} \quad (\text{A-15})$$

where: $\left(\frac{\mu_3}{\rho_3}\right)$ is the mass attenuation coefficient of lead target

$x_3 = \text{target thickness} - \text{range of electrons in the target}$

$= 0.1803 \text{ cm} - 0.17 - 0.0033 \text{ cm}$

$\rho_3 = 11.347 \text{ g/cm}^3$

A.2.3 Detector Efficiency

The detector efficiency is simply that portion of the x-ray flux that is attenuated. Thus, if the portion of the signal that escapes

without any interaction in the gas volume is:

330

$$\text{Portion that escapes the active volume} = e^{-\left(\frac{\mu_2}{\rho_2}\right) x_2 \rho_2} \quad (\text{A-16})$$

where: $\left(\frac{\mu_2}{\rho_2}\right)$ is the mass attenuation coefficient of the gas inside the detector

x_2 = thickness of the detector active volume
0.125 inches

ρ_2 = the density of the gas inside the detector

The portion that will interact (or detector efficiency) is therefore

$$\text{Detector efficiency} = 1 - e^{-\left(\frac{\mu_2}{\rho_2}\right) x_2 \rho_2} \quad (\text{A-17})$$

A.2.4 Geometry Factor

The radiation absorbed by a CIC is a function of the solid angle. The solid angle depends on several factors such as, 1) detector length, 2) detector radius, 3) detector distance from the source, 4) source radius, 5) source length. Generally the solid angle subtended by an object at a point p is

$$\Omega = \int_A \frac{n(r - r_p)}{|r - r_p|^3} dA, \quad (\text{A-18})$$

where r is the variable position vector of the surface element dS "visible" at point p , n is the unit vector normal to dA pointing away from p , and A is the surface over which the integration is to be carried out.

The above equations cannot be solved analytically (except for very simple cases). However, calculation of the solid angle may be done by a Monte Carlo method utilizing total variance reduction [32]. In the calculation of solid angle, it is assumed that the source is a "point" source compared to the detector. This is, in fact, a reasonable assumption, since the detector height is larger than the source, and the distance is large compared with the source diameter. The position of the source relative to the detector is shown in Figure A.5.

A program written for calculation of the solid angle was applied to the problem as discussed in Reference [32]. The geometry factor was calculated using the relation:

$$\frac{N}{S} = \text{Geometry Factor} = \frac{\text{solid angle, } \Omega}{4\pi} \quad (\text{A-19})$$

where: N = number of events at the detector location

S = number of high energy electrons emitted
by the LINAC.

A.2.5 Detected X-Ray Flux by the CIC

Considering all factors such as geometry, efficiency and attenuation in the detector and target, the total Bremstrahlung detected using the following relation is estimated by

Figure A.5: A Point Source(Fast Electron from LINAC) Location Relative to the CIC detector

$$\begin{aligned}
 E_d &= \int_0^{E_{\max}} \underbrace{(\text{EGEOM}(E))(\text{TARATT}(E))(\text{DETEFF}(E))(\text{DETATT}(E))}_{\text{FACT}} \frac{dE_{xx}}{dE} dE \quad (\text{A-20}) \\
 &= \sum_0^{E_{\max}} (\text{FACT}(E_{xx}))
 \end{aligned}$$

A.3 High Voltage Wetted Contact Relay Switch Design

One method of perturbing the high voltage is by using a High Voltage Mercury Wetted Relay Switch. The switch circuit is shown in Figure A.6 (and its photograph in Figure A.7). As it can be seen, the Figure is composed of several blocks. One is an oscillator with a variable frequency, the other is the mercury wetted relay, and the rest are components to decrease the noise and overshoot. First the H.V. input would charge the 2 μ F capacitor, and then discharge it at the desired rate. The design of the oscillator to change the frequency of the switch and then the mercury wetted relay design criteria are explained.

A.3.1 Variable Frequency Sign Wave Generator Using Wein-Bridge Oscillator

The variable frequency sine wave generator design is composed of three circuit components: sine wave generator, and two phase shift circuits as are shown in Figure A.6.

The sine wave generator is accomplished by the use of a Wein-Bridge oscillator. With an operational amplifier as a gain element, such an

Figure A.6: High Voltage Mercury-Wetted Contact Relay Switch

Figure A.7: Photographs of the High Voltage Mercury-Wetted Contact Relay Switch Constructed for the High Voltage Perturbation Experiments

oscillator will have a frequency that is precisely controlled by a bridge element. To have a variable frequency, one must use two phase shift circuits (a tunable active filter) to have an automatic gain control of the circuit. Otherwise, changing the frequency determining element would change the critical gain of the positive feedback loop. The variable phase shift circuit with constant gain allows one to change the frequency without disturbing the gain magnitude. This is accomplished using the circuit shown in Figure A.6. In this circuit the phase shift is controlled by a potentiometer. While the phase shift circuits formed with op-amp number 1 and 2, the circuits have gain magnitudes which are constant over the bandwidth of the amplifiers. This independence of gain magnitude and phase shift responses permits phase response variation for changing oscillation frequency without disturbing the gain magnitude of the feedback loop. The initial gain around the loop is set slightly greater than unity to initiate oscillation. As the oscillation amplitude rises, the generator diode feedback provides automatic gain control action by lowering gain. At one frequency the phase shift around the overall feedback loop reaches 360° , and this will be the frequency of oscillation. For the phase shift circuits the phase shift responses are determined by R_1 and R_2 , and the capacitors, C_1 and C_2 (equal to $C = 1\mu\text{F}$), as expressed by

$$\phi_1 = -2 \tan^{-1} \omega R_1 C_1 - 180^\circ, \quad (\text{A-21})$$

and

$$\phi_2 = -2 \tan^{-1} \omega R_2 C_2 - 180^\circ. \quad (\text{A-22})$$

Added to these phase shifts is the 180° phase shift of the amplitude limiter, and the combination results in an oscillation at

$$f_o = \frac{1}{2\pi C\sqrt{R_1 R_2}} \quad (A-23)$$

To vary f_o , either R_1 or R_2 or both can be adjusted. A 10:1 range can be achieved by varying only one resistor such as R_2 . It is important to mention that the maximum frequency limit is imposed by either the slowing rates or the phase shifts of op-amps. The minimum oscillation frequency is achieved by the maximum value of potentiometer. Thus,

$$f_{o_{\min}} = \frac{1}{2\pi(1 \times 10^{-6})\sqrt{(10^4)(10^4)}} \approx 16 \text{ Hz.} \quad (A-24)$$

A.3.2 Mercury-Wetted Contact Relay

The mercury-wetted contact relay is a long life, very high speed, and unvarying dependability relay in existence today. The relay is a dramatically sealed glass capsule. It contains the contact arrangement and a small reservoir of mercury sealed in a high pressure hydrogen atmosphere. A film of mercury is renewed for every operation; that is why you can think in terms of billions of operations contact bounce, pits or welds. There are several types of mercury relays on the market today. There are two basic rules which one must follow in choosing a relay for a special purpose. First, one must include all the necessary requirements which would apply for the given application. These requirements for the purpose of high voltage switch are:

- a) maximum high voltage: 500 volts or higher
- b) maximum current: 1 amp
- c) types of contacts: Break Before make (BBW)
- d) speed of switching: below 50 nsec
- e) size and mounting: no choice
- f) coil voltage and power requirements: no choice

Second, exclude all unnecessary or superfluous requirements which would not be needed in the given application. For example, there is no need to choose a switch with more than one pole (only SPDT needed).

The choice with specifications of the mercury relay for this application is shown below:

C.P. CLARE & Company (General Instrument Corporation) mercury-wetted contact relay

part number: HGS - 5017

minimum operating voltage DC for the coil: 6.3 volts

type of relay: chopper

break-before-make contacts

plug in type

rated current: 2 amps

rated voltage: 500 volts

maximum VA : 100 VA

response time: less than 20 nsec.

A.4 The Ohio State University Research Reactor (OSURR)

The OSURR is a light water cooled and moderated swimming pool reactor. Its nuclear fuel is a 93% enriched U-235. The reactor core

is reflected on three sides with graphite. The rectangular core has an active fuel volume of 24 x 15 x 15 (height = 24 inches, width = depth = 15 inches). Twenty 3 x 3 fuel elements are arranged in a rectangular array (see Figure 3.4). The fuel elements consist of flat plates of U-Al alloy with ten plates per element. A general description of the OSURR is presented in Table A.3 [31, 36].

The OSURR has several experimental facilities. They are Beam Port Nos. 1 and 2, the Central Irradiation Facility (CIF), the 3- $\frac{1}{2}$ " Dry Tube, and the thermal column. Usually Beam Port Nos. 1 and 2 are used to insert the CIC for experimental purposes. However, due to the long CIC gas tube used in this work, all experiments in the OSURR were performed by inserting the CIC in the Dry Tube sitting on a polyethylene structure designed and contracted by Mr. Talnagi (project manager). The thermal neutron fluxes in the Dry Tube at reactor power levels used in this work are listed in Table A.4. These flux values are only estimates which are based on the CIC output current and its sensitivity.

Table A.3 Reactor Description [30]

Reactor Type	Swimming Pool
Power Level	10 kW
Maximum thermal flux in fuel region	2.2×10^{11} n/cm ² /sec
Average thermal flux in fuel region	1.1×10^{11} n/cm ² /sec
Fuel Elements	
Type	flat plate with picture frame assembly
Dimensions of element	3 x 3 x 35 inches overall
Dimensions of fuel plate	3 x 0.108 x 28 inches overall with a 24-inch active fuel length
Fuel material	U-Al alloy, aluminum clad
Enrichment	93% U-235
Cladding	0.036 inch thick, type 1100 aluminum
Number of standard elements	20
number of fuel plates per standard element	10
U-235 content per standard element	nominal 140 grams
Number of control rod elements	4
number of fuel plates per control rod element	6
U-235 content per control rod element	nominal 34 grams
Number of special elements	5
number of fuel plates per special element	3, 4, 5, 6, and 10 respectively
U-235 content per special element	nominal 42, 56, 71, 85, and 178 grams, respectively
Constant volume critical mass of U-235	2840 grams
Nominal operating mass of U-235	3136 grams
Moderator	light water
Reflector	light water and graphite
Thermal neutron lifetime	7×10^{-5} seconds
Excess Reactivity	1.5% dk/k
Reactivity Effects	
Temperature Coefficient	-2.1×10^{-4} dk/k per °C
Void Coefficient	-2.8×10^{-3} dk/k per % volume

Table A.3 (continued)

Regulating Rod Worth	0.6% dk/k (estimated)
Shim Safety Rod Worth	6.4% dk/k (total, estimated)
Control Rods	
Regulating Rod	
number	1
material	type 304 stainless steel
nominal drive speed	11 cm/min
maximum reactivity insertion rate	0.0029%/sec
average reactivity insertion rate	0.0018%/sec
Shim Safety Rods	
number	3
material	boron-stainless steel
nominal drive speed	11 cm/min
maximum reactivity insertion rate	0.116%/sec
average reactivity insertion rate for most worthwhile rod	0.0075%/sec

Table A.4: Thermal Neutron Flux in the Dry Tube at Various Reactor Power Levels Using a Nitrogen-Filled CIC*

Reactor Power (watts)	Measured CIC Current (Amp)	Estimated Neutron Flux (n/cm ² -sec)
10	2.425×10^{-6}	3.5145×10^7
100	2.4×10^{-5}	3.4783×10^8
1K	2.35×10^{-4}	3.4058×10^9
10K	2.35×10^{-3}	3.4058×10^{10}

*Nitrogen-filled CIC sensitivity = 6.9×10^{-14} Amp/n/cm²-sec

A.5 Varian V-7715A Linear Accelerator

The Varian V-7715A Linear Accelerator (LINAC) is housed in the Department of Chemistry at The Ohio State University. It is used to obtain step and impulse X-ray pulses in experiments to measure CIC time response. The LINAC has the capability of accelerating electrons in the pulse mode. The pulsed electron beam has the shape of a square wave. The rise time of the X-ray pulses are less than 20 nsec. Pulses with durations as short as 20 nsec. and as large as 1 microsecond can be obtained (the actual specification of the LINAC is from 15 nsec to 1.4 micro sec.). The average energy of the electrons can be varied between 3.5 and 4 MeV. The beam current depends on the pulse duration. A beam composed of pulses with a duration below 80 nsec. has a current of 600 mamp, and a beam with pulses above 100 nsec. has a current of 300 mamp.

Figures A.8 through A.11 show photographs of the LINAC facility used in the experiments.

A simplified theory of the operation of the LINAC is discussed in the following [31].

A. Elements of the System

1. A source of pulsed radio-frequency energy (3.0 G.Hz. S-band microwave magnetron rated for 2 megawatts peak pulse power).
2. A 'disc-loaded' waveguide structure (the beam centerline is colinear with this waveguide).
3. A source of non-relativistic electrons with a means of switching the electrons on and off very rapidly (the electron gun and inflector system).
4. Electron optics for controlling the position and shape of the electron beam as it is injected into the waveguide.

Figure A.8: Photograph of the LINAC Radiation Room

Figure A.9: Photograph of the Point where the High Energy Electrons are Emitted

Figure A.10: Photograph of the LINAC Adjustment Panel

Figure A.11: Photograph of the Equipment at the Analysis Room at the LINAC Facility

5. A magnetic quadrupole set for controlling the focus and position of the relativistic electrons as they emerge from the outlet window.
6. A pulsed power supply to form the main pulse which drives both the magnetron and the electron gun.
7. Timing circuits to synchronize the main pulse and the inflector (electron switching) pulses.

B. The Acceleration Process (Single Pulse Mode)

1. The microwave energy is pulsed into the waveguide twice. The first pulse establishes stability of the wave in the waveguide. The second pulse accelerates the electrons.
2. The electrons are injected into the waveguide for the period of time selected with the inflector system. The electron pulse width may be varied over the range from 15 nanoseconds to 1400 nanoseconds (width at half-height).
3. As the electrons enter the microwave field region they 'bunch' into packets which are attracted by the microwave electric field. The propagation velocity of the wave may be thought to be varying periodically around an average value due to the effect of the loading discs. The angular period of the velocity variation is $2\pi/3$ radians, or $1/3$ of a full cycle of the microwave frequency. As the electrons are accelerated by the force of the microwave field 'pumping action', the RF field associated with the electrons in the packet and the field of the wave interact either to speed up or to slow down the electrons until they 'bunch' very tightly and are travelling at the microwave average phase velocity (nearly the speed of light). After the electrons have achieved synchronism with the microwave crests they simply pass

out of the guide through the quadrupole focus system to the target. The phase velocity (as well as the electron energy) is a function of the beam loading, i.e. the number of electrons per unit time or peak pulse current.

C. Operational Characteristics

1. Modes of Energy Action

a. Steady State (long pulse mode) - if the electron pulse is long compared with the period of time required to propagate the microwave along the full length of the waveguide, equilibrium will be established between the induced RF field in the electron beam and the RF field in the microwave guide. The rate of energy extraction by the electron beam is then matched by the rate of energy input from the microwave source. Electron pulse duration in this mode ranges between 0.1 and 1.4 microseconds for a rectangular pulse. When tuned for maximum efficiency, the mean particle energy is about 3.5 M.E.V. with 70% of the electrons having energy in the range 2.9 to 4.1 M.E.V. The beam current for this mode is about 320 M.A. (maximum value with flat-top pulse). The total energy in the beam under these conditions and with a maximum pulse width (1.4 microseconds) is about 1.6 joules per pulse.

b. The Stored Energy Mode (Short Pulse, High Intensity Mode) - If the electron pulse duration is comparable with the microwave propagation time (pulse width range of 10 to 60 nanoseconds) the electrons will extract stored energy from the microwave field already existent in the waveguide. The result is a very narrow pulse with higher current than the steady state pulse; however, the

energy spread along the pulse is somewhat more broad. In other words, the energy of an electron passing through the accelerator at some time ($t_0 + t$) after the start of the pulse will have a lower energy than an electron at time t_0 . Experiments with absorbers show that the nominal maximum energy is around 5 M.E.V. at 10 nanoseconds from the start of the pulse. The nominal energy at 50 nanoseconds from the start of the pulse is about 4 M.E.V. If spectral purity at a particular time along the pulse were comparable to that for the steady state mode¹, the total energy spread over the pulse would be 3.4 to 5.6 M.E.V. The practical range of the stored energy pulse is from 20 to 60 nanoseconds with peak current equal to 600 M.A. and total beam energy from 0.06 to 0.16 joules.

2. Stability - The long term stability of the pulse width in the range from 100 to 1400 nanoseconds is better than 3% of the setting. The long term stability of the current setting is about 5%. Thus the total area variation of the pulse should not exceed 10% over a four hour period.

The area stability of the stored energy pulse is mainly determined by the short term (pulse to pulse) 'jitter' of the pulse width timer. This jitter is about 2 nanoseconds from pulse to pulse so that the worst case area variation of the 20 nanosecond pulse is about 15%.

The positional stability of the beam is excellent. The dose delivered to a 3 m.m. wide cell has been found to be constant over a 4 hour period.

¹ The current vs. absorber thickness curves for the stored energy mode are at least as well behaved as those for the steady state mode.

3. Multiple Pulse Operation - The machine can be arranged to deliver a measured burst of pulses (1 to 50) having the same characteristics as in the single pulse mode and 3 millisecond spacing between them. Continuous operation is also possible at pulse repetition rates to 120 pulses per second.

A.6 Nicolet Scientific Corporation Model 660A, Dual-Channel FFT Analyzer

The 660A FFT Analyzer accepts two inputs simultaneously and computes impulse response, transfer function, power and auto spectral densities, power spectrum, cross-correlation function, coherence, signal enhancement, RMS spectrum, instant spectra, transmissibility, probability density function, and other analysis functions. In this research, the FFT Analyzer was used for two purposes. One, using only one input, the FFT Analyzer was used to calculate the power spectrum of the CIC output current. Second, using both inputs (one connected to the input and the other to the output of an instrument), the FFT Analyzer was used to calculate the transfer function of different instruments.

The FFT Analyzer has the capabilities of performing and storing the data to permit ease of comparison of different signal analysis functions on the same input data. The model 660A has an upper frequency limit of 100 KHz. Table A.5 lists some of the specifications of the FFT Analyzer (Model 660A).

A.7 General Radio Company Model 1308-A Audio Oscillator and Power Amplifier

The type 1308-A Audio Oscillator and Power Amplifier is an AC power source whose frequency can be varied over the range of 20 Hz to 20 KHz. It can generate sinusoidal output from 0 to 400 volt rms. This instrument

Table A.5 Specifications for FFT Analyzer
(Model 660A)

FUNCTIONS CALCULATED AND DISPLAYED	FIVE MEASUREMENT MODES (Traces x no. of data points displayed in each)			
	# 1 SIG. ENH.	# 2 CH A 2K	# 3 DUAL 1K or # 4 CORR ⁽³⁾	# 5 PROB
Input Time History (IT)	2x1024 ⁽¹⁾	1x2048	2x1024 ⁽¹⁾	2x1024 ⁽¹⁾
Averaged Time History (AT)	2x1024 ⁽¹⁾			
Avg. Linear Spectrum (IS)	2x400			
Inst. Spec. of Input (IS)		1x800	2x400	
RMS Spectrum (RS)		1x800	2x400	
Power Spectrum (PS)		1x800	2x400	
Cross Spectrum (CS)			1x400 ⁽²⁾	
Transfer Function (TF)			1x400 ⁽²⁾	
Equalized Trans. Function (ETF)			1x400 ⁽²⁾	
Transmissibility Function (TM)			1x400	
Equal. Transmiss. Function (ETM)			1x400	
Coherence Function (COH)			1x400	
Coherent Output Power (COP)			1x400	
Impulse Response (IR)			1x1024	
Equalized Impulse Resp. (EIR)			1x1024	
Auto Correl. Function (ACF)			2x1024	
Cross Correl. Function (CCF)			1x1024	
Prob. Density Function (PDF)				2x127
Cumulative Dist. Function (CDF)				2x127
NUMBER OF FUNCTIONS AVAILABLE WITHOUT CHANGING MODES OR RUNNING DATA	6	4	20	6

FOOTNOTES

(1) 1024 data points A vs. B in NYQ

(2) Complex data points: 400 real and 400 imaginary, or 400 magnitude and

400 phase or 400 Nyquist (R vs. I)

(3) Weighting removed and pad zeros applied in correlation

INPUT CHARACTERISTICS (Each Input Channel)

MAXIMUM AMPLITUDE: 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100 peak

COUPLING: AC (3 dB at 0.5 Hz) or DC normal or digitally inverted digital ZERO is effective input ground

IMPEDANCE: 100K ohms

TEST SIGNALS: (a) Single peak, approximately 1/2 full scale amplitude, appears in each channel at 64K or any other range (normal input is disconnected when test signal is on 16 KHz panel). Digitally generated random and digital filtered random noise outputs provide standard comparison function regardless of frequency range. Random sequences over 1,000,000 samples (clocked in time with input ADC amplitude 0.1K) trigger restarts sequence after each sequence of 2048 samples to create pseudo random noise

INPUT SAMPLING: 12 bit A/D conversion at 2.56 times maximum frequency in the range selected. 256,000 per second maximum external clock

INPUT FILTERS: Range switch automatically selects a pair of matched low-pass anti-aliasing filters which provide at least 70 dB attenuation of those input frequencies which can cause aliasing (10 Hz filter used on 1, 2 and 5 KHz ranges; frequency responses 2.0 dB roll-off at 2.0 dB on 100 KHz range)

TRANSIENT CAPTURE CONTROL: Digital data in input buffer memory held manually by placing the HOLD/REL button in HOLD (right on) or automatically by triggering on the transient waveform in either A or B input channels at a preset trigger level (1:1, 2:1, 4:1, 8:1, 16:1 or 32:1) after ARM is pushed (right on) anticipation or delay of the trigger set using the keyboard (F→A) from 1 to 63 time windows

INPUT AMPLITUDE MONITORS: Lights indicate peak signal levels. OVERLOAD: 6 dB (greater than 1.2 full

scale) 12 dB (between 1/2 and 1/4 FS) 18 dB (between 1/4 and 1/8 FS) 24 dB (between 1/8 and 1/16 FS) electronic graticule top and bottom in time display indicates amplitude limits

FREQUENCY RANGES: (any other coverage up to 100 kHz can be set using external sampling at 2.56 x Fmax and calibrated to read correctly using ORDERS; the anti-aliasing low-pass input filters associated with the range switch appear in the signal path)

RANGE (Hz)	DUAL 1K MODE ¹ % OF NOMINAL BW (Hz)	TIME WINDOW ² (SEC)
100K	250	004
50K	125	008
20K	50	02
10K	25	04
5K	12.5	08
2K	5.0	2
1K	2.5	4
800	1.25	8
200	0.5	2
100	0.25	4
50	0.125	8
20	0.05	20
10	0.025	40
5	0.0125	80
2	0.005	200
1	0.0025	400

¹ For CH A 2K mode nominal BW is X 1/2; time window is X 2; BW is span (lowest frequency that can be read

STORED FUNCTIONS (Non-volatile Memory)

STORE: retains any 600-line spectrum, one 1024-sample sine waveform, or two 400-line spectra on display for cross-spectrum or TF, stores R and I regardless of display

RECALL: displays stored data, reverts back to current data display upon second activation of pushbutton (LED off)

COMPAR: displays one stored trace and corresponding current trace if both processed in a similar manner

SOL TF/TM: Equates current transfer function with stored TF (if both processed in a similar manner) by dividing magnitude of current by stored and subtracting phase of stored from current; also equates IR and TM

BUILT IN ANNOTATED DISPLAY

VERTICAL DISPLAY: linear full scale can be set to 1, 1.25, 1.5, 2, 2.5, 3, 4, 5, 6 or 8 x 10³ or to cursor amplitude or to other number entered with keyboard; log offset from +300 dB to -300 dB in 10 dB steps; display range from 20 dB to 160 dB in 20 dB steps via keyboard (DSPL dB)

TIME DISPLAYS: self-aligning electronic graticule; input maximum amplitude written on CRT in volts 0 post

FREQUENCY DISPLAYS: self-aligning electronic graticule; annotation includes display and scaling as well as input settings and running H or average if recalled

DISPLAY FORMATS: Time A vs. time B single or dual channel where applicable; cross-spectra magnitude and/or phase real and/or imaginary; or real vs. imaginary; Nyquist for frequency; lin-log vertical and horizontal

CALIBRATION AT CURSOR

MARKER: single line cursor intensifies each waveform at its intersection to indicate location of measurement; in KARAOKE multiples of cursor frequency are illuminated with multiple dots

AMPLITUDE: E, E² or dB (engineering units) using keyboard to switch E at number of sampling (as V/E reference IR set for relative measurements; V/V (power) or dB vs. readings normalized per Hz (such as PSD) using the per Hz button

FREQUENCY: Hz (cycles/sec), CPM (cycles/minute), or number, fraction of FS or orders; reads absolute or as difference from reference frequency

TIME: sec, msec, fraction of FS per number of cycles (1:1 or 2:1)

KEYBOARD SETTINGS (Set and recalled)

AVG N: number of functions averaged (1-9999) running N can be displayed

DLY T→A: delay for anticipation between trigger signal and start of Channel A data window set in time window from 1,000 to 63,000

DLY A→B: delay introduced between Channels A and B in time window 0 to 64,000

PNL: stores 9 sets of complete panel settings with ID numbers for recall (see below)

CUR LOC: 9 cursor locations stored with ID numbers for recall

RMS 1-2: calculates total RMS power between any two stored cursor locations; cursor alternates between recalled locations in display

1/dk dB: effective time domain integration or differentiation (single or double effect) at functions unit; cleared (E) converts acceleration to velocity to displacement

COH B/L/AN: set level of display branching based on degree of coherence (0-1.00)

PLOT RATE: five X-Y plot speeds from very slow (1:1) to very fast (12.5:1)

DSPL dB: 20 dB to 160 dB in 20 dB steps

LIN: amplitude at cursor on CH A or CH B set to a linear reference (recall is in V/EU)

dB: amplitude at cursor on CH A or CH B set to a dB reference (recall is in V/EU)

V/EU: calibration sensitivity of CH A or CH B set in engineering units

FREQ REF cursor location set in the units of the display, to which all future cursor locations are referenced.

ORDER REF cursor location set for ORD1, setting future cursor locations proportionately. For example, if cursor at 1 FS is assigned "30", then FS will be "300".

DEFINE AUX auxiliary codes used for secondary operations.

PANEL STORAGE (PHL) stores and recalls nine sets of setup, processing and display settings.

CURSOR TYPE	COHERENCE BLANK
FREQ READ	PLOT RATE
DISPLAY GAIN (offset)	DISPLAY DB
AVERAGE MODE	INPUT AMPLITUDE
AVERAGE N	for ddr
DELAY T→A	AUX CODE
DELAY A→B	CAL VIEW ICH A and CH B
MODE	CAPTURE CONTROL
FUNCTION	FREQ REF
DISPLAY CH	ORDER REF
DISPLAY FORMAT	XPND WIDTH
DISPLAY MEMORY	XPND MODE or *

* with 2D Digis Extension

NUMERIC CALCULATION Numbers in entry field manually entered or transferred from another field can be added, subtracted, multiplied or divided, or the square root or reciprocal taken.

AVERAGING 19 types.

SUM adds N power spectra (N = 1-9999 set with keyboard); redundancy spectra 0% or 50%.

DIFF subtracts N power spectra from previous average.

EX follows the changing statistics of a signal exponentially with a time constant of 1N1 in time window.

PEAK produces the profile of the maximum amplitude at each frequency element during N spectra.

SWEEP averages with maximum redundancy.

TRANS averages power spectra of N transients automatically in SUM, DIFF, EX or PEAK modes, except Mode 86-2A, which overrides input after each capture, the entry must be 9999, automatic, and is aimed used for time averaging.

AVERAGING CONTROL

START clears memory and starts averaging.

STOP halts averaging.

CONT resumes averaging unit N1 is reached; averaging completed, restarts averaging without clearing memory.

ANALOG OUTPUTS X, Y and Z outputs for external CRT displays, X, Y and pen plot for X, Y plotters, timing pulses for 3 D displays; uses Mode 86-2A; PLOT CAL provides power left and upper right of grid for setup; output of amplitude at cursor.

DIGITAL INTERFACES Standard Built-In:

- For duplex RS232 serial interface with selectable baud rates of 110, 150, 300, 600, 1200, 2400, 4800, 9600. Internal programming communications with digital plotters through the RS232C interface when used to communicate with external devices, the output from the RS232C interface pre-programmed in ASCII characters.
- IEEE488-975 interface full standard to use.
- High speed 12 bit A/D converter output interface using 16 bit parallel words (two channels simultaneously) 16 bit digital input to time buffer.

MODEM OPERATION A simple interconnect cable over the 880A is connected to any standard modem and about 1000 ft. The 880A may be controlled and its data received over voice grade telephone lines up to 3000 baud. This permits the user to remotely control the 880A and plot the results on a trace Mode 126A Digis Plotting Associate.

POWER 425 watts @ 800 VA

WEIGHT 36.4 kgm (80 pounds) nominal

SIZE 35.56 cm (14 in.) high, 43.18 cm (17 in.) wide, 52.79 cm (20.78 in.) deep

Definition of Functions

DISPLAY SELECT	FUNCTION COMPUTED	DESCRIPTION
Time (Δ) (Inpt. Time - IT)	A(t)	Digital time history of input signal (Display shows actual data processed)
Instant FFT (Δ) (Inst. Spec - IS)	$S_A = \mathcal{F}\{A(t)\}$ $= S_A \cos(\phi_A) + j S_A \sin(\phi_A)$ $ S_A $ $20 \log_{10} S_A $ ϕ_A $ S_A \cos \phi_A$ $ S_A \sin \phi_A$	Complex spectrum of time history, A(t). Magnitude S _A defines instantaneous spectral content. Phase angle, φ _A , describes relative phasing of periodic harmonic components. Absolute angles are only meaningful if analysis window is synchronized to periodic harmonic data.
Aver. Spec (Δ) (Pwr. Spec - PS)	$G_{AA} = \overline{S_A S_A^*}$ $= \overline{ S_A ^2}$ G_{AA} $10 \log_{10} G_{AA}$ $\sqrt{G_{AA}}$	Ensemble average of squared spectrum magnitude (formed by multiplying complex spectrum by its conjugate). A real (rather than complex) spectrum defining average power at each frequency.
Aver. Cross Spec (X Spec - CS)	$G_{AB} = \overline{S_B S_A^*}$ $= S_A S_B \cos(\phi_B - \phi_A) + j S_A S_B \sin(\phi_B - \phi_A)$ G_{AB} $10 \log_{10} G_{AB}$ $\phi_B - \phi_A$ $G_{AB} \cos(\phi_B - \phi_A)$ $G_{AB} \sin(\phi_B - \phi_A)$	Ensemble averaged complex product of spectrum S _B with conjugated spectrum S _A [*] . Indicates those frequencies where both A(t) and B(t) have content. Phase angles indicate average phase difference between signals at each frequency.
Transfer Function (TF)	$H_{AB} = \frac{G_{AB}}{G_{AA}}$ $= \frac{G_{AB}}{G_{AA}} \cos(\phi_B - \phi_A) + j \frac{G_{AB}}{G_{AA}} \sin(\phi_B - \phi_A)$ $ H_{AB} $ $20 \log_{10} H_{AB} $ $\phi_B - \phi_A$ $ H_{AB} \cos(\phi_B - \phi_A)$ $ H_{AB} \sin(\phi_B - \phi_A)$	Complex ratio of cross spectrum G _{AB} to input power spectrum G _{AA} . Defines the gain and phase lag introduced by a transmission system excited by A(t) and responding with B(t).
Transmissibility (TM)	$ H_{AB} = \frac{G_{BB}}{G_{AA}}$ $ H_{AB} $ $20 \log_{10} H_{AB} $	Real ratio of output power spectrum to input power spectrum.
Impulse Response (Imp. Resp. - IR)	$IR = \mathcal{F}^{-1}\{H_{AB}\}$	Impulse response of the system assuming input A(t) and response B(t).

Definition of Functions

DISPLAY SELECT	FUNCTION COMPUTED	DESCRIPTION
Coherent Output Power (COP)	$COP = \frac{G_{AB} \cdot G_{AB}^*}{G_{AA}}$ $= \gamma^2_{AB} G_{BB}$	Coherent output power (COP) spectrum indicates power in signal, B(t), that is coherent with signal, A(t). Total power spectrum G _{BB} indicates entire content of B(t) while COP indicates only that portion caused by A(t) thru a linear process. When B(t) is caused by unrelated multiple inputs, COP indicates only that portion due to single input, A(t).
LOG	10 LOG ₁₀ COP	
Coherence (COH)	$\gamma^2_{AB} = \frac{G_{AB} \cdot G_{AB}^*}{G_{AA} \cdot G_{BB}}$ $= \frac{ G_{AB} ^2}{G_{AA} \cdot G_{BB}}$	Real Spectrum "power squared" ratio indicates linear cause/effect relationship between A(t) and B(t). Linear transmission system excited only by A(t) yields $\gamma^2_{AB} = 1$ at all frequencies. Non linearities or inputs in addition to A(t) produce γ^2_{AB} between "0" and "1".
Auto-Correlation Function (Auto Corr - ACF)	$R_{AA}(\tau) = \frac{1}{P_A} \int_{-\infty}^{\infty} G_{AA} \{A(t)\} \cdot A^*(t+\tau) dt$	Time domain statistic comparing similarity of A(t) to replicates of itself, delayed by time τ . At $\tau = 0$, R_{AA} = mean square of A(t); As $\tau \rightarrow \infty$, R_{AA} approaches square of mean value. Oscillations in R_{AA} indicate bandwidth and periodicity of A(t).
Cross-Correlation Function (X Corr - CCF)	$R_{AB}(\tau) = \frac{1}{P_A} \int_{-\infty}^{\infty} G_{AB} \{A(t)\} \cdot B^*(t+\tau) dt$	Time statistic comparing similarity of A(t) and B(t). Value of τ that maximizes R_{AB} indicates time lag between signals. Maximum value of R_{AB} divided by square root of $\{R_{AA}(0)\} \{R_{BB}(0)\}$ yields correlation coefficient (equal to 1 for identical signals, 0 for unrelated signals).
Statistical Ensemble Average (Avg Time - AT)	$\bar{A}$	Ensemble averaged time histories computed at each time point across a series of instantaneous time histories, each triggered from a common condition. Used to extract mean value time history.
Complex Spectrum (Inst Spec - IS)	$S_A = \frac{1}{T} \int_{-\infty}^{\infty} \{A(t)\} e^{-j\omega t} dt$ $= S_A \cos \phi_A + j S_A \sin \phi_A$	Complex spectrum of the average time data. Magnitude $ S_A $ defines the spectral content. Phase angle ϕ_A describes relative phasing of periodic harmonic components. Absolute angles are only meaningful if analysis windows were synchronized to periodic harmonic data.
LIN MAG	$ S_A $	
LOG MAG	20 LOG ₁₀ $ S_A $	
PHASE	ϕ_A	
REAL	$ S_A \cos \phi_A$	
IMAG	$ S_A \sin \phi_A$	
Probability Density Function (PDF)	$q(x) = \frac{d Q(x) }{dx} \text{ such that}$ $\int_{-\infty}^{\infty} q(x) dx = 1 \text{ and } 0 \leq q(x) \leq 1$	Statistic defining most probable amplitude of A(t).
Cumulative Distribution Function (CDF)	$Q(x) = P \left\{ A \leq x \right\} = \int_{-\infty}^x q(x) dx$	Statistic defining probability that time signal A(t) has instantaneous amplitude of x or less.

Definition of Symbols

A(t)	Input time function on Channel A	S*	Complex conjugate of S = S _{REAL} - jS _{IMAG}
B(t)	Input time function on Channel B	ensemble	Ensemble average
S	Magnitude of instant FFT = $\sqrt{S_{REAL}^2 + S_{IMAG}^2}$	t	Time
τ	Phase angle of instant FFT = $\tan^{-1} \frac{S_{IMAG}}{S_{REAL}}$	τ	Artificially introduced time delay
γ^2_{AB}	$\gamma^2_{AB} = \frac{ G_{AB} ^2}{G_{AA} \cdot G_{BB}}$	$\mathcal{F} \{ \}$	Direct Fourier Transformation
γ^2_{AB}	$\gamma^2_{AB} = \frac{ G_{AB} ^2}{G_{AA} \cdot G_{BB}}$	$\mathcal{F}^{-1} \{ \}$	Inverse Fourier Transform

Δ Similar for Channel B

was used in the sinusoidal frequency response measurements. The DC level of the sinusoidal output can be varied by supplying an appropriate DC power bias. The specifications are presented in Table A.6.

Table A.6 Audio Oscillator and Power Amplifier Specifications

FREQUENCY

Range: 20 to 20,000 c/s in 3 decade ranges. Accuracy: $\pm 3\%$.

Stability: Approx 0.1% from no load to full load; short-term, approx 0.03%; warm-up drift at full load, 100 c/s, 1.5%; 1 kc/s and 10 kc/s, 0.03%.

OUTPUT

Power: 200 VA, 50 c/s to 1 kc/s; see curves.

Load Power Factor: (At full ratings) any for continuous operation to 30°C ambient or intermittent operation to 50°C ambient. 0.7 to 1.0 for continuous operation to 50°C ambient.

Overload Protection: Electronic overload circuit trips at about $1\frac{1}{2}$ full-scale current (manual reset); thermal protection on transistor heat sink (automatic reset).

Voltage: 0 to 400 V, rms, in 5 ranges of 0 to 4, 12.5, 40, 125, and 400 V. Regulation (see curves) less than 20%, no load to full load, 20 c/s to 1 kc/s (bandwidth greater than 10 kc/s provides essentially instantaneous regulation).

Output Voltmeter: 0 to 5, 15, 50, 150, 500 V, full scale.

Current: 0 to 5 A, rms, in 6 ranges of 0 to 0.016, 0.05, 0.16, 0.5, 1.6, and 5 A. Ammeter output monitor, 0 to 0.05, 0.16, 0.5, 1.6, and 5 A full scale.

Optimum Load Impedance: 0.8, 2.5, 8, 80, 800 Ω . Operates satisfactorily with higher impedance or nonlinear loads. Output transformer passes dc equal to rated ac. Amplifier output imped-

ance is approximately 0.3, 0.3, 1.6, 19, and 220 ohms, respectively, below 1 kc/s.

Harmonic Distortion: 1%, 100 c/s to 10 kc/s (with linear loads at rated output, see curves); 2%, 50 c/s to 100 c/s, with linear loads. With non-linear loads additional distortion in the load voltage is caused by the voltage drop in the amplifier output impedance.

Hum: 50 dB or more below max output.

AMPLIFIER

Sensitivity: About 2 V for full output. Input impedance: 10 k Ω .

GENERAL

Power Required: 105 to 125 or 210 to 250 V, 50 to 60 c/s, 70 to 500 W depending on load. For 50-cycle supply, maximum output must be reduced slightly.

Accessories Supplied: TYPE CAP-22 Power Cord, spare fuses.

MECHANICAL DATA Rack-Bench Cabinet

Model	Width		Height		Depth		Net Wt		Ship Wt	
	in	mm	in	mm	in	mm	lb	kg	lb	kg
Bench	19	485	7	180	16 $\frac{1}{4}$	414	91	42	145	67
Rack	19	485	7	180	15*	385	91	42	145	67

* Behind panel.

See also *General Radio Experimenter*, January 1964.

A.8 Keithley Model 240A High Voltage Power Supply

MODEL 240A VOLTAGE SUPPLY

GENERAL DESCRIPTION

GENERAL DESCRIPTION

1-1. **GENERAL.** The Keithley Model 240A is a compact high voltage supply which provides accurate, stable outputs from 0 to 1200 volts dc. Accuracy is $\pm 1\%$ of the dial setting for all outputs. Stability is $\pm 0.02\% \pm 2$ millivolts the first hour or in subsequent 8-hour periods, after a 30-minute warm-up. Line regulation is $\pm 0.005\% \pm 2$ millivolts for a 10% change in line voltage, and load regulation is $\pm 0.005\% \pm 2$ millivolts from no load to full load.

1-2. FEATURES.

a. Three in-line calibrated dials set the output voltage in 1-volt steps. A TRIM Control permits interpolation between steps with better than 5-millivolt resolution. Output can be selected positive or negative with respect to ground.

b. Repeated overloading or operation in an overloaded condition for long periods will not damage the Model 240A. Overload protection limits the output current to less than 13 milliamperes and, when the overload is removed, automatically returns the Supply to its set value.

c. The circuit for the Model 240A takes advantage of the reliability and stability of a solid-state comparator amplifier, and the high voltage capability of a series regulator tube to provide a high performance circuit. Metal-film range resistors and a selected zener diode contribute to its overall accuracy and stability.

1-3. APPLICATIONS.

a. In the laboratory the Model 240A is a general-purpose high voltage supply. Applications include use in surface and volume resistivity measurements and with high resistance bridges. The Model 240A will supply operating potentials for photomultiplier tubes, electron multipliers, solid-state radiation detectors and ionization chambers. It can also be used in the calibration of meters and electrostatic probes.

b. Typical production testing applications are semiconductor and capacitor leakage measurements. The output of the Voltage Supply may be remotely controlled or programmed by adding a connector to the rear panel. A mounting hole is provided to easily modify the Model 240A.

1-4. ACCESSORIES.

a. Model 4003A Rack Mounting Kit adapts the Model 240A for standard 5-1/4 inch x 19 inch rack mounting.

b. Model 4004A Dual Rack Mounting Kit adapts two Model 240A's for side-by-side

FIGURE 1. Keithley Instruments Model 240A High Voltage Supply.

Continued

GENERAL DESCRIPTION

MODEL 240A VOLTAGE SUPPLY

standard 5-1/4 inch x 19 inch rack mounting. The Kit will accommodate any two 5-1/4 inch high Keithley half-rack Models.

1-5. SPECIFICATIONS.

OUTPUT:

Voltage: 0 to 1200 volts dc in 1-volt steps.
Current: 10 milliamperes dc maximum.
Polarity: Positive or negative with respect to chassis.

ACCURACY: $\pm 1\%$ of dial setting.

RESOLUTION: A TRIM Control permits interpolation between steps with a resolution of better than 5 millivolts.

STABILITY: $\pm 0.02\% \pm 2$ millivolts the first hour or in subsequent 8-hour periods, after a 30-minute warm up.

LINE REGULATION: $\pm 0.005\% \pm 2$ millivolts for 10% change in line voltage.

LOAD REGULATION: $\pm 0.005\% \pm 2$ millivolts from no load to full load.

RIPPLE AND NOISE: Less than 1 millivolt rms above 5 cps.

RECOVERY TIME: No load to full load, less than 35 milliseconds to within 0.1% of no-load output.

OVERLOAD PROTECTION:

Electronic current limiting to less than 13 milliamperes within 15 milliseconds for 200% or greater overloads.

Automatic recovery from overload to within 1% of no-load output within 1/4 second at 1200 volts. Proportionally faster at lower voltages.

CONNECTORS: Output: Teflon-insulated uhf type.

POWER: 105-125 or 210-250 volts (switch-selected), 50-60 cps, 65 watts.

DIMENSIONS, WEIGHT: 5-1/2 inches high x 8-3/4 inches wide x 13 inches deep; net weight, 12 pounds.

ACCESSORIES SUPPLIED: Mating output connector.
3:2 adapter for power line

1-6 EQUIPMENT SHIPPED. The Model 240A is factory calibrated and is shipped for bench use. A mating connector and Instruction Manual are also in the shipping carton.

A.9 Keithley Model 414S Solid-State Picometer

MODEL 414S PICOAMMETER

GENERAL DESCRIPTION

GENERAL DESCRIPTION

1-1. GENERAL.

a. The Keithley Model 414S is a completely solid-state picoammeter which measures currents over 17 ranges from 10^{-2} to 10^{-10} ampere full scale. Accuracy is $\pm 2\%$ of full scale on the 10^{-2} to 10^{-8} ampere ranges and $\pm 4\%$ of full scale on the 3×10^{-9} to 10^{-10} ampere ranges.

b. The Picoammeter employs matched MOS FET transistors in the input followed by a differential amplifier stage, a transistor driver and a transistor output stage. Negative feedback is used for stability and accuracy.

1-2. FEATURES.

a. The time and temperature stability of the 414S Picoammeter is unmatched by any other inexpensive picoammeter. The Model 414S will operate for days without requiring rezeroing. Zero drift with time is less than 0.5% of full scale per week. Temperature drift is equally small — a change of 10°C affects the reading less than 0.5% of full scale on the most sensitive range.

b. A unique circuit provides complete overload protection for Model 414S without compromising the outstanding features of the MOS FET input. The Picoammeter will withstand transient overloads up to 1000 volts without damage, and overload recovery is almost instantaneous.

c. Fast warm-up is an inherent characteristic of the Picoammeter. It can be used almost immediately on its most sensitive range. For maximum stability, however, about 10 minutes warm-up time should be allowed.

d. One volt or 1 milliamperere at full-scale deflection on all ranges is provided to drive chart recorders. The 1 milliamperere recorder output will drive the Keithley 370 Recorder directly. When potentiometric recorders are used, the output voltage can be conveniently divided by a shunt resistor and adjusted for full scale with the rear panel Calibration potentiometer.

e. In addition, the Model 414S provides up to 100 times current suppression over a range of 10^{-3} to 10^{-9} ampere. By suppressing background currents, variations as small as 1% in a larger signal can be displayed full scale. Currents of either polarity may be suppressed.

FIGURE 1. Keithley Model 414S Picoammeter.

Continued

SPECIFICATIONS

MODEL 414S PICOAMMETER

TABLE 1. Keithley Model 414S Specifications.

RANGE: 10^{-10} ampere full scale to 10^{-2} ampere in seventeen 1x and 3x ranges, positive or negative currents.

ACCURACY: $\pm 2\%$ of full scale on 10^{-2} to 10^{-8} ampere ranges; $\pm 4\%$ of full scale on 3×10^{-9} to 10^{-10} ampere ranges.

ZERO DRIFT: Less than 0.5% of full scale per week plus 0.05% per $^{\circ}\text{C}$ on any range after a 10-minute warm-up and with source voltages greater than 1 volt.

INPUT VOLTAGE DROP: Less than 1 millivolt for full-scale meter deflection on any range when properly zeroed.

EFFECTIVE INPUT RESISTANCE: Less than 0.1 ohm on 10^{-2} ampere range, increasing to less than 10^7 ohms on 10^{-10} ampere range.

RISE TIME, MAXIMUM: Seconds, from 10% to 90%.	Range, ampere	With up to 500 pF Across Input
	10^{-10}	0.75
	10^{-9}	0.15
	10^{-8}	0.13
	10^{-7}	0.09
	10^{-6}	0.05
	10^{-5} and above	less than 0.001

MAXIMUM INPUT OVERLOAD:

Transient: 1000 volts for up to 3 seconds using a Keithley (or other 10 mA limited) High Voltage Supply.

Continuous: 600 volts on 10^{-10} to 10^{-6} ampere ranges, decreasing to 12 volts on the 10^{-2} ampere range.

CURRENT SUPPRESSION: Up to 100 times full scale.

Suppression Range: 10^{-9} ampere to 10^{-3} ampere in 7 decade steps, precision 10-turn potentiometer for interpolation between steps. Selectable polarity.

CONNECTORS: Input: Teflon-insulated UHF type. Output: Amphenol 80PC2F.

RECORDER OUTPUT:

Output: ± 1 volt or 1 milliampere for full-scale meter deflection. Output polarity is opposite input polarity.

Noise: Less than 0.3% of full scale peak-to-peak.

POWER: 105-125 or 210-250 volts (switch selected), 50-60 Hz, 5 watts.

DIMENSIONS, WEIGHT: 5-1/2" high x 8-1/2" wide x 10" deep; net weight, 8 pounds.

ACCESSORIES SUPPLIED: Mating input and output connectors.

A.10 Hewlett-Packard 1741A Oscilloscope

Specifications

VERTICAL AMPLIFIERS (2)

Bandwidth and Rise Time at all deflection factors from 0°C to +55°C

BANDWIDTH: 3 dB down from 6 div reference signal

DC-Coupled: dc to 100 MHz in both 50Ω and 1 MΩ input modes

AC-Coupled: approx 10 Hz to 100 MHz: 1 Hz with 10:1 divider probes

BANDWIDTH LIMIT: limits upper bandwidth to approx 20 MHz

RISE TIME: ≤3.5 ns, measured from 10% to 90% points of a 6 div input step

DEFLECTION FACTOR

Ranges: 5 mV/div to 20 V/div (12 calibrated positions) in 1, 2, 5 sequence, accurate within 3%

Vernier: continuously variable between all ranges, extends maximum deflection factor to at least 50 V/div. UNCAL light indicates when vernier is not in CAL position

POLARITY: channel B may be inverted, front panel pushbutton

INPUT RC (selectable)

AC or DC: 1 MΩ ±2% shunted by approx 20 pF

50 Ohm: 50Ω ±3%

MAXIMUM INPUT

AC or DC: 250 V (dc + peak ac at 1 kHz or less) or 500 V (p-p ac at 1 kHz or less)

50 Ohm: 5 V rms

A-B OPERATION

Amplifier: bandwidth and deflection factors are unchanged, channel B may be inverted for A-B operation

Differential (A-B) Common Mode: CMRR is at least 20 dB from dc to 20 MHz. Common mode signal amplitude equivalent to 8 divisions with one vernier adjusted for optimum rejection.

VERTICAL MAGNIFICATION (X5)

BANDWIDTH: 3 dB down from 6 div reference signal

DC-Coupled: dc to approx 30 MHz

AC-Coupled: approx 10 Hz to 30 MHz

RISE TIME: ≤12 ns (measured from 10% to 90% points of 8 div input step)

DEFLECTION FACTOR: increases sensitivity of the 5 and 10 mV/div deflection factor settings by a factor of 5 for a maximum sensitivity of 1 mV on channels A and B.

TRIGGER SOURCE

Selectable from channel A, channel B, composite, or line frequency

CHANNEL A: all display modes triggered by channel A signal

CHANNEL B: all display modes triggered by channel B signal

COMPOSITE: all display modes triggered by displayed signal except in Chop. In Chop mode, trigger signal is derived from channel A

Model 1741A

Specifications (Cont'd)

LINE FREQUENCY: trigger signal is derived from power line frequency.

TRIGGER VIEW

Displays internal or external trigger signal. In Alternate or Chop mode, channel A, channel B, and the trigger signals are displayed. In channel A or B mode, Trigger View overrides that channel. Internal trigger signal amplitude approximates vertical signal amplitude. External trigger signal deflection factor is approx 100 mV/div or 1 V/div in EXT +10. Triggering point is approx center screen. With identically timed signals to a vertical input and the Ext trigger input, trigger signal delay is 2.5 ns $\pm$ 1 ns.

MAIN AND DELAYED TIME BASES**RANGES**

Main: 50 ns/div to 2 s/div (24 ranges) in 1, 2, 5 sequence

Delayed: 50 ns/div to 20 ms/div (18 ranges) in 1, 2, 5 sequence

Accuracy:

Sweep Time/Div	*Accuracy		Temp Range
	X1	X10	
50 ns to 20 ms	$\pm 3\%$	$\pm 4\%$	0°C to +15°C
	$\pm 2\%$	$\pm 3\%$	+15°C to +35°C
	$\pm 3\%$	$\pm 4\%$	+35°C to +55°C

*Add 1% for 50 ms to 2 s ranges.

MAIN SWEEP VERNIER: continuously variable between all ranges extends slowest sweep to at least 5 s/div. UNCAL light indicates when vernier is not in CAL position.

MAGNIFIER (X10): expands all sweeps by a factor of 10, extends fastest sweep to 5 ns/div.

CALIBRATED SWEEP DELAY

DELAY TIME RANGE: 0.5 to 10 X Main Time/Div settings of 100 ns to 2 s (minimum delay 150 ns)

DIFFERENTIAL TIME MEASUREMENT ACCURACY

Main Time Base Setting	*Accuracy (+15°C to +35°C)
100 ns/div to 20 ms/div	$\pm 0.5\% \pm 0.1\%$ of full scale)
50 ms/div to 2 s/div	$\pm 1\% \pm 0.1\%$ of full scale)

*Add 1% for temperatures from 0°C to +15°C and +35°C to +55°C.

DELAY JITTER: <0.002% (1 part in 50 000) of maximum delay in each step from +15°C to +35°C; <0.005% (1 part in 20 000) from 0°C to +15°C and +35°C to +55°C.

TRIGGERING

INTERNAL: dc to 25 MHz on signals causing 0.3 division or more vertical deflection, increasing to 1 division of vertical deflection at 100 MHz in all display modes (required signal level is increased by 2 when in Chop mode and by 5 when X5 vertical magnifier is used). Triggering on Line frequency is also selectable.

EXTERNAL: dc to 50 MHz on signals of 50 mV p-p or more increasing to 100 mV p-p at 100 MHz (required signal level is increased by 2 when in Chop mode)

EXTERNAL INPUT RC: approx 1 M Ω shunted by approx 20 pF.

MAXIMUM EXTERNAL INPUT: 250 V (dc + peak ac at 1 kHz or less) or 500 V (p-p ac at 1 kHz or less).

LEVEL and SLOPE

Internal: at any point on the positive or negative slope of the displayed waveform

External: continuously variable from +1 V to -1 V on either slope of the trigger signal, +10 V to -10 V in divide by 10 mode (± 10)

COUPLING: AC, DC, LF REJ, or HF REJ.

AC: attenuates signals below approx 20 Hz.

LF Reject (Main Sweep): attenuates signals below approx 4 kHz

HF Reject (Main Sweep): attenuates signals above approx 4 kHz.

CALIBRATED MIXED TIME BASE

Dual time base in which the main time base drives the first portion of sweep and the delayed time base completes the sweep at the faster delayed sweep. Also operates in single sweep mode. Accuracy, add 2% to main time base accuracy.

A vs B OPERATION**BANDWIDTH**

Channel A (Y-AXIS): same as channel A.

Channel B (X-AXIS): dc to 5 MHz.

DEFLECTION FACTOR: 5 mV/div to 20 V/div (12 calibrated positions) in 1, 2, 5 sequence

PHASE DIFFERENCE BETWEEN CHANNELS: <3°, dc to 100 kHz.

CATHODE-RAY TUBE AND CONTROLS

Z-AXIS INPUT (INTENSITY MODULATION): +4 V, ≥ 50 ns width pulse blanks trace of any intensity usable to <10 MHz for normal intensity. Input R, 1 k Ω $\pm 10\%$. Maximum input ± 20 V (dc + peak ac).

PERSISTENCE

Variable: approx 100 ms to 1 min

Conventional: natural persistence of P31 phosphor (approx 40 μ s)

STORAGE WRITING SPEED: ≥ 100 cm/ μ s (118 div/ μ s) over center 7 x 9 div (with viewing hood)

STORAGE TIME

Display Mode: at least 10 s at 22°C

Store Mode: at least 30 s at 22°C

BRIGHTNESS: approx 170 cd/m² (50 fL)

ERASE TIME: approx 300 ms

A.11 Keithly Model 427 Current Amplifier

MODEL 427

GENERAL DESCRIPTION

GENERAL DESCRIPTION

1-1. **GENERAL.** The Model 427 Current Amplifier is a high-speed, feedback-type amplifier with particular features useful for automated semiconductor testing, mass spectrometry, and gas chromatography applications.

1-2. FEATURES.

a. **Wide Dynamic Range.** Selectable rise times permit low-noise operation important when resolving small current levels.

b. **High Speed.** Typical resolution is 20 picoamperes out of a 10^{-8} ampere signal with a 100 microsecond rise time.

c. **Built-in Current Suppression.** Small changes in the signal level can be measured since large ambient current levels can be easily suppressed.

d. **Overload Indication.** Accurate measurements are assured since overloads are automatically indicated.

e. **Variable Gain.** The GAIN Switch is designated in eight gain positions from 10^4 to 10^{11} volts per ampere - therefore gain adjustment is straight forward.

f. **Variable Rise Time.** Optimum response can be selected for each gain setting since a separate RISE TIME switch is provided on the front panel.

SPECIFICATIONS

MODEL 427

SPECIFICATIONS

RANGE: 10^4 to 10^{11} volts per ampere in eight decade ranges. (10^{-13} ampere resolution to 10^{-3} ampere full output.)

OUTPUT: ± 10 volts at up to 3 milliamperes. Output polarity is opposite input polarity.

OUTPUT RESISTANCE: Less than 10 ohms d-c to 30kHz.

OUTPUT ACCURACY: $\pm 2\%$ of reading to the 10^9 volts per ampere range, $\pm 4\%$ of reading on the 10^{10} and 10^{11} volts per ampere ranges exclusive of noise, drift and current offset.

RISE TIME (10% to 90%): Adjustable in 1x and 3.3x steps from "Fast Rise Time" listed below to 330 msec.

STABILITY: Current offset doubles per 10°C above 25°C . Voltage drift is less than 0.005% per $^\circ\text{C}$ and less than 0.005% per day of full output after 1-hour warm-up.

OFFSET CURRENT: Less than 10^{-12} ampere at 25°C and up to 70% relative humidity.

CURRENT SUPPRESSION: 10^{-10} ampere to 10^{-3} ampere in eight decade ranges with 0.1% resolution (10-turn potentiometer). Stability is $\pm 0.2\%$ of suppressed value per $^\circ\text{C}$ $\pm 0.2\%$ per day.

NOISE VS. RISE TIME*:

* With up to 100 pF input shunt capacitance. Noise and/or rise time increase as input shunt capacitance increases (1000 picofarads maximum).

INPUT VOLTAGE DROP: Less than 400 μV for full-scale output on the 10^6 to 10^{11} volts per ampere ranges when properly zeroed.

EFFECTIVE INPUT RESISTANCE: Less than 15 ohms on the 10^4 and 10^5 volts per ampere ranges, increasing to less than 4 megohms on the 10^{11} volts per ampere range.

MAXIMUM INPUT OVERLOAD:

Transient: 1000 volts on any range for up to 3 seconds using a Keithley (or other 10mA -limited) high-voltage supply.

Continuous: 500 volts on the 10^{11} to 10^7 volts per ampere ranges, decreasing to 200 volts on the 10^6 , 70 volts on the 10^5 , and 20 volts on the 10^4 volts per ampere ranges.

OVERLOAD INDICATION: Lamp indicates pre-filter or post-filter overload.

DYNAMIC RESERVE: 10 (20dB)

CONNECTORS:

Input: BNC (Front)

Output: BNC (Front and rear)

POWER: 90-125 volts (or 180-250v, switch selected), 50-60 Hz, 5 watts.

DIMENSIONS; WEIGHT: Overall bench size - 4" high x 8-1/2" wide x 12-1/8" deep (100 x 217 x 310mm): (Style "M" 3-1/2" half-rack). Net weight, 7 lbs. (3.2 kg).

FAST RISE TIME

GAIN V/A	RISE TIME (10%-90%)	DYNAMIC RANGE	NOISE (ampere rms)
10^{11}	1500 μs	100	4×10^{-13}
10^{10}	400 μs	200	2×10^{-12}
10^9	220 μs	400	1×10^{-11}
10^8	60 μs	800	5×10^{-11}
10^7	40 μs	2000	2×10^{-10}
10^6	15 μs	2000	----

WIDE DYNAMIC RANGE

DYNAMIC RANGE	NOISE (ampere rms)	RISE TIME (10%-90%)
13000	3×10^{-15}	330 ms
20000	2×10^{-14}	100 ms
20000	2×10^{-13}	10 ms
20000	2×10^{-12}	1 ms
20000	2×10^{-11}	100 μs
20000	----	100 μs

APPENDIX B

BIAS CURVES FOR NITROGEN AND XENON-FILLED
CIC AT DIFFERENT REACTOR POWER LEVELS

Table B-1: Bias Curve Data for Nitrogen-filled CIC at 10 Watts
Reactor Power

Bias Voltage (volts)	CIC Current Output ($\times 10^{-6}$ Amp)
5	0.55
8	1.125
10	1.35
15	1.85
20	2.125
25	2.15
30	2.15
50	2.16
100	2.16
200	2.17

Figure B-1: Bias Curve for Nitrogen-filled CIC at 10 W Reactor Power

Table B-2: Bias Curve Data for Nitrogen-filled CIC at 100 Watts
Reactor Power

Bias Voltage (volts)	CIC Current Output ($\times 10^{-5}$ Amp)
5	0.58
10	0.97
20	1.46
50	2.10
100	2.18
150	2.18
200	2.19
300	2.20
400	2.20
500	2.20
600	2.21
700	2.21
800	2.21
900	2.21
1000	2.21

Figure B-2: Bias Curve for Nitrogen-filled CIC at 100 W Reactor Power

Table B-3: Bias Curve Data for Xenon-filled CIC at 10 and 100 Watts
Reactor Power

Bias Voltage (volts)	CIC Current Output at 10 W ($\times 10^{-6}$ Amp)	CIC Current Output at 100 W ($\times 10^{-5}$ Amp)
2	—	0.055
5	0.50	0.31
10	1.54	0.88
20	2.65	1.55
50	4.15	2.55
70	4.20	3.00
100	4.20	3.65
150	4.25	4.10
200	4.30	4.20
250	4.30	4.20
300	4.30	4.20
400	4.30	4.20
500	4.30	4.20

Figure B-3: Bias Curve for Xenon-filled CIC at 10 and 100 Watts Reactor Power

Table B-4: Bias Curve Data for Xenon-filled CIC at 1 K Watt and 10 K Watt Reactor Power

Bias Voltage (volts)	CIC Current Output at 1 KW ($\times 10^{-3}$ Amp)	CIC Current Output at 10 KW ($\times 10^{-3}$ Amp)
5	0.0132	0.07
10	0.0455	0.025
20	0.090	0.48
50	0.155	0.85
70	0.175	1.125
100	0.214	1.35
150	0.260	1.60
200	0.296	1.825
250	0.335	2.00
300	0.370	2.20
400	0.410	2.50
500	0.415	2.75
600	0.420	2.975

Figure B-4: Bias Curve for Xenon-filled CIC at 1K and 10K Watts Reactor Power

APPENDIX C

Table of
the Experimental
Results of the
Sinusoidal High Voltage
Perturbation Experiments

TABLE C.1: Sinusoidal Frequency Response Analysis for Nitrogen-Filled CIC at No Reactor Power
(Graphical presentation of the results is shown in Figs. 4.5.1 and 4.5.2)

Frequency HZ	Period msec	CIC Output p - p volt (calib)	H.V. Input p - p volt (calib)	Mag Ratio	20 log $\frac{\text{output}}{\text{input}}$ (db)	Phase $\frac{\text{msec}}{\text{period}} \times 360$ (degrees)
22	44.84	3.4x1	8x20	0.02	-33.45	+48.17
100	10	6.3x2	7.4x20	0.09	-21.40	+39.60
500	2	4.3x5	7.2x20	0.15	-16.52	+14.40
1K	1	4.4x5	7.1x20	0.15	-16.20	+10.80
1.5K	.6658	4.4x5	7 x20	0.16	-16.07	+ 5.41
1.7K	.588	4.4x5	7 x20	0.16	-16.07	0
2K	.4998	4.4x5	6.9x20	0.16	-15.95	0
3K	.333	4.2x5	6.7x20	0.16	-16.10	0
4K	.25	4.1x5	6.5x20	0.16	-16.04	0
5K	0.2	4 x 5	6.4x20	0.16	-16.12	0
7K	.1429	3.7x5	6 x20	0.15	-16.24	0
10K	0.1	3.5x5	5.8x20	0.15	-16.43	0
15K	0.0667	3.6x5	5.8x20	0.16	-16.18	0
20K	0.05	7 x2	4.6x20	0.15	-16.35	0

TABLE C.2: Sinusoidal Frequency Response Analysis for Xenon-Filled CIC at No Reactor Power
(Graphical presentation of the results are shown in Fig. 4.5.1 and 4.5.2)

Frequency HZ	Period msec	CIC Output (P.P.V)	H.V. Input (P.P.V)	Mag Ratio	20 log $\frac{\text{output}}{\text{input}}$ (db)	Phase Degree
22	45.2	50.05	6 x 20	0.02	-33.62	55.75
100	9.95	5.2x2	6 x 20	0.09	-21.24	50.65
500	2	3.6x5	6 x 20	0.15	-16.48	18.00
1K	1	3.6x5	6 x 20	0.15	-16.48	3.60
1.5K	.666	3.8x5	6 x 20	0.16	-16.01	5.41
1.7K	.5885	3.7x5	6 x 20	0.15	-16.24	0
2K	0.5	3.8x5	6 x 20	0.16	-16.01	0
3K	.3334	3.8x5	6 x 20	0.16	-16.01	0
4K	.25	3.8x5	6 x 20	0.16	-16.01	0
5K	.2	3.8x5	6 x 20	0.16	-16.01	0
7K	0.1427	3.8x5	6 x 20	0.16	-16.01	0
10K	0.1	3.7x5	6 x 20	0.15	-16.24	0
15K	0.667	3.7x5	6 x 20	0.15	-16.24	0
20K	0.05	3.6x5	6 x 20	0.15	-16.48	0

TABLE C.3 Sinusoidal Frequency Response Analysis for Nitrogen-Filled CIC at No Reactor Power
(Graphical presentation of the results are shown in Fig. 4.5.3 and 4.5.4)

Frequency HZ	Period msec	CIC Output P.P.V. (No D.C.V.)	H.V. Input 35 VDC + PP	$\frac{\text{Output}}{\text{Input}}$	$20 \log \frac{\text{output}}{\text{input}}$ (db)	Phase (degree)
22	45.2	7.3x2	70	0.02	-33.61	+63.72
100	9.95	6	70	0.09	-21.34	+54.27
500	2	5.2x2	70	0.15	-16.56	+18.00
1K	1	5.3x2	70	0.15	-16.40	+ 7.20
1.5K	.666	5.4x2	70	0.15	-16.23	+ 2.70
1.7K	.5881	5.4x2	70	0.15	-16.23	+ 3.06
2K	.5	5.45x2	70	0.156	-16.15	0
3K	.333	5.5x2	70	0.157	-16.07	0
4K	.25	5.5x2	70	0.157	-16.07	0
5K	.2	5.5x2	70	0.157	-16.07	0
7K	.1427	5.5x2	70	0.157	-16.07	0
10K	0.1	5.4x2	70	0.15	-16.23	0
15K	0.0667	5.4x2	70	0.15	-16.23	0
20K	0.05	5.4x2	70	0.15	-16.23	0

TABLE C.4: Sinusoidal Frequency Response Analysis for Xenon-Filled CIC at No Reactor Power
(Graphical presentation of the results is shown in Fig. 4.5.3 and 4.5.4)

Frequency Hz	Period msec	CIC Output PPV (No D.C.V)	H.V. Input 35 VDC PP Volts	<u>Output</u> <u>Input</u>	20 Log <u>output</u> <u>input</u> (db)	Phase (degrees)
22	45.2	7.2x2	70	0.02	-33.73	+63.72
100	9.95	6	70	0.09	-21.34	+54.27
500	2	(5.2)2	70	0.15	-16.56	+18.00
1K	1	5.4x2	70	0.15	-16.23	+ 7.20
1.5K	.666	5.4x2	70	0.15	-16.23	+ 5.41
1.7K	0.5885	5.4x2	70	0.15	-16.23	+ 3.06
2K	0.5	5.4x2	70	0.15	-16.23	0
3K	.3334	5.4x2	70	0.15	-16.23	0
4K	.25	5.4x2	70	0.15	-16.23	0
5K	.2	5.4x2	70	0.15	-16.23	0
7K	.1427	5.4x2	70	0.15	-16.23	0
10K	.1427	5.4x2	70	0.15	-16.23	0
15K	0.0667	5.4x2	70	0.15	-16.23	0
20K	0.05	5.4x2	70	0.15	-16.23	0

TABLE C.5: Sinusoidal Frequency Response Analysis for Nitrogen-Filled CIC at 10KW Reactor Power
(Graphical presentation of the results are shown in Fig. 4.5.5 and 4.5.6)

Frequency HZ	Period msec	CIC Output P-T Volt	H.V. Input P-P Volt	<u>Output</u> <u>Input</u>	20 Log $\frac{\text{output}}{\text{input}}$ (db)	Phase (degree)
22	45.6	8x10	8x10	1	0	0
100	9.917	7.6x10	7.8x10	0.97	-0.23	0
500	2	7.6x10	7.8x10	0.97	-0.23	0
1K	1	7.6x10	7.8x10	0.92	-0.70	-14.40
1.5K	0.665	7.1x10	7.3x10	0.97	-0.24	-22.15
2K	0.5	6.7x10	7.3x10	0.92	-0.74	-28.80
3K	0.333	6x10	7.2x10	0.83	-1.58	-21.82
5K	0.2	4.8x10	6.4x10	0.75	-2.50	-36.0
7K	.1426	4x10	6x10	0.67	-3.52	-51.43
10K	0.0998	3.4x10	5.4x10	0.63	-4.08	-36.0
15K	0.0666	3x10	4.8x10	0.63	-4.08	-11.08
20K	0.05	4.3x5	3.8x10	0.57	-4.95	- 7.50

TABLE C.6: Sinusoidal Frequency Response Analysis for Xenon-Filled CIC at 10KW Reactor Power
(Graphical presentation of the results are shown in Fig. 4.5.5 and 4.5.6)

Frequency HZ	Period msec	CIC Output V P-P (+92 VDC)	H.V. Input PPV (+100 VDC)	<u>Output</u> <u>Input</u>	20 Log <u>Output</u> <u>input</u> (db)	Phase (Degrees)
22	45.2	8x20	8x20	1	0	0
100	9.95	8x20	8x20	1	0	0
500	2	8x20	8x20	1	0	0
1K	1	7.7x20	8x20	0.96	-.33	-7.20
1.5K	.666	7.4x20	8x20	0.93	-.68	-10.81
1.7K	0.5885	7.3x20	8x20	0.91	-0.80	-12.23
2K	0.5	7.1x20	8x20	0.89	-1.24	-14.40
3K	.3334	6.4x20	8x20	0.80	-1.94	-16.20
5K	.2	5.2x20	8x20	0.65	-3.74	-21.60
7K	0.1428	4.7x20	8x20	0.59	-4.62	-20.17
10K	0.1	4.3x20	8x20	0.54	-5.39	-18.00
15K	0.0667	7.7x10	8x20	0.48	-6.35	-10.79
20K	0.05	7.5x10	8x20	0.47	-6.58	-14.40

Frequency Responses of the Current Amplifier and the CablesD.1 Frequency Response Analysis of the Keithly Current Amplifier (CA)

In order to experimentally determine the transfer function of the CA in the noise analysis technique, the input of the CA was connected to a random noise generator (Hp-3722A) through a $10K\Omega$ resistance (to convert the output voltage of the noise generator to current), as shown in block diagram of Fig. D.1. . The transfer functions using the above technique is shown in Fig. D.2. The cutoff frequency of 28500 Hz is observed. The second cutoff is due to the limited band width of the noise generator (50K HZ).

Table D.1 shows the experimental results of the magnitude of the frequency response using the conventional sine wave input. Fig. D.3 shows the plotted data using sinusoidal frequency response analysis. The results show an agreement with the method using random noise input.

D.2 Frequency Response of the Coaxial Cables

Figure D.4 shows the magitude plot of the frequency response of different coaxial cables used in this research work.

Figure D.1: Block Diagram of the Experimental Set-up for Determining the Frequency Response of the Keithly 427 Current Amplifier

Figure D.2: Experimental Results of the Transfer Function Measurements of the Keithley 427 Current Amplifier Using Noise Analysis Techniques

Table D.1: Keithly 427 Transfer Function Measurement

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Rise Time = 0.01 msec

Gain = 10^4 v/aResistance = $10K\Omega$ Input = $1V_{p-p} = 0.1 ma_{p-p}$

Frequency KHz	Output in V_{p-p}	$\left(\frac{V_{out}}{V_{in}}\right)$	db Gain
0.010	1	10^4	80
0.101	1	10^4	80
1.000	1	10^4	80
1.999	1	10^4	80
5.006	1	10^4	80
9.999	0.92	9.2×10^3	79.28
15.008	0.90	9×10^3	79.08
20.023	0.82	8.2×10^3	78.28
30.007	0.60	6.6×10^3	76.39
39.866	0.46	4.6×10^3	73.26
50.038	0.32	3.2×10^3	70.10
59.924	0.215	2.15×10^3	66.65
70.058	0.150	1.5×10^3	63.52
80.094	0.110	1.1×10^3	60.83
90.001	0.078	7.8×10^2	57.84
100.127	0.058	5.8×10^2	55.27
125.126	0.030	3×10^2	49.54
150.344	0.018	1.8×10^2	45.11
169.968	0.012	1.2×10^2	41.58
200.055	0.009	9×10^1	39.08

Figure D.3: Magnitude Plot of the Frequency Response of the Keithley Current Amplifier

Figure D.4: Frequency Response Plots for different coaxial Cables

APPENDIX E

Stability Analysis, Time Step, and Error Analysis for the Solution of the CIC Response Time Simulation via CSMP

Selection of a numerical method to obtain a solution of a given system of differential equations depends on three major factors: convergence, stability, and consistency. A method is convergent if the solution of the differential equation approaches the exact solution when grid size (Δr) and the time increment (Δt) approach zero, and it is stable if the asymptotic solution of the finite difference equation is bounded. "Consistency" of the finite difference procedure implies that the procedure may in fact approximate the original partial differential equation (PDE) modeled for the CIC. Since in the finite difference approximation, the original PDE is replaced with a few terms of a Taylor expansion, some error called "truncation error" is introduced. The truncation error approaches zero when Δt and Δr both approach zero, and the finite difference equations are then called consistent with the original PDE.

In this research, the PDE (parabolic type) were solved using the central difference formula for the spatial variable and using Runge-Kutta via CSMP for the time variable. The PDE's were first converted into ordinary differential equations (with respect to time) using the central difference approximation, and then the equations were solved using the Fourth order Runge-Kutta with fixed interval (RKSF4) via CSMP. The method

of solving the PDE used in the CSMP package and the central difference approximation was first suggested by Cheng [14].

In the central difference approximation, one actually replaces the first and second derivatives (in this case, spatial variables) with their approximate values using a Taylor series expansion. The truncation error in the x direction that is introduced here is in the order of magnitude

$$O(\Delta r)^2.$$

The resulting simultaneous differential equations are then solved by CSMP packing. In the CSMP using RKSPX method for integration, the error is in the order of magnitude

$$O(\Delta t)^5.$$

The stability and convergence problem with any numerical integration can be handled using different Δt values. Since Δx is kept constant in this solution, Δt must be carefully chosen.

Applying Nakamura's [39] condition for stability for parabolic type differential equations results in

$$(D_p) \frac{\Delta t}{(\Delta r)^2} < \frac{1}{2},$$

and

$$(W_i + \frac{DN}{R_i}) \frac{\Delta t}{(\Delta r)^2} < 1,$$

where constants are defined in the computer program (see Appendix).

To simulate the exact experimental conditions, the input of the system is

simulated by a first order system with the time constant of 4×10^{-9} sec.

Thus, the time step (Δt) must be chosen so as not to overflow the program, and to be able to observe the input compared with the output. These conditions satisfy the above stability conditions as well.

In the problems that do not require a fast transients of the input using the RKSFX, one must choose the proper integration step size. Δt (DELT in CSMP) should be chosen such that it is sufficiently small to insure an accurate solution and not too small to result in excess run time (and thus cost). The dynamic response of the system determines the necessary step size. The faster the response, the smaller should be the integration interval (Δt).

APPENDIX F
LIST OF COMPUTER
PROGRAMS

Program to calculate the CIC Frequency Response Data from

Impulse Response Data

```

    DIMENSION XR1(130), W1(130), XII1(130)
    REAL XR(128), XI(128), XII(128), W(128)
    DATA XR/5*0.0,.125,.003,-.031,-.094,-.147,-.178,-.206,-.178,-.13
15,-.084,-.019,.048,.224,.192,.286,.366,.429,.485,.526,.536,.546,
2.554,.546,.516,.502,.449,.407,.357,.317,.278,.249,.23,.197,.177,
3.178,.183,.183,.197,2*.202,.205,.210,.213,2*.217,.225,.227,.210,
4.191,.183,.172,.156,.144,2*.141,.13,.116,.099,.108,.113,.1,.089,
52*.097,.084,.072,.075,.074,.059,2*.048,.061,.048,2*.038,.045,.03
68,.023,.019,.028,.031,.02,.011,.019,.025,.016,.005,.008,.019,.01
77,.009,.011,.02,.027,.016,.022,2*.027,.025,3*.028,.027,2*.028,.0
823,.015,.017,.025,.019,.008,.006,.016,.025,.011,.0,.016,6*0.0/
    CALL FFT128 (XR, XII)
    DO 11 I=1, 128
    XR(I)=20.*ALOG10(XR(I))
    XII(I)=XII(I)*57.295775131
    W(I)=1/1.E-6
11 CONTINUE
    WRITE(6,200)
200 FORMAT(1H1,1X,'FREQ(HZ)',7X,'MAC(DB)',8X,'PHASE(DEGREE)',/)
    DO 12 I=1, 128
    WRITE(6,100) W(I), XR(I), XII(I)
100 FORMAT(1X, E10.3,5X,F10.3, 5X, F10.3)
12 CONTINUE
    DO 300 I=1, 128
    W1(I)=ALOG10(W(I))
    XR1(I)=XR(I)
    XII1(I)=XII(I)
300 CONTINUE
    CALL PLOTS (0,0,0)
    CALL FACTOR (.75)
    CALL PLOT(.75,.75,-3)
    CALL SCALE(W1,8.,128,1)
    CALL SCALE(XR1,5.,128,1)
    CALL LINE(W1,XR1,128,1,+1,0)
    CALL AXIS(0.,0.,17HLOC FREQUENCY HZ, -17,8.,0.,W1(129),W1(130))
    CALL AXIS(0.,0.,13HMAGNITUDE DB, 13,5.,90.,XR1(129),XR1(130))
    CALL SYMBOL (1.75,5.,.14,18HCIC MAGNITUDE PLOT,0.,+18)
    CALL PLOT(0.,0.,+999)
    CALL PLOTS (0,0,0)
    CALL FACTOR (.75)
    CALL PLOT(.75,.75,-3)
    CALL SCALE(W1,8.,128,1)
    CALL SCALE(XII1,5.,128,1)
    CALL LINE(W1,XII1,128,1,+1,0)
    CALL AXIS(0.,0.,17HLOC FREQUENCY HZ, -17,8.,0.,W1(129),W1(130))
    CALL AXIS(0.,0.,13HPHASE DEGREE, 13,5.,90.,XII1(129),XII1(130))
    CALL SYMBOL(1.75,5.,.14,14HCIC PHASE PLOT,0.,+14)
    CALL PLOT(0.,0.,+999)
    STOP
    END

```



```

SUBROUTINE FFT128(XR,XII)
REAL XR(128),XI(128),XII(128)
PI = 3.14159265358979
C
C -- ZERO OUT THE IMAGINARY ARRAY XI, XII ARRAY
C
      DO 5 I = 1,128
        XI(I) = 0.0
        XII(I) = 0.0
C
C -- REARRANGE THE SAMPLES IN REAL ARRAY XR
C
      J = 1
C
      DO 40 I=1,127
        IF (I .GE. J) GOTO 10
        T = XR(I)
        XR(J) = XR(I)
        XR(I) = T
C
      10 CONTINUE
      K = 64
      20 IF (K .GE. J) GOTO 30
      J = J - K
      K = K/2
      GOTO 20
C
      30 J = J+K
      40 CONTINUE
C
C -- PREFROM THE INPLACE FFT
C
      DO 60 L = 1,7
        LE = 2**L
        LE1 = LE/2
        UR = 1.0
        UI = 0.0
        WR = COS(PI/FLOAT(LE1))
        WI = SIN(PI/FLOAT(LE1))
C
      DO 60 J = 1,LE1
        DO 50 I = J,128,LE
          IP = I+LE1
          TEMPR = XR(IP) * UR - XI(IP) * UI
          TEMPI = XR(IP) * UI + XI(IP) * UR
          XR(IP) = XR(I) - TEMPR
          XI(IP) = XI(I) - TEMPI
          XR(I) = XR(I) + TEMPR
          XI(I) = XI(I) + TEMPI
        50 CONTINUE
        UR = UR * WR - UI * WI
        UI = UR * WI + UI * WR
      60 CONTINUE
C
C -- COMPUTE THE POWER FOR EACH POINTAND THE PHASE
C
      DO 70 I = 1,128
        XII(I) = ATAN(XI(I)/XR(I))
      70 XR(I) = SQRT( XR(I)*XR(I) + XI(I)*XI(I) )
C
C
      RETURN
      END

```

Calculated Frequency Response Data From Impulse Response Data

FREQ(HZ)	MAG(DB)	PHASE(DEG)	FREQ(HZ)	MAG(DB)	PHASE(DEG)
0.100E+07	25.221	0.0	0.670E+08	-2.952	-62.983
0.200E+07	6.290	-60.286	0.680E+08	-5.330	-76.029
0.300E+07	10.448	23.471	0.690E+08	-3.643	13.020
0.400E+07	9.672	58.640	0.700E+08	-3.986	-32.563
0.500E+07	12.304	84.643	0.710E+08	-14.440	48.087
0.600E+07	8.892	-44.892	0.720E+08	-11.204	76.802
0.700E+07	-1.323	-11.299	0.730E+08	1.885	-49.073
0.800E+07	-13.454	53.272	0.740E+08	-7.352	-5.193
0.900E+07	-1.387	9.724	0.750E+08	-14.618	-35.780
0.100E+08	-9.781	-24.591	0.760E+08	-6.563	62.005
0.110E+08	0.273	-25.890	0.770E+08	-4.296	-33.205
0.120E+08	-0.213	11.124	0.780E+08	-9.056	-72.361
0.130E+08	-12.246	68.225	0.790E+08	-3.830	-27.185
0.140E+08	-1.964	84.529	0.800E+08	-5.718	-27.754
0.150E+08	-0.290	89.075	0.810E+08	16.819	-1.786
0.160E+08	-3.442	-69.703	0.820E+08	-1.402	23.262
0.170E+08	16.445	-3.498	0.830E+08	2.364	48.851
0.180E+08	1.495	-12.196	0.840E+08	-2.954	67.102
0.190E+08	-1.074	28.853	0.850E+08	2.277	61.589
0.200E+08	-7.878	66.346	0.860E+08	-5.790	-63.513
0.210E+08	-0.829	61.042	0.870E+08	-9.435	-36.303
0.220E+08	-13.550	57.250	0.880E+08	-13.482	22.376
0.230E+08	-5.667	68.671	0.890E+08	3.712	30.906
0.240E+08	-9.561	84.044	0.900E+08	-11.108	-72.011
0.250E+08	5.834	33.243	0.910E+08	-14.650	-55.502
0.260E+08	-3.939	-39.570	0.920E+08	-10.713	-63.918
0.270E+08	-21.082	48.258	0.930E+08	-1.259	-12.824
0.280E+08	-9.585	-53.067	0.940E+08	-4.259	-29.448
0.290E+08	-0.671	-16.379	0.950E+08	-7.925	27.349
0.300E+08	-1.563	-23.169	0.960E+08	-15.762	36.809
0.310E+08	-5.742	-14.816	0.970E+08	1.576	21.361
0.320E+08	-13.410	49.743	0.980E+08	-0.026	64.525
0.330E+08	1.433	-21.734	0.990E+08	-2.986	-26.592
0.340E+08	-1.435	81.055	0.100E+09	-3.328	9.237
0.350E+08	-5.340	-52.220	0.101E+09	-1.007	3.945
0.360E+08	-7.246	29.127	0.102E+09	-3.780	87.024
0.370E+08	1.121	6.703	0.103E+09	-8.963	-52.184
0.380E+08	-9.694	-66.133	0.104E+09	-8.308	51.539
0.390E+08	-11.183	24.736	0.105E+09	5.450	-39.988
0.400E+08	-13.571	80.037	0.106E+09	-4.498	-56.695
0.410E+08	3.341	-35.077	0.107E+09	-9.537	-57.155
0.420E+08	-7.396	-52.234	0.108E+09	-21.138	-6.151
0.430E+08	-10.566	3.466	0.109E+09	-0.598	-58.424
0.440E+08	-9.572	31.786	0.110E+09	-15.023	-19.232
0.450E+08	0.142	-71.330	0.111E+09	-8.512	-13.726
0.460E+08	-7.005	-63.622	0.112E+09	-5.079	29.654
0.470E+08	-1.806	-56.436	0.113E+09	16.495	3.478
0.480E+08	-6.500	-9.120	0.114E+09	-0.103	70.117
0.490E+08	16.844	1.781	0.115E+09	2.562	69.830
0.500E+08	0.361	27.981	0.116E+09	1.601	84.374
0.510E+08	0.924	31.272	0.117E+09	-1.082	64.284
0.520E+08	-1.758	66.714	0.118E+09	-0.081	-58.673
0.530E+08	-1.860	39.997	0.119E+09	-2.443	-13.028
0.540E+08	-7.811	86.424	0.120E+09	-7.949	-1.240
0.550E+08	-23.260	16.868	0.121E+09	-0.997	3.587
0.560E+08	-12.748	-58.803	0.122E+09	-0.055	62.024
0.570E+08	2.550	43.670	0.123E+09	-1.095	-37.966
0.580E+08	-10.533	26.551	0.124E+09	2.792	30.236
0.590E+08	-12.891	64.754	0.125E+09	9.057	81.901
0.600E+08	-20.163	-84.278	0.126E+09	8.885	-56.959
0.610E+08	-5.465	-28.146	0.127E+09	6.767	-27.505
0.620E+08	-2.677	1.087	0.128E+09	1.486	-2.472
0.630E+08	-7.828	23.018			
0.640E+08	-0.970	-32.939			
0.650E+08	11.112	0.0			
0.660E+08	9.555	45.772			

Program to Predict CIC Long X-Ray Pulse Response
(N₂-Filled CIC)

```

C *****PULSED X-RAY EXPERIMENT PREDICTIONS*****
C *****LEAD TARGET*****NITROGEN-FILLED DETECTOR*****
C
C DIMENSION UM1(25), UM2(25), UM3(25), E(25), EX(25), W(1000)
C ZTAR IS TARGET ATOMIC NUMBER
C EMAX IS KINETIC ENERGY OF ELECTRON( MAXIMUM EXPECTED X-RAY ENERGY)
C AK IS A CONSTANT = 5.E-4
C DATA ZTAR, EMAX, AK/ 82., 4., 5.000E-04/
C ROE1 IS ALUMINUM DENSITY ( DETECTOR WALL DENSITY )
C ROE2 IS DENSITY OF DETECTOR GAS
C ROE3 IS TARGET DENSITY
C DATA ROE1, ROE2, ROE3/ 2.699, .0013, 11.347/
C UM1 IS MASS ATTENUATION COEF OF DETECTOR WALL
C UM2 IS MASS ATTENUATION COEFFICIENT OF THE DETECTOR GAS
C UM3 IS TARGET MASS ATTENUATION COEFFICIENT
C DATA UM1/
- 0.0E+00, 5.106E+01, 2.648E+01,
-7.942E+00, 3.411E+00, 1.115E+00, 5.653E-01, 3.693E-01, 2.808E-01,
-2.040E-01, 1.723E-01, 1.390E-01, 1.230E-01,
- 1.045E-01, 9.294E-02, 8.456E-02,
- 7.807E-02, 6.844E-02, 6.145E-02, 6.080E-02, 5.004E-02, 4.322E-02,
-4.273E-02, 3.539E-02, 3.093E-02/
C DATA UM3/ 0.0E+00,
- 2.362E+02, 1.338E+02, 1.083E+02, 8.586E+01, 2.989E+01, 1.413E+01,
- 7.913E+00, 4.940E+00, 2.362E+00, 5.081E+00, 2.001E+00, 1.009E+00,
- 4.009E-01, 2.257E-01, 1.546E-01, 1.187E-01, 8.449E-02, 6.816E-02,
- 6.692E-02, 5.093E-02, 4.477E-02, 4.439E-02, 4.145E-02, 4.077E-02/
C DATA UM2/
- 0.0E+00, 7.058E+00, 3.537E+00, 1.101E+00, 5.549E-01,
- 2.874E-01, 2.210E-01, 1.942E-01, 1.797E-01, 1.631E-01, 1.527E-01,
- 1.352E-01, 1.233E-01, 1.068E-01, 9.551E-02, 8.717E-02, 8.061E-02,
- 7.078E-02, 6.361E-02, 6.294E-02, 5.177E-02, 4.443E-02, 4.391E-02,
- 3.575E-02, 3.062E-02/
C DATA E/
-0.0E+00, 8.0E-03, 1.0E-02, 1.5E-02, 2.0E-02, 3.0E-02, 4.0E-02,
- 5.0E-02, 6.0E-02, 8.0E-02, 1.0E-01, 1.5E-01, 2.0E-01, 3.0E-01,
- 4.0E-01, 5.0E-01, 6.0E-01, 8.0E-01, 1.0E+00, 1.022E+00, 1.5E+00,
- 2.0E+00, 2.044E+00, 3.0E+00, 4.0E+00/
C X1=(0.125+0.125)*2.54
C X2=0.125*2.54
C X3=.0033
C SUNEDD=0.
C SUM1=0.0
C SUM2=0.0
C SUM3=0.0
C SUM4=0.0
C
C SOLID ANGLE CALCULATION USING MONTE CARLO METHOD
C
C N=1000
C PI=3.1415926
C SUM=0.
C SUMSQ=0.0
C IX=111111
C
C DL IS DETECTOR LENGTH

```

(cont.)

```

C      RO IS DETECTOR RADIUS
C      H IS THE HEIGHT BETWEEN THE SOURCE AND THE TOP OF THE DETECTOR
C      P IS THE DISTANCE BETWEEN THE SOURCE AND THE CENTER OF DETECTOR
C
      DL=35.08
      RO=3.97
      H=-DL/2.
      P=8.
      DO 8 I=1,N
C
C      CALCULATION OF THE SOLID ANGLE
C      FOR A GIVEN POINT SOURCE
C
      IF(P,CT,RO) GO TO 2
      TMIN=0.
      TMAX=ATAN((RO+P)/H)
      TCR1=ATAN((RO-P)/H)
C
C      GENERATION OF RANDOM VARIABLES; DISTRIBUTION FUNCTIONS
C
      CALL RANDU(IX,IY,X)
      IX=IY
      TETA=ARCOS(COS(TMIN)-X*(COS(TMIN)-COS(TMAX)))
      TT=TAN(TETA)
      W1=(COS(TMIN)-COS(TMAX))/2.0
      IF(TETA,GT,TCR1) GO TO 1
      W2=1.0
      GO TO 7
1     ALNX=ARCOS((P*P+H*H*TT*TT-RO*RO)/(2.0*H*TT*P))
      W2=ALNX/P1
      GO TO 7
2     ALNX=ARSIN(RO/P)
      ALNN=-ALNX
      CALL RANDU(IX,IY,X)
      IX=IY
      ALPHA=ALNX*(2.0*X-1.0)
      W1=ALNX/P1
      S1=SIN(ALPHA)
      XL=P*COS(ALPHA)-SQRT(RO*RO-P*P*S1*S1)
      IF (II) 55,4,3
3     XLL=P*COS(ALPHA)+SQRT(RO*RO-P*P*S1*S1)
      TMAX=ATAN(XLL/H)
      GO TO 6
4     TMAX=P1/2.0
      GO TO 6
55    TMAX=P1/2.0+ATAN(-H/XL)
6     TMIN=ATAN(XL/(H+DL))
      W2=(COS(TMIN)-COS(TMAX))/2.0
7     W(1)=W1*W2
      SUMSQ=SUMSQ+W(1)*W(1)
8     SUM=SUM+W(1)
      OMEGA=SUM/N
      S=(SUMSQ-N*OMEGA*OMEGA)/(N-1)
      SOLAN=4.0*P1*OMEGA
      SERB=4.0*P1*SQRT(S/N)
      EGEOM=SOLAN/(4.*P1)
      WRITE(6,98)
98    FORMAT(1H1,18X,' *** LEAD TARGET/NITROGEN FILLED DETECTOR ***')

```

```

WRITE(6,99)
99  FORMAT(///,4X,'E',10X,'UM1',8X,'UM2',8X,'UM3',8X,'DETATT',
-5X,'TARATT',5X,'DETEFF',5X,'EX',9X,'EXX',8X,'EDD',/)
EX(1)= 2.*AK*ZTAR*EMAX
DO 5 I =2, 25
DETATT=EXP(-(UM1(I))*X1*ROE1)
TARATT=EXP(-(UM3(I))*X3*ROE3)
DETEFF=1.-EXP(-(UM2(I))*X2*ROE2)
EX(I)=2.*AK*ZTAR*(EMAX-E(I))
EXX=.5*(EX(I-1)+EX(I))*(E(I)-E(I-1))
EDD=EXX*EGEOM*DETATT*TARATT*DETEFF
WRITE(6,100) E(I),UM1(I),UM2(I),UM3(I),DETATT,TARATT,DETEFF,
- EX(I), EXX, EDD
100 FORMAT(2X,10(2X,E9.3))
SUMEDD=SUMEDD+ EDD
SUM1= SUM1 + DETATT
SUM2= SUM2 + TARATT
SUM3= SUM3 + DETEFF
SUM4 = SUM4 + EXX
ED= SUMEDD
EXX= SUM4
5  CONTINUE
AVGDA=SUM1/24.
AVGTA=SUM2/24.
AVGDE=SUM3/24.
ELCPP=.32*1.E-6/1.6021E-19
EABS=ELCPP*ED
CHARG=1.6021E-19*EABS*1.0E+06/35.
CRNT=CHARG/1.E-6
WRITE(6,200)AVGDA
WRITE(6,201)AVGTA
WRITE(6,202)AVGDE
WRITE(6,199)EGEOM
WRITE(6,203)EXX
WRITE(6,204)ED
WRITE(6,205)EABS
WRITE(6,206)CHARG
WRITE(6,207)CRNT
200 FORMAT(//,2X,'AVERAGE DETECTOR ATTENUATION-----',E12.5)
201 FORMAT(2X,'AVERAGE TARGET ATTENUATION-----',E12.5)
202 FORMAT(2X,'AVERAGE DETECTOR EFFICIENCY-----',E12.5)
199 FORMAT(2X,'GEOMETRICAL FACTOR-----',E12.5)
203 FORMAT(2X,'TOTAL BREMSSTRAHLUNG ENERGY-----',E12.5,
-' MEV/ABSORBED ELECTRON')
204 FORMAT(2X,'TOTAL BREMSSTRAHLUNG ENERGY(DET)---',E12.5,
-' MEV/ABSORBED ELECTRON')
205 FORMAT(2X,'TOTAL ABSORBED ENERGY-----',E12.5,
-' MEV/PULSE')
206 FORMAT(2X,'CIC CHARGE FOR EACH PULSE-----',E12.5,
-' COULOMBS')
207 FORMAT(2X,'THEORETICAL CIC CURRENT-----',E12.5,
-' AMPS')
VT50= CRNT*50.
VT93= CRNT*93.
WRITE(6,208) VT50
WRITE(6,209) VT93
208 FORMAT(2X,'OSC VOLTAGE WITH 50-OHM TERMINATOR-',E12.5,' VOLTS')
209 FORMAT(2X,'OSC VOLTAGE WITH 93-OHM TERMINATOR-',E12.5,' VOLTS')

-/////////
STOP
END

```

```

SUBROUTINE RANDU(IX, IY, YFL)
IY=IX*65539
IF (IY) 15, 16, 16
15 IY=IY+2147483647+1
16 YFL=IY
YFL=YFL*.4656613E-9
RETURN
END

```

Program to Predict CIC X-Ray Pulse Response

(Xe-Filled CIC)

```

C
C *****PULSED X-RAY EXPERIMENT PREDICTIONS*****
C
C *****LEAD TARGET*****XENON-FILLED DETECTOR*****
C
C DIMENSION UM1(25), UM2(25), UM3(25), E(25), EX(25), W(1000)
C ZTAR IS TARGET ATOMIC NUMBER
C EMAX IS KINETIC ENERGY OF ELECTRON( MAXIMUM EXPECTED X-RAY ENERGY)
C AK IS A CONSTANT = 5.E-4
C DATA ZTAR, EMAX, AK/ 82., 4., 5.000E-04/
C ROE1 IS ALUMINUM DENSITY ( DETECTOR WALL DENSITY )
C ROE2 IS DENSITY OF DETECTOR GAS
C ROE3 IS TARGET DENSITY
C DATA ROE1, ROE2, ROE3/2.699, 0.005896, 11.347/
C UM1 IS MASS ATTENUATION COEF OF DETECTOR WALL
C DATA UM1/
- 0.0E+00, 5.106E+01, 2.648E+01,
- 7.942E+00, 3.411E+00, 1.115E+00, 5.653E-01, 3.693E-01, 2.808E-01,
- 2.040E-01, 1.723E-01, 1.390E-01, 1.230E-01,
- 1.045E-01, 9.294E-02, 8.456E-02,
- 7.807E-02, 6.844E-02, 6.145E-02, 6.080E-02, 5.004E-02, 4.322E-02,
- 4.273E-02, 3.539E-02, 3.093E-02/
C UM3 IS TARGET MASS ATTENUATION COEFFICIENT
C DATA UM3/ 0.0E+00,
- 2.362E+02, 1.338E+02, 1.083E+02, 8.586E+01, 2.989E+01, 1.413E+01,
- 7.913E+00, 4.940E+00, 2.362E+00, 5.081E+00, 2.001E+00, 1.009E+00,
- 4.009E-01, 2.257E-01, 1.546E-01, 1.187E-01, 8.449E-02, 6.816E-02,
- 6.692E-02, 5.093E-02, 4.477E-02, 4.439E-02, 4.145E-02, 4.077E-02/
C UM2 IS MASS ATTENUATION COEFFICIENT OF THE DETECTOR GAS
C DATA UM2/
- 0.E+0, 3.133E+2, 1.733E+2, 5.812E+1, 2.656E+1, 8.751E+0,
- 2.287E+1, 1.200E+1, 7.885E+0, 3.641E+0, 2.005E+0, 7.126E-1,
- 3.710E-1, 1.772E-1, 1.207E-1, 9.565E-2, 8.168E-2, 6.613E-2,
- 5.719E-2, 5.644E-2, 4.565E-2, 4.05E-2, 4.015E-2, 3.657E-2,
- 3.516E-2/
C DATA E/
- 0.0E+00, 8.0E-03, 1.0E-02, 1.5E-02, 2.0E-02, 3.0E-02, 4.0E-02,
- 5.0E-02, 6.0E-02, 8.0E-02, 1.0E-01, 1.5E-01, 2.0E-01, 3.0E-01,
- 4.0E-01, 5.0E-01, 6.0E-01, 8.0E-01, 1.0E+00, 1.022E+00, 1.5E+00,
- 2.0E+00, 2.044E+00, 3.0E+00, 4.0E+00/
C X1=(0.125+0.125)*2.54
C X2=0.125*2.54
C X3=.0033
C SUMEDD=0.
C SUM1=0.0
C SUM2=0.0
C SUM3=0.0
C SUM4=0.0
C
C SOLID ANGLE CALCULATION USING MONTE CARLO METHOD
C
C N=1000
C P1=3.1415926
C SUM=0.
C SUMSQ=0.0
C IX=111111
C
C DL IS DETECTOR LENGTH

```

```

C      RO IS DETECTOR RADIUS
C      H IS THE HEIGHT BETWEEN THE SOURCE AND THE TOP OF THE DETECTOR
C      P IS THE DISTANCE BETWEEN THE SOURCE AND THE CENTER OF DETECTOR
C
      DL=35.08
      RO=3.97
      H=-DL/2.
      P=8.
      DO 8 I=1,N
C
C          CALCULATION OF THE SOLID ANGLE
C          FOR A GIVEN POINT SOURCE
C
      IF(P.GT.RO) GO TO 2
      TMIN=0.
      TMAX=ATAN((RO+P)/H)
      TCRI=ATAN((RO-P)/H)
C
C          GENERATION OF RANDOM VARIABLES; DISTRIBUTION FUNCTIONS
C
      CALL RANDU(IX,IY,X)
      IX=IY
      TETA=ARCOS(COS(TMIN)-X*(COS(TMIN)-COS(TMAX)))
      TT=TAN(TETA)
      W1=(COS(TMIN)-COS(TMAX))/2.0
      IF(TETA.GT.TCRI) GO TO 1
      W2=1.0
      GO TO 7
1      ALMX=ARCOS((P*P+H*H*TT*TT-RO*RO)/(2.0*H*TT*P))
      W2=ALMX/PI
      GO TO 7
2      ALMX=ARCSIN(RO/P)
      ALMN=-ALMX
      CALL RANDU(IX,IY,X)
      IX=IY
      ALPHA=ALMX*(2.0*X-1.0)
      W1=ALMX/PI
      S1=SIN(ALPHA)
      XL=P*COS(ALPHA)-SQRT(RO*RO-P*P*S1*S1)
      IF (ID) 55,4,3
3      XLL=P*COS(ALPHA)+SQRT(RO*RO-P*P*S1*S1)
      TMAX=ATAN(XLL/H)
      GO TO 6
4      TMAX=PI/2.0
      GO TO 6
55     TMAX=PI/2.0+ATAN(-H/XL)
6      TMIN=ATAN(XL/(H+DL))
      W2=(COS(TMIN)-COS(TMAX))/2.0
7      W(I)=W1*W2
      SUMSQ=SUMSQ+W(I)*W(I)
8      SUM=SUM+W(I)
      OMEGA=SUM/N
      S=(SUMSQ-N*OMEGA*OMEGA)/(N-1)
      SOLAN=4.0*PI*OMEGA
      SERR=4.0*PI*SQRT(S/N)
C
      EGEOM=SOLAN/(4.*PI)
      WRITE(6,9B)

```

```

98  FORMAT(1H1,18X,' *** LEAD TARGET/XENON FILLED DETECTOR ***')
    WRITE(6,99)
99  FORMAT(///,4X,'E',10X,'UM1',8X,'UM2',8X,'UM3',8X,'DETATT',
-5X,'TARATT',5X,'DETEFF',5X,'EX',9X,'EXX',8X,'EDD',/)
    EX(1)= 2.*AK*ZTAR*EMAX
    DO 5 I =2, 25
      DETATT=EXP(-(UM1(I))*X1*ROE1)
      TARATT=EXP(-(UM3(I))*X3*ROE3)
      DETEFF=1.-EXP(-(UM2(I))*X2*ROE2)
      EX(I)=2.*AK*ZTAR*(EMAX-E(1))
      EXX=.5*(EX(I-1)+EX(I))*(E(1)-E(I-1))
      EDD=EXX*ECEOM*DETATT*TARATT*DETEFF
      WRITE(6,100) E(1),UM1(I),UM2(I),UM3(I),DETATT,TARATT,DETEFF,
- EX(I), EXX, EDD
100  FORMAT(2X,10(2X,E9.3))
      SUMEDD=SUMEDD+ EDD
      SUM1= SUM1 + DETATT
      SUM2= SUM2 + TARATT
      SUM3= SUM3 + DETEFF
      SUM4 = SUM4 + EXX
      ED= SUMEDD
      EXX= SUM4
5    CONTINUE
      AVGDA=SUM1/24.
      AVGTA=SUM2/24.
      AVGDE=SUM3/24.
      ELCPP=.32*1.E-6/1.6021E-19
      EABS=ELCPP*ED
      CHARG=1.6021E-19*EABS*1.0E+6/22.1
      CRNT=CHARG/1.E-6
      WRITE(6,200)AVGDA
      WRITE(6,201)AVGTA
      WRITE(6,202)AVGDE
      WRITE(6,199)ECEOM
      WRITE(6,203)EXX
      WRITE(6,204)ED
      WRITE(6,205)EABS
      WRITE(6,206)CHARG
      WRITE(6,207)CRNT
200  FORMAT(//,2X,'AVERAGE DETECTOR ATTENUATION-----',E12.5)
201  FORMAT(2X,'AVERAGE TARGET ATTENUATION-----',E12.5)
202  FORMAT(2X,'AVERAGE DETECTOR EFFICIENCY-----',E12.5)
199  FORMAT(2X,'GEOMETRICAL FACTOR-----',E12.5)
203  FORMAT(2X,'TOTAL BREMSSTRAHLUNG ENERGY-----',E12.5,
- ' MEV/ABSORBED ELECTRON')
204  FORMAT(2X,'TOTAL BREMSSTRAHLUNG ENERGY(DET)---',E12.5,
- ' MEV/ABSORBED ELECTRON')
205  FORMAT(2X,'TOTAL ABSORBED ENERGY-----',E12.5,
- ' MEV/PULSE')
206  FORMAT(2X,'CIC CHARGE FOR EACH PULSE-----',E12.5,
- ' COULOMBS')
207  FORMAT(2X,'THEORETICAL CIC CURRENT-----',E12.5,
- ' AMPS')
      VT50= CRNT*50.
      VT93= CRNT*93.
      WRITE(6,208) VT50
      WRITE(6,209) VT93
208  FORMAT(2X,'OSC VOLTAGE WITH 50-OHM TERMINATOR-', E12.5, ' VOLTS')
209  FORMAT(2X,'OSC VOLTAGE WITH 93-OHM TERMINATOR-', E12.5, ' VOLTS',
- ' ')
      STOP
      END

      SUBROUTINE RANDU(IX, IY, YFL)
      IY=IX*65539
      IF (IY) 15, 16, 16
15  IY=IY+2147483647+1
16  YFL=IY
      YFL=YFL*.4656613E-9
      RETURN
      END

```


Program to Predict CIC X-Ray Impulse Response (Xe-Filled CIC)

```

C
C *****PULSED X-RAY EXPERIMENT PREDICTIONS*****
C
C *****LEAD TARGET*****XENON-FILLED DETECTOR*****
C
C DIMENSION UM1(25), UM2(25), UM3(25), E(25), EX(25), W(1000)
C ZTAR IS TARGET ATOMIC NUMBER
C EMAX IS KINETIC ENERGY OF ELECTRON( MAXIMUM EXPECTED X-RAY ENERGY)
C AK IS A CONSTANT = 5.E-4
C DATA ZTAR, EMAX, AK/ B2., 4., 5.000E-04/
C ROE1 IS ALUMINUM DENSITY ( DETECTOR WALL DENSITY )
C ROE2 IS DENSITY OF DETECTOR GAS
C ROE3 IS TARGET DENSITY
C DATA ROE1, ROE2, ROE3/2.699, 0.005896, 11.347/
C UM1 IS MASS ATTENUATION COEF OF DETECTOR WALL
C DATA UM1/
- 0.0E+00, 5.106E+01, 2.648E+01,
- 7.942E+00, 3.411E+00, 1.115E+00, 5.653E-01, 3.693E-01, 2.808E-01,
- 2.040E-01, 1.723E-01, 1.390E-01, 1.230E-01,
- 1.045E-01, 9.294E-02, 8.456E-02,
- 7.807E-02, 6.844E-02, 6.145E-02, 6.080E-02, 5.004E-02, 4.322E-02,
- 4.273E-02, 3.539E-02, 3.093E-02/
C UM3 IS TARGET MASS ATTENUATION COEFFICIENT
C DATA UM3/ 0.0E+00,
- 2.362E+02, 1.338E+02, 1.083E+02, 8.586E+01, 2.989E+01, 1.413E+01,
- 7.913E+00, 4.940E+00, 2.362E+00, 5.081E+00, 2.001E+00, 1.009E+00,
- 4.009E-01, 2.257E-01, 1.546E-01, 1.187E-01, 8.449E-02, 6.816E-02,
- 6.692E-02, 5.093E-02, 4.477E-02, 4.439E-02, 4.145E-02, 4.077E-02/
C UM2 IS MASS ATTENUATION COEFFICIENT OF THE DETECTOR GAS
C DATA UM2/
- 0.E+0, 3.133E+2, 1.733E+2, 5.812E+1, 2.656E+1, 8.751E+0,
- 2.287E+1, 1.280E+1, 7.885E+0, 3.641E+0, 2.005E+0, 7.126E-1,
- 3.710E-1, 1.772E-1, 1.207E-1, 9.565E-2, 8.168E-2, 6.613E-2,
- 5.719E-2, 5.644E-2, 4.565E-2, 4.05E-2, 4.015E-2, 3.657E-2,
- 3.516E-2/
C DATA E/
- 0.0E+00, 8.0E-03, 1.0E-02, 1.5E-02, 2.0E-02, 3.0E-02, 4.0E-02,
- 5.0E-02, 6.0E-02, 8.0E-02, 1.0E-01, 1.5E-01, 2.0E-01, 3.0E-01,
- 4.0E-01, 5.0E-01, 6.0E-01, 8.0E-01, 1.0E+00, 1.022E+00, 1.5E+00,
- 2.0E+00, 2.044E+00, 3.0E+00, 4.0E+00/
C X1=(0.125+0.125)*2.54
C X2=0.125*2.54
C X3=.0033
C SUMEDD=0.
C SUM1=0.0
C SUM2=0.0
C SUM3=0.0
C SUM4=0.0
C
C SOLID ANGLE CALCULATION USING MONTE CARLO METHOD
C
C N=1000
C P1=3.1415926
C SUM=0.
C SUMSQ=0.0
C IX=111111
C
C DL IS DETECTOR LENGTH

```

(cont.)

```

C      RO IS DETECTOR RADIUS
C      H IS THE HEIGHT BETWEEN THE SOURCE AND THE TOP OF THE DETECTOR
C      P IS THE DISTANCE BETWEEN THE SOURCE AND THE CENTER OF DETECTOR
C
DL=35.08
RO=3.97
H=-DL/2.
P=8.
DO 8 I=1,N
C
C      CALCULATION OF THE SOLID ANGLE
C      FOR A GIVEN POINT SOURCE
C
IF(P.GT.RO) GO TO 2
TMIN=0.
TMAX=ATAN((RO+P)/H)
TCRI=ATAN((RO-P)/H)
C
C      GENERATION OF RANDOM VARIABLES; DISTRIBUTION FUNCTIONS
C
CALL RANDU(IX,IY,X)
IX=IY
TETA=ARCOS(COS(TMIN)-X*(COS(TMIN)-COS(TMAX)))
TT=TAN(TETA)
W1=(COS(TMIN)-COS(TMAX))/2.0
IF(TETA.GT.TCRI) GO TO 1
W2=1.0
GO TO 7
1  ALMX=ARCOS((P*P+H*H*TT*TT-RO*RO)/(2.0*H*TT*P))
W2=ALMX/PI
GO TO 7
2  ALMX=ARSIN(RO/P)
ALMN=-ALMX
CALL RANDU(IX,IY,X)
IX=IY
ALPHA=ALMX*(2.0*X-1.0)
W1=ALMX/PI
S1=SIN(ALPHA)
XL=P*COS(ALPHA)-SQRT(RO*RO-P*P*S1*S1)
IF(H) 55,4,3
3  XLL=P*COS(ALPHA)+SQRT(RO*RO-P*P*S1*S1)
TMAX=ATAN(XLL/H)
GO TO 6
4  TMAX=PI/2.0
GO TO 6
55 TMAX=PI/2.0+ATAN(-H/XL)
6  TMIN=ATAN(XL/(H+DL))
W2=(COS(TMIN)-COS(TMAX))/2.0
7  W(I)=W1*W2
SUMSQ=SUMSQ+W(I)*W(I)
8  SUM=SUM+W(I)
OMEGA=SUM/N
S=(SUMSQ-N*OMEGA*OMEGA)/(N-1)
SOLAN=4.0*PI*OMEGA
SERR=4.0*PI*SQRT(S/N)
C
EGEOM=SOLAN/(4.*PI)
WRITE(6,98)

```

```

98  FORMAT(1H1,18X,' *** LEAD TARGET/XENON FILLED DETECTOR20 NSEC PULS
-E ****')
   WRITE(6,99)
99  FORMAT(///,4X,'E',10X,'UM1',8X,'UM2',8X,'UM3',8X,'DETATT',
-5X,'TARATT',5X,'DETEFF',5X,'EX',9X,'EXX',8X,'EDD',/)
   EX(1)= 2.*AK*ZTAR*EMAX
   DO 5 I =2, 25
   DETATT=EXP(-(UM1(I))*X1*ROE1)
   TARATT=EXP(-(UM3(I))*X3*ROE3)
   DETEFF=1.-EXP(-(UM2(I))*X2*ROE2)
   EX(I)=2.*AK*ZTAR*(EMAX-E(I))
   EXX=.5*(EX(I-1)+EX(I))*(E(I)-E(I-1))
   EDD=EXX*EGEOM*DETATT*TARATT*DETEFF
   WRITE(6,100) E(I),UM1(I),UM2(I),UM3(I),DETATT,TARATT,DETEFF,
- EX(I), EXX, EDD
100 FORMAT(2X,10(2X,E9.3))
   SUMEDD=SUMEDD+ EDD
   SUM1= SUM1 + DETATT
   SUM2= SUM2 + TARATT
   SUM3= SUM3 + DETEFF
   SUM4 = SUM4 + EXX
   ED= SUMEDD
   EXX= SUM4
5   CONTINUE
   AVGDA=SUM1/24.
   AVGTA=SUM2/24.
   AVCDE=SUM3/24.
   ELCPP=.6*20.E-9/1.6021E-19
   EABS=ELCPP*ED
   CHARG=1.6021E-19*EABS*1.0E+6/22.1
   CRNT=CHARG/20.E-9
   WRITE(6,200)AVGDA
   WRITE(6,201)AVGTA
   WRITE(6,202)AVCDE
   WRITE(6,199)EGEOM
   WRITE(6,203)EXX
   WRITE(6,204)ED
   WRITE(6,205)EABS
   WRITE(6,206)CHARG
   WRITE(6,207)CRNT
200 FORMAT(//,2X,'AVERAGE DETECTOR ATTENUATION-----',E12.5)
201 FORMAT(2X,'AVERAGE TARGET ATTENUATION-----',E12.5)
202 FORMAT(2X,'AVERAGE DETECTOR EFFICIENCY-----',E12.5)
199 FORMAT(2X,'GEOMETRICAL FACTOR-----',E12.5)
203 FORMAT(2X,'TOTAL BREMSSTRAHLUNG ENERGY-----',E12.5,
- ' MEV/ABSORBED ELECTRON')
204 FORMAT(2X,'TOTAL BREMSSTRAHLUNG ENERGY(DET)---',E12.5,
- ' MEV/ABSORBED ELECTRON')
205 FORMAT(2X,'TOTAL ABSORBED ENERGY-----',E12.5,
- ' MEV/PULSE')
206 FORMAT(2X,'CIC CHARGE FOR EACH PULSE-----',E12.5,
- ' COULOMBS')
207 FORMAT(2X,'THEORETICAL CIC CURRENT-----',E12.5,
- ' AMPS')
   VT50= CRNT*50.
   VT93= CRNT*93.
   WRITE(6,208) VT50
   WRITE(6,209) VT93
208 FORMAT(2X,'OSC VOLTAGE WITH 50-OHM TERMINATOR-',E12.5,' VOLTS')
209 FORMAT(2X,'OSC VOLTAGE WITH 93-OHM TERMINATOR-',E12.5,' VOLTS',
- ' ')
   STOP
   END

```

C

```

SUBROUTINE RANDU(IX, IY, YFL)
  IY=IX*65539
  IF (IY) 15, 16, 16
15  IY=IY+2147483647+1
16  YFL=IY
   YFL=YFL*.4656613E-9
   RETURN
   END

```

Program (CSMP) to Simulate CIC Response (N_2 -Filled CIC Step
High Voltage Response)

```
// TIME=(10,00),REGION=192K
//JOBPARM LINES=8000,CARDS=1000,DISKIO=80000,TAPEIO=0
//STEP EXEC CSMPVRS.TIME=(10,00)
//X.SYSIN DD *
*
* *****
*
* *CSMP SOLUTION OF CIC RESPONSE TIME BY ALIREZA BEHBAHANI *
* *****C G S *****
* *CIRCULAR CYLINDERICAL COORDINATES ** ONE-DIMENTIONAL *
*
* *****
*
METHOD RKSPFX
* EC ELECTRON CHARGE, COLUMBS
* P GAS PRESSURE INSIDE CIC, MMHG
* ANP NO. OF POSITIVE IONS/CM**3
* ANN NO. OF ELECTRONS/CM**3
* ANZ NO. OF ION-PAIRS/CM**3 - SECOND
* V HIGH VOLTAGE INPUT TO ELECTROD,VOLTS
* PHI NEUTRON FLUX, NO. OF NEUTRONS/CM**2-SEC.
* APMOB MOBILITY OF POSITIVE IONS,(CM**2/VOLT-SEC)MMHG
* ANMOB MOBILITY OF ELECTRONS,(CM**2/VOLT-SEC)MMHG
* DP DIFFUSION COEFFICIENT FOR POSITIVE IONSIN N2 GAS,CM**2/SEC
* DN DIFFUSION COEFFICIENT FOR ELECTRONS IN N2 GAS,CM**2/SEC
* RALPHA N2 GAS RECOMBINATION COEFFICIENT,CM**3/SEC
* RB RADIUS OF THE H.V. ELECTRODE,CM
* RA RADIUS OF THE INNER ELECTRODE,CM
* DL DETECTOR LENGTH, CM
* E1 CONSTANT ELECTRIC FIELD AT A GRID POINT,VOLT/CM
* CRNTP CURRENT DUE TO POSITIVE IONS, AMP
* CRNTN CURRENT DUE TO ELECTRONS, AMP
* CRNT TOTAL CIC CURRENT OUTPUT, AMP
* CD DETECTOR CAPACITOR(SIG. TO H.V.), F
* RM OSCILLOSCOPE OR MEASUREMENT SYSTEM INPUT RESISTANCE, OHM
* RC DETECTOR RESISTANCE(SIG. TO H.V.), OHM
* CC CABLE CAPACITANCE, F
* CM OSCILLOSCOPE OR MEASUREMENT SYSTEM INPUT RESISTANCE, OHM
* VOSC CIC VOLTAGE OBSERVED AT THE OSCILLOSCOPE, VOLT
* EDV ELECTRON DRIFT VELOCITY, CM/SEC
* W1 ELECTRON DRIFT VELOCITY AT A GRID POINT, CM/SEC
*
STORAGE E(10), W(10), EE(10)
FUNCTION CURVE1=(0.0, 0.0)...
, (.05,.237),(.1,.296),(.2,.356),(.3,.385),(.4,.455)...
, (.5,.485),(.6,.515),(.7,.576),(.8,.624),(.9,.654),(1,.7)...
, (1.1,.761),(1.2,.792),(1.3,.826),(1.4,.879),(1.5,.917)...
, (1.6,.955),(1.7,1.),(1.8,1.045),(1.9,1.1),(2.,1.139)...
, (2.1,1.187),(2.2,1.225),(2.3,1.278)
INIT
DP=APMOB*2.5E-2/P
DN=438.79
DELR=(RB-RA)/9.
X=RB/RA
Q=ALOG(RB/RA)
R2=RA+DELR
R3=RA+2.*DELR
R4=RA+3.*DELR
R5=RA+4.*DELR
R6=RA+5.*DELR
R7=RA+6.*DELR
R8=RA+7.*DELR
R9=RA+8.*DELR
R=R3*RC/(R3+RC)
RNT=R8*RC/(R8+RC)
CS=CD+CC
C=CM+CS+320.E-12
*
```

```

PARAM EC=1.6021E-19, P=760., APMOB=2000., RALPHA=1.5E-6
PARAM RA=2.54, RB=2.8575, DL=35.56
PARAM RC=5.E+13, CM=12.E-12, CD=24.8E-12, CC=810.E-12
PARAM FIP=6.047E+3
PARAM PHI=3.4058E+9
PARAM HV=500.
PARAM RM=50.
PARAM RNM=1.E+6
*
DYNAM
PROCED E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,W1,W2,W3,W4,W5,W6,W7,W8,W9,W10=...
  DRVL(V,RA,DELR,Q,P)
  DO 55 I=1,10
    EE(I)=-V/((RA+(I-1)*DELR)*Q)
    ZZ=-EE(I)/P
    E(I)=EE(I)
    EDV=FUNGEN(CURVE1,3,ZZ)
55    W(I)=EDV*1.E+6
    E1=E(1)
    E2=E(2)
    E3=E(3)
    E4=E(4)
    E5=E(5)
    E6=E(6)
    E7=E(7)
    E8=E(8)
    E9=E(9)
    E10=E(10)
    W1=W(1)
    W2=W(2)
    W3=W(3)
    W4=W(4)
    W5=W(5)
    W6=W(6)
    W7=W(7)
    W8=W(8)
    W9=W(9)
    W10=W(10)
  ENDPROCEDURE
  PHIS=STEP(0.)
  V=HV*PHIS
  ANZ=FIP*PHI
  YY=DP-(APMOB*V)/(P*Q)
  ANP10=0.
  ANPD9=DP*(ANP10-2.*ANP9+ANP8)/(DELR**2)...
  +YY*(1./(RA+8.*DELR))*(ANP8-ANP10)/(2.*DELR)...
  -RALPHA*ANP9*ANN9+ANZ
  ANPD8=DP*(ANP9-2.*ANP8+ANP7)/(DELR**2)...
  +YY*(1./(RA+7.*DELR))*(ANP7-ANP9)/(2.*DELR)...
  -RALPHA*ANP8*ANN8+ANZ
  ANPD7=DP*(ANP8-2.*ANP7+ANP6)/(DELR**2)...
  +YY*(1./(RA+6.*DELR))*(ANP6-ANP8)/(2.*DELR)...
  -RALPHA*ANP7*ANN7+ANZ
  ANPD6=DP*(ANP7-2.*ANP6+ANP5)/(DELR**2)...
  +YY*(1./(RA+5.*DELR))*(ANP5-ANP7)/(2.*DELR)...
  -RALPHA*ANP6*ANN6+ANZ
  ANPD5=DP*(ANP6-2.*ANP5+ANP4)/(DELR**2)...
  +YY*(1./(RA+4.*DELR))*(ANP4-ANP6)/(2.*DELR)...
  -RALPHA*ANP5*ANN5+ANZ
  ANPD4=DP*(ANP5-2.*ANP4+ANP3)/(DELR**2)...
  +YY*(1./(RA+3.*DELR))*(ANP3-ANP5)/(2.*DELR)...
  -RALPHA*ANP4*ANN4+ANZ
  ANPD3=DP*(ANP4-2.*ANP3+ANP2)/(DELR**2)...
  +YY*(1./(RA+2.*DELR))*(ANP2-ANP4)/(2.*DELR)...
  -RALPHA*ANP3*ANN3+ANZ
  ANPD2=DP*(ANP3-2.*ANP2+ANP1)/(DELR**2)...
  +YY*(1./(RA+1.*DELR))*(ANP1-ANP3)/(2.*DELR)...
  -RALPHA*ANP2*ANN2+ANZ

```

```

ANP1=ANP2
ANP9=INTCRL(0.,ANPD9)
ANP8=INTCRL(0.,ANPD8)
ANP7=INTCRL(0.,ANPD7)
ANP6=INTCRL(0.,ANPD6)
ANP5=INTCRL(0.,ANPD5)
ANP4=INTCRL(0.,ANPD4)
ANP3=INTCRL(0.,ANPD3)
ANP2=INTCRL(0.,ANPD2)
ANN1=0.
ANND2=DN*(ANN3-2.*ANN2+ANN1)/(DELR**2)...
-ANN2*((W2/(RA+1.*DELR))+(W3-W1)/(2.*DELR))...
+(-W2+(DN/(RA+1.*DELR)))*(ANN3-ANN1)/(2.*DELR)...
-RALPHA*ANP2*ANN2+ANZ
ANND3=DN*(ANN4-2.*ANN3+ANN2)/(DELR**2)...
-ANN3*((W3/(RA+2.*DELR))+(W4-W2)/(2.*DELR))...
+(-W3+(DN/(RA+2.*DELR)))*(ANN4-ANN2)/(2.*DELR)...
-RALPHA*ANP3*ANN3+ANZ
ANND4=DN*(ANN5-2.*ANN4+ANN3)/(DELR**2)...
-ANN4*((W4/(RA+3.*DELR))+(W5-W3)/(2.*DELR))...
+(-W4+(DN/(RA+3.*DELR)))*(ANN5-ANN3)/(2.*DELR)...
-RALPHA*ANP4*ANN4+ANZ
ANND5=DN*(ANN6-2.*ANN5+ANN4)/(DELR**2)...
-ANN5*((W5/(RA+4.*DELR))+(W6-W4)/(2.*DELR))...
+(-W5+(DN/(RA+4.*DELR)))*(ANN6-ANN4)/(2.*DELR)...
-RALPHA*ANP5*ANN5+ANZ
ANND6=DN*(ANN7-2.*ANN6+ANN5)/(DELR**2)...
-ANN6*((W6/(RA+5.*DELR))+(W7-W5)/(2.*DELR))...
+(-W6+(DN/(RA+5.*DELR)))*(ANN7-ANN5)/(2.*DELR)...
-RALPHA*ANP6*ANN6+ANZ
ANND7=DN*(ANN8-2.*ANN7+ANN6)/(DELR**2)...
-ANN7*((W7/(RA+6.*DELR))+(W8-W6)/(2.*DELR))...
+(-W7+(DN/(RA+6.*DELR)))*(ANN8-ANN6)/(2.*DELR)...
-RALPHA*ANP7*ANN7+ANZ
ANND8=DN*(ANN9-2.*ANN8+ANN7)/(DELR**2)...
-ANN8*((W8/(RA+7.*DELR))+(W9-W7)/(2.*DELR))...
+(-W8+(DN/(RA+7.*DELR)))*(ANN9-ANN7)/(2.*DELR)...
-RALPHA*ANP8*ANN8+ANZ
ANND9=DN*(ANN10-2.*ANN9+ANN8)/(DELR**2)...
-ANN9*((W9/(RA+8.*DELR))+(W10-W8)/(2.*DELR))...
+(-W9+(DN/(RA+8.*DELR)))*(ANN10-ANN8)/(2.*DELR)...
-RALPHA*ANP9*ANN9+ANZ
ANN2=INTCRL(0.,ANND2)
ANN3=INTCRL(0.,ANND3)
ANN4=INTCRL(0.,ANND4)
ANN5=INTCRL(0.,ANND5)
ANN6=INTCRL(0.,ANND6)
ANN7=INTCRL(0.,ANND7)
ANN8=INTCRL(0.,ANND8)
ANN9=INTCRL(0.,ANND9)
ANN10=ANN9
WP=ANP1*E1**2*RA+ANP2*E2**2*R2+ANP3*E3**2*R3+ANP4*E4**2*R4...
+ANP5*E5**2*R5+ANP6*E6**2*R6+ANP7*E7**2*R7+ANP8*E8**2*R8...
+ANP9*E9**2*R9+ANP10*E10**2*RB
WN=ANN1*E1*W1*RA+ANN2*E2*W2*R2+ANN3*E3*W3*R3+ANN4*E4*W4*R4...
+ANN5*E5*W5*R5+ANN6*E6*W6*R6+ANN7*E7*W7*R7+ANN8*E8*W8*R8...
+ANN9*E9*W9*R9+ANN10*E10*W10*RB
CRNTN=-6.283185*EC*DL*WN*DELR/V
CRNTP=6.283185*EC*DL*APMOB*WP*DELR/(V*P)
CRNT=CRNTP+CRNTN
*
DYNAMICS OF MEASUREMENT SYSTEM
VDOT=(R*CRNT-VOSC)/(R*C)
VOSC=INTCRL(0.,VDOT)
VDOTN=(RNT*CRNT-VNOSC)/(RNT*C)
VNOSC=INTCRL(0.,VDOTN)
VOUT=CRNT*RM
VROUT=CRNT*RNM
TIMER FINTIM=5.E-3, OUTDEL=2.E-6, PRODEL=2.E-6, DELT=5.E-8
PRINT CRNTP, CRNTN, CRNT, VOSC, VOUT, V, VNOSC, VROUT
OUTPUT TIME, CRNT, VOSC, VNOSC
PAGE MERGE, XYPLT, HEIGHT=5.5, WIDTH=8.
LABEL CIC STEP H.V. RESPONSE( N2 )
END
STOP
ENDJOB
/*

```

Program (CSMP) to Simulate Xe-Filled CIC Step Flux Response

```
// TIME=(10,00), REGION=192K
//JOBPARM LINES=30000,CARDS=0,DISKIO=34000,TAPEIO=0
//STEP EXEC CSMPVRS,TIME=(10,00)
//X.SYSIN DD *
*
* *****
*
* *CSMP SOLUTION OF CIC RESPONSE TIME BY ALIREZA BEHBAHANI *
* *****C C S *****
* *CIRCULAR CYLINDERICAL COORDINATES ** ONE-DIMENTIONAL *
* *****
*
METHOD RKSFX
* EC ELECTRON CHARGE, COLUMBS
* P GAS PRESSURE INSIDE CIC, MMHG
* ANP NO. OF POSITIVE IONS/CM**3
* ANN NO. OF ELECTRONS/CM**3
* ANZ NO. OF ION-PAIRS/CM**3 - SECOND
* V HIGH VOLTAGE INPUT TO ELECTROD,VOLTS
* PHI NEUTRON FLUX, NO. OF NEUTRONS/CM**2-SEC.
* APMOB MOBILITY OF POSITIVE IONS,(CM**2/VOLT-SEC)MMHG
* ANMOB MOBILITY OF ELECTRONS,(CM**2/VOLT-SEC)MMHG
* DP DIFFUSION COEFFICIENT FOR POSITIVE IONSIN XE GAS,CM**2/SEC
* DN DIFFUSION COEFFICIENT FOR ELECTRONS IN XE GAS,CM**2/SEC
* RALPHA N2 GAS RECOMBINATION COEFFICIENT,CM**3/SEC
* RB RADIUS OF THE H.V. ELECTRODE,CM
* RA RADIUS OF THE INNER ELECTRODE,CM
* DL DETECTOR LENGTH, CM
* E1 CONSTANT ELECTRIC FIELD AT A GRID POINT,VOLT/CM
* CRNTP CURRENT DUE TO POSITIVE IONS, AMP
* CRNTN CURRENT DUE TO ELECTRONS, AMP
* CRNT TOTAL CIC CURRENT OUTPUT, AMP
* CD DETECTOR CAPACITOR(SIG. TO H.V.), F
* RM OSCILLOSCOPE OR MEASUREMENT SYSTEM INPUT RESISANCE, OHM
* RM OSCILLOSCOPE OR MEASUREMENT SYSTEM INPUT RESISTANCE, OHM
* RC DETECTOR RESISTANCE(SIG. TO H.V.), OHM
* CC CABLE CAPACITANCE, F
* CM OSCILLOSCOPE OR MEASUREMENT SYSTEM INPUT RESISTANCE, OHM
* VOSC CIC VOLTAGE OBSERVED AT THE OSCILLOSCOPE, VOLT
* EDV ELECTRON DRIFT VELOCITY, CM/SEC
* W1 ELECTRON DRIFT VELOCITY AT A GRID POINT, CM/SEC
*
STORAGE E(10), W(10), EE(10)
FUNCTION CURVE1=(0.,0.),(.01,.041),(.1,.089),(.2,.107),(.25,.111)...
, (.4,.13),(.5,.133),(.75,.148),(1.,.159)
INIT
DP=APMOB*2.5E-2/P
DN=37.25
DELR=(RB-RA)/9.
X=RB/RA
Q=ALOG(RB/RA)
R2=RA+DELR
R3=RA+2.*DELR
R4=RA+3.*DELR
R5=RA+4.*DELR
R6=RA+5.*DELR
R7=RA+6.*DELR
R8=RA+7.*DELR
R9=RA+8.*DELR
R=RM*RC/(RM+RC)
CS=CD+CC
C=CM+CS
*
PARAM EC=1.6021E-19, P=3040., APMOB=440., RALPHA=0.7E-6
PARAM RA=2.54, RB=2.8575, DL=35.56
PARAM RC=5.E+13, CM=12.E-12, CD=24.8E-12, CC=810.E-12
PARAM FIP=9.852E+3
```

PARAM PHI=3.5143E+7

PARAM HV=500.

PARAM RM=50.

*

DYNAM

PROCED E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,W1,W2,W3,W4,W5,W6,W7,W8,W9,W10=...

DRVL(V,RA,DELR,Q,P)

DO 55 I=1,10

EE(I)=-V/((RA+(I-1)*DELR)*Q)

ZZ=-EE(I)/P

E(I)=EE(I)

EDV=FUNGEN(CURVE1,3,ZZ)

55 W(I)=EDV*1.E+6

E1=E(1)

E2=E(2)

E3=E(3)

E4=E(4)

E5=E(5)

E6=E(6)

E7=E(7)

E8=E(8)

E9=E(9)

E10=E(10)

W1=W(1)

W2=W(2)

W3=W(3)

W4=W(4)

W5=W(5)

W6=W(6)

W7=W(7)

W8=W(8)

W9=W(9)

W10=W(10)

ENDPROCEDURE

V=HV

PHIS=STEP(0.)

FLUX=PHI*PHIS

ANZ=FIP*FLUX

YY=DP-(APMOB*V)/(P*Q)

ANP10=0.

ANPD9=DP*(ANP10-2.*ANP9+ANP8)/(DELR**2)...

+YY *(1./(RA+8.*DELR))*(ANP8-ANP10)/(2.*DELR)...

-RALPHA*ANP9*ANN9+ANZ

ANPD8=DP*(ANP9-2.*ANP8+ANP7)/(DELR**2)...

+YY *(1./(RA+7.*DELR))*(ANP7-ANP9)/(2.*DELR)...

-RALPHA*ANP8*ANN8+ANZ

ANPD7=DP*(ANP8-2.*ANP7+ANP6)/(DELR**2)...

+YY *(1./(RA+6.*DELR))*(ANP6-ANP8)/(2.*DELR)...

-RALPHA*ANP7*ANN7+ANZ

ANPD6=DP*(ANP7-2.*ANP6+ANP5)/(DELR**2)...

+YY *(1./(RA+5.*DELR))*(ANP5-ANP7)/(2.*DELR)...

-RALPHA*ANP6*ANN6+ANZ

ANPD5=DP*(ANP6-2.*ANP5+ANP4)/(DELR**2)...

+YY *(1./(RA+4.*DELR))*(ANP4-ANP6)/(2.*DELR)...

-RALPHA*ANP5*ANN5+ANZ

ANPD4=DP*(ANP5-2.*ANP4+ANP3)/(DELR**2)...

+YY *(1./(RA+3.*DELR))*(ANP3-ANP5)/(2.*DELR)...

-RALPHA*ANP4*ANN4+ANZ

ANPD3=DP*(ANP4-2.*ANP3+ANP2)/(DELR**2)...

+YY *(1./(RA+2.*DELR))*(ANP2-ANP4)/(2.*DELR)...

-RALPHA*ANP3*ANN3+ANZ

ANPD2=DP*(ANP3-2.*ANP2+ANP1)/(DELR**2)...

+YY *(1./(RA+1.*DELR))*(ANP1-ANP3)/(2.*DELR)...

-RALPHA*ANP2*ANN2+ANZ

ANP1=ANP2

ANP9=INTGRL(0.,ANPD9)

ANP8=INTGRL(0.,ANPD8)

ANP7=INTGRL(0.,ANPD7)


```

ANP6=INTGRL(0.,ANPD6)
ANP5=INTGRL(0.,ANPD5)
ANP4=INTGRL(0.,ANPD4)
ANP3=INTGRL(0.,ANPD3)
ANP2=INTGRL(0.,ANPD2)
ANN1=0.
ANND2=DN*(ANN3-2.*ANN2+ANN1)/(DEL**2)...
-ANN2*((W2/(RA+1.*DELR))+(W3-W1)/(2.*DELR))...
+(-W2+(DN/(RA+1.*DELR)))*(ANN3-ANN1)/(2.*DELR)...
-RALPHA*ANP2*ANN2+ANZ
ANND3=DN*(ANN4-2.*ANN3+ANN2)/(DEL**2)...
-ANN3*((W3/(RA+2.*DELR))+(W4-W2)/(2.*DELR))...
+(-W3+(DN/(RA+2.*DELR)))*(ANN4-ANN2)/(2.*DELR)...
-RALPHA*ANP3*ANN3+ANZ
ANND4=DN*(ANN5-2.*ANN4+ANN3)/(DEL**2)...
-ANN4*((W4/(RA+3.*DELR))+(W5-W3)/(2.*DELR))...
+(-W4+(DN/(RA+3.*DELR)))*(ANN5-ANN3)/(2.*DELR)...
-RALPHA*ANP4*ANN4+ANZ
ANND5=DN*(ANN6-2.*ANN5+ANN4)/(DEL**2)...
-ANN5*((W5/(RA+4.*DELR))+(W6-W4)/(2.*DELR))...
+(-W5+(DN/(RA+4.*DELR)))*(ANN6-ANN4)/(2.*DELR)...
-RALPHA*ANP5*ANN5+ANZ
ANND6=DN*(ANN7-2.*ANN6+ANN5)/(DEL**2)...
-ANN6*((W6/(RA+5.*DELR))+(W7-W5)/(2.*DELR))...
+(-W6+(DN/(RA+5.*DELR)))*(ANN7-ANN5)/(2.*DELR)...
-RALPHA*ANP6*ANN6+ANZ
ANND7=DN*(ANN8-2.*ANN7+ANN6)/(DEL**2)...
-ANN7*((W7/(RA+6.*DELR))+(W8-W6)/(2.*DELR))...
+(-W7+(DN/(RA+6.*DELR)))*(ANN8-ANN6)/(2.*DELR)...
-RALPHA*ANP7*ANN7+ANZ
ANND8=DN*(ANN9-2.*ANN8+ANN7)/(DEL**2)...
-ANN8*((W8/(RA+7.*DELR))+(W9-W7)/(2.*DELR))...
+(-W8+(DN/(RA+7.*DELR)))*(ANN9-ANN7)/(2.*DELR)...
-RALPHA*ANP8*ANN8+ANZ
ANND9=DN*(ANN10-2.*ANN9+ANN8)/(DEL**2)...
-ANN9*((W9/(RA+8.*DELR))+(W10-W8)/(2.*DELR))...
+(-W9+(DN/(RA+8.*DELR)))*(ANN10-ANN8)/(2.*DELR)...
-RALPHA*ANP9*ANN9+ANZ
ANN2=INTGRL(0.,ANND2)
ANN3=INTGRL(0.,ANND3)
ANN4=INTGRL(0.,ANND4)
ANN5=INTGRL(0.,ANND5)
ANN6=INTGRL(0.,ANND6)
ANN7=INTGRL(0.,ANND7)
ANN8=INTGRL(0.,ANND8)
ANN9=INTGRL(0.,ANND9)
ANN10=ANN9
WP=ANP1*E1**2*RA+ANP2*E2**2*R2+ANP3*E3**2*R3+ANP4*E4**2*R4...
+ANP5*E5**2*R5+ANP6*E6**2*R6+ANP7*E7**2*R7+ANP8*E8**2*R8...
+ANP9*E9**2*R9+ANP10*E10**2*RB
WN=ANN1*E1*W1*RA+ANN2*E2*W2*R2+ANN3*E3*W3*R3+ANN4*E4*W4*R4...
+ANN5*E5*W5*R5+ANN6*E6*W6*R6+ANN7*E7*W7*R7+ANN8*E8*W8*R8...
+ANN9*E9*W9*R9+ANN10*E10*W10*RB
CRNTN=-6.283185*EC*DL*WN*DEL/V
CRNTP=6.283185*EC*DL*APMOB*WP*DEL/(V*P)
CRNT=CRNTP+CRNTN
*
DYNAMICS OF MEASUREMENT SYSTEM
VDOT=(R*CRNT-VOSC)/(R*C)
VOSC=INTGRL(0.,VDOT)
VOUT=CRNT*RM
TIMER FINTIM=3.E-3, OUTDEL=1.E-6, PRDEL=1.E-6, DELT=1.E-7
PRINT CRNTP, CRNTN, CRNT, VOSC, VOUT, V, FLUX, ANZ
OUTPUT TIME, CRNT, CRNTP, CRNTN, FLUX, VOSC
PAGE MERGE, XYPLOT, HEIGHT=5.5, WIDTH=8.
LABEL STEP FLUX(XE)
END
STOP
ENDJOB

```

Program (CSMP) to Simulate OSU Reactor Scram (Rods Drop) Response

```

/*JOBPARM LINES=30000,CARDS=0,DISKIO=00000,TAPEIO=0
//STEP EXEC CSMPVRS,TIME=(1,00)
//X.SYSIN DD *
*
TITLE O.S.U. REACTOR SCRAM (RODS DROP) RESPONSE
TITLE STEP RESPONSE OF REACTIVITY FROM 51.0 CM
PARAM Q=0.0, PFB=5.6E-05
PARAM AL1=.0124,AL2=.0305,AL3=.111,AL4=.301,AL5=1.14,AL6=3.01
PARAM B=0.0076
PARAM GG=980., ZK=4.88, PH11=3.14,5926, HH=51., TREAC=6.29, X0=51.0
INCON ANO=159.75
INIT
    B1=0.033*B
    B2=0.219*B
    B3=0.196*B
    B4=0.395*B
    B5=0.115*B
    B6=0.042*B
    C10=(B1*ANO)/(.00007*AL1)
    C20=(B2*ANO)/(.00007*AL2)
    C30=(B3*ANO)/(.00007*AL3)
    C40=(B4*ANO)/(.00007*AL4)
    C50=(B5*ANO)/(.00007*AL5)
    C60=(B6*ANO)/(.00007*AL6)
DYNAM
NOSORT
    XP=X0+(GG/(ZK **2))*(1.-EXP(-ZK*TIME))-GG*TIME/ZK
    IF (XP.LE.0.) XP=0.0
SORT
    RR=TREAC*((XP/HH)-1.-(SIN(2.*PH11*XP/HH))/(2.*PH11))
    PP=(RR+PFB)/100.
    AK=(PP-B)/7.0E-05
    AND=(AK*AN)+(AL1*C1)+(AL2*C2)+(AL3*C3)+(AL4*C4)+(AL5*C5)+AL6*C6
    AN=INTGRL(ANO,AND)
    C1D=(B1/.00007)*AN-AL1*C1
    C2D=(B2/.00007)*AN-AL2*C2
    C3D=(B3/.00007)*AN-AL3*C3
    C4D=(B4/.00007)*AN-AL4*C4
    C5D=(B5/.00007)*AN-AL5*C5
    C6D=(B6/.00007)*AN-AL6*C6
    C1=INTGRL(C10,C1D)
    C2=INTGRL(C20,C2D)
    C3=INTGRL(C30,C3D)
    C4=INTGRL(C40,C4D)
    C5=INTGRL(C50,C5D)
    C6=INTGRL(C60,C6D)
    FLUX=AN*2.2E+5
TIMER FINTIM=.490, OUTDEL=1.E-3, PRDEL=1.E-3, DELT=1.E-3
PRINT AN, FLUX, RR, PP, XP
OUTPUT TIME, AN, FLUX, RR
PAGE MERGE, XYPLOT, HEIGHT=5.5, WIDTH=8.
LABEL O.S.U. REACTOR SCRAM RESPONSE
END
STOP
ENDJOB
/*
//

```