Chipmunk IV

Development of and Experience with a New Generation of Radiation Area Monitors for Accelerator Applications

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Abstract

The operation of a high-energy accelerator complex presents challenging problems for radiation monitoring during 'beam-on' conditions. As a response to these needs, Fermilab has developed several families of radiation monitoring instruments intended for use under beam-on conditions. One of these instruments is a tissue equivalent, ion chamber based, area monitor called a "Chipmunk". This article describes the latest version of these monitors, specifically the Chipmunk IV, as developed at Fermilab[1].

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Introduction

The combination of narrow beam pulse widths, mixed radiation fields and the potential for high instantaneous dose rates make most commercial radiation monitoring instrumentation inadequate for conditions around a high energy accelerator complex. The Chipmunk was designed at Fermilab for use in high-energy proton accelerator environments. It uses a tissue equivalent ionization chamber to provide radiation monitoring of photons, charged particles and non-thermal neutrons in continuous or pulsed radiation fields.

Chipmunks are the most common instruments used to monitor the radiation levels around the Fermilab accelerator areas, colliding beam experimental halls, and external beam lines. These instruments are used both inside beam enclosures and outside radiation shielding to provide personnel protection. Data from these Chipmunks are continuously collected for logging and safety interlock purposes. At the present time, there are over 300 Chipmunks in use at Fermilab.

Description

The basic components of a Chipmunk consist of power supplies, an ionization chamber, digitizing electrometer, processing electronics, and output drivers. Figure 1 shows the block diagram of a Chipmunk IV. A regulated high voltage power supply provides bias voltage to the ion chamber. The ion chamber, when exposed to penetrating ionizing radiation, produces an electrical charge proportional to the dose. This charge is measured using a sensitive zero-loss digitizing electrometer operating as a current-to-frequency converter. The processing electronics controls the digitizing electrometer and provides logic for the various functions. These functions are made available through the output drivers. A front panel rate meter, colored lamps and an audible alarm provide audio/visual indications of the dose equivalent rate levels.

History

The Chipmunk was originally developed at Fermilab in 1971 in response to the radiation monitoring challenges posed by the accelerator environment.

The original Chipmunk design used a high-pressure ionization chamber developed by LND, Inc.[2]. An unsealed electrometer digitizer measured the output current. An upgrade (Chipmunk II, approximately 1977) added fail-safe circuits as well as 3 selectable dosimetric quality factors: 1, 2.5, and 5 [1].

The Chipmunk III was a major redesign carried out in 1980, which used a larger volume (3.4 liter) one-atmosphere propane filled ion chamber produced by Health Physics Instruments[3]. A new high voltage supply was developed to provide a better-stabilized detector bias. The Chipmunk III electrometer circuit was designed with increased sensitivity plus temperature compensation. It was packaged in a sealed enclosure, thus minimizing the effects of humid environments. This allowed the Chipmunk III to be used effectively indoors or outdoors (within a small, unheated shed equivalent in size and construction to a dog house).

The ionization chamber, originally developed for the Chipmunk III, is now a standard item produced by Far West Technology, Inc. as the Model 1055. Tests were performed at Fermilab, with a variety of radioactive sources, to determine the photon and fast neutron energy response characteristics of the Model 1055 chamber (Figures 2 and 3) [2]. Further extensive tests were performed at Argonne National Laboratory to determine the response of this detector to pulsed photon fields of various dose and time structures (Figure 4) [3].

Requirements for a New Generation

It was determined in early 1993 that additional Chipmunks would be required to fulfill the monitoring needs of future accelerator operations. Desirable improvements were investigated. Subsequently, design proceeded on all improvements which could be implemented within the available time. The improvement objectives were to: increase the highest pre-settable quality factor to 10 to properly accommodate radiation fields of high linear energy transfer (LET); provide remote monitoring capability of quality factors; modernize the regulated power supplies and reduce the number of PC boards;

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[2] LND, Inc., 3230 Lawson Blvd. Oceanside, New York 11572, USA.

[3] Health Physics Instruments, Inc., 330 South Kellog Ave., Suite D, Goleta, CA 93117, USA.

improve temperature shock response; allow for a more comprehensive fail-safe function; and maintain complete compatibility with previous versions of the Chipmunk.

Design Considerations

Critical Component Selection

The characteristics of several components used in the current digitizer are extremely critical to the operation of the Chipmunk. The electrometer, integrating capacitors and integrator reset components must be selected and tested for the complete operating range of the instrument. Not all manufacturers produce devices that function as desired under all conditions. Some components are manufacturer specific. Sample testing was thus mandatory.

Digitizer

The National LMC6041ICN electrometer selected for the Chipmunk IV has a bias current of < 2fA. This allowed a sensitivity of 0.5pCoul/count for the new design (compared to 1pCoul/count for the Chipmunk III). The maximum dose rate capabilities of the previous generation Chipmunk were maintained by requiring the new instrument digitizer to operate over a dynamic range from 0.01 Hz to 10kHz.

The physical layout of the electrometer input and reset circuits have considerable effect on the linear operation of the digitizer due to inter-component capacitance. Device selection, experimental placement and testing yielded the optimal component layout. The digitizer linearity is illustrated in Figure 5.

Calibration Control

Precise and stable control of the digitizer calibration was accomplished with the design of a 10 MHz time base digitizer controller to replace the previous RC one-shot design. This controller provides ease of adjustment with approximately 0.5% change per control increment, and excellent long-term stability.

Temperature Compensation

Temperature stability is a mandatory requirement in the design of a monitoring instrument that will be used outdoors. Early in the design phase of this project, the digitizer was characterized for temperature. A compensation technique was employed which adjusted the amplitude of the reset voltage with temperature. The linearity of the completed instrument over a wide temperature range is shown in Figure 6. These tests were performed over the dynamic range of the instrument at each temperature point. Additionally, a layer of low-density polyurethane foam sheeting, affixed to the interior walls of the detector enclosure, improved the temperature transient characteristics of the instrument.

Humidity Effects

High levels of relative humidity can produce extremely detrimental effects on the functioning of electrometer circuits. Early versions of the Chipmunk (I & II) used an unsealed digitizer. The electrometer circuits of these units would routinely malfunction under the high relative humidity conditions present at times in various monitoring areas. A sealed electrometer enclosure was developed during the Chipmunk III design project. All seals and sealing techniques were reviewed during the Chipmunk IV development to further minimize the effects of humid environments. Test results are shown in Table 1.

AC Line Stability Effects

AC line voltage stability is typically poor around accelerators due to varying magnet power supply loads on the alternating current (AC) mains. Transient changes in the AC mains are most readily seen as small changes in the regulated HV chamber bias. These changes in bias voltage result in detectable changes in chamber current, due to capacitive coupling, which ultimately produce an erroneous reading by the instrument (at background radiation levels). To minimize the effects of these transient AC changes, a secondary stabilizing circuit in the ground leg of the HV regulator senses and corrects for small changes in the chamber bias voltage.

Specifications and Design Features of the Final Instrument

Physical Properties:

The complete instrument weighs approximately 10 Kg., and has maximum external dimensions of 19.7-cm. deep x 38-cm. wide x 47-cm. high, including the transport handle.

AC Power Dependency:

The instrument operates with good stability with line voltage variations from 90VAC to 130VAC.

Detector Specifications:

The ionization chamber is a Far West Technology, Inc., Model 1055. The outer wall is an aluminum cylinder. The inner surface of the chamber has phenolic lining, which is coated with aquadag. The chamber has a volume of 3.4 liters, which is filled with propane to nominally 1 atmosphere pressure. The sensitivity of the chamber is 200 microCoul/gray, with an efficiency of 97% at 10 microGray of instantaneous dose. The chamber's ion collection time is approximately 5 milliseconds.

Radiation Response:

Figures 2 and 3 show the response of the Chipmunk to photons and fast neutrons, respectively. The response of the chamber to pulsed photon fields of different doses and time structures is documented in Ref. 3 and Figure 4. A 0.11 MBq ^{137}Cs source placed in contact with the outer surface of the ion chamber yields approximately 7 x 10^{-14} A from the chamber. This results in a background counting rate of 0.15 Hz from the pulse stream output on a quality factor setting of 10. The Chipmunk's native sensitivity is 2.5 x 10^{-9} Gy/count (pulse stream output).

Linearity:

The digital (pulse stream) output of the Chipmunk is linear within ±10% over the dynamic range of 0.15 Hz to 10 kHz (1.3 microGy/hr to 90 milliGy/hr) of the instrument

(Figure 5). The rate meter is accurate within ±10% over the display range of 0.01milliSv/hr to 1milliSv/hr (The actual display markings are 1 to 100 millirem/hr).

Power Up Time-Out:

The pulse stream output is disabled for 4 minutes (nominal) following instrument power-up. This allows the detector bias and digitizer circuits to stabilize prior to providing data to radiation monitoring systems.

Fail Safe Time-Out:

This circuit removes +24 volts from one of the pins of the 26 pin external connector if the digitizer fails to count for 2 minutes (nominal). This output may be monitored by the radiation safety interlock system to provide a failure check of instrument operation.

Temperature Sensitivity:

The Chipmunk IV is compensated for temperature variations from -30˚C to +50˚C over the entire dynamic range of the pulse stream output, in the quality factor 10 setting, from 0.15 Hz to 10 kHz, corresponding to absorbed dose rates ranging from 1.3 microGy/hr to 90 milliGy/hr. Temperature tests of the prototype revealed less than +10% to -15% deviation from +25˚C measurements over the entire dynamic range, as shown in Figure 6. The instrument response is stable under temperature transients up to 10C°/hr.

Humidity Sensitivity:

The digitizing electrometer is extremely sensitive to humidity. A well-sealed enclosure is used to provide a dry environment for this circuit. Table 1 presents the test results of a prototype instrument, showing less than 1% change in response at background and at 100 microGy/hr absorbed dose rates when varying the ambient relative humidity from 40% to 95% to 40%. Situations where condensation of humidity on the electrometer is possible should, as a matter of practice, be avoided.

Further Development

Evolutionary changes to regulations and operational expectations have necessitated lower radiation trip levels. These requirements place increasing demand on the Chipmunk instrument to operate in a wide range of environmental and electrical power conditions, while maintaining freedom from apparent failures and false trips. Accomplishing this task required changes in some of the electronic circuitry. In addition, an automated temperature profile test has been developed to test each new or suspected defective instrument over the specified temperature range. This test, illustrated in Figure 7, examines the digitizer pulse interval time at background radiation levels to expose anomalies in the test unit's operation.

A fail-safe board has been developed to monitor critical voltages and signals generated by the Chipmunk. A failed instrument can now be identified in 20 seconds or less. Previously, 2 minutes was required for this identification. Provision was made during the Chipmunk IV project to accommodate the possibility of this addition.

Experience has shown the difficulty in maintaining the seal integrity of the digitizer enclosure. A desiccant container attached to the digitizer enclosure has been incorporated. This will help maintain a dry atmosphere for the electrometer circuit.

The indicator lamps are the primary power consumption devices in the Chipmunk IV. During accelerator magnet power supply ramping at Fermilab, the AC line voltage can drop sufficiently to affect the power supplies. Lower current lamps have been selected to effectively increase the power supply overhead. Additionally, this modification reduces instrument self-heating.

AC line voltage changes also affect the high voltage (HV) supply. Though the supply is double regulated, fractional (<1v) output voltage changes can occur with large AC line changes. At low interlock trip levels, these changes can result in interlock fail-safe or radiation trips. A new HV supply has been developed to operate from the regulated low voltage (LV) supplies. This produces an extremely stable HV supply. Component selection and layout have minimized power supply noise at temperature and humidity extremes. Additionally, the elimination of the power transformer high voltage winding has allowed an increase in the power available to the low voltage circuits.

These improvements, resulting from years of changing requirements and experience, are being implemented as a scheduled modification to all existing Chipmunk IV units.

Conclusion

The Chipmunk IV project resulted in upgrading most of the calibration sensitive circuitry in the instrument. The digitizer sensitivity and maximum operating frequency were doubled, while adding a fourth quality factor (QF = 10). Calibration stability was improved by controlling the digitizer calibration with a 10MHz crystal time base. Temperature compensation provides stability over a range of more than 5 orders of magnitude of absorbed dose measurement. All power supplies were upgraded and simplified where possible. Provision was made for remote readout of the quality factor setting. A layer of low density insulating foam was applied to the inside of the ionization chamber enclosure to reduce the effects of temperature transients. Provisions were made for the future installation of additional self-check features. For logistics reasons the design changes satisfy all previous requirements for display and external connections. This allows the new Chipmunk IV's to be interchangeable with previous generations. All fifty of the Chipmunk IVs were built at Fermilab, with some subassemblies produced under contract. The quality of every instrument produced during this project was assured by extensive testing including a three-point temperature test and detailed calibration over the dynamic range of the instrument. Additional tests were performed on randomly selected units to obtain detailed characterization of environmental and radiological effects.

Efforts continue to further improve and develop the chipmunk instrument in order to accommodate regulatory changes as well as new operational conditions.

Acknowledgements

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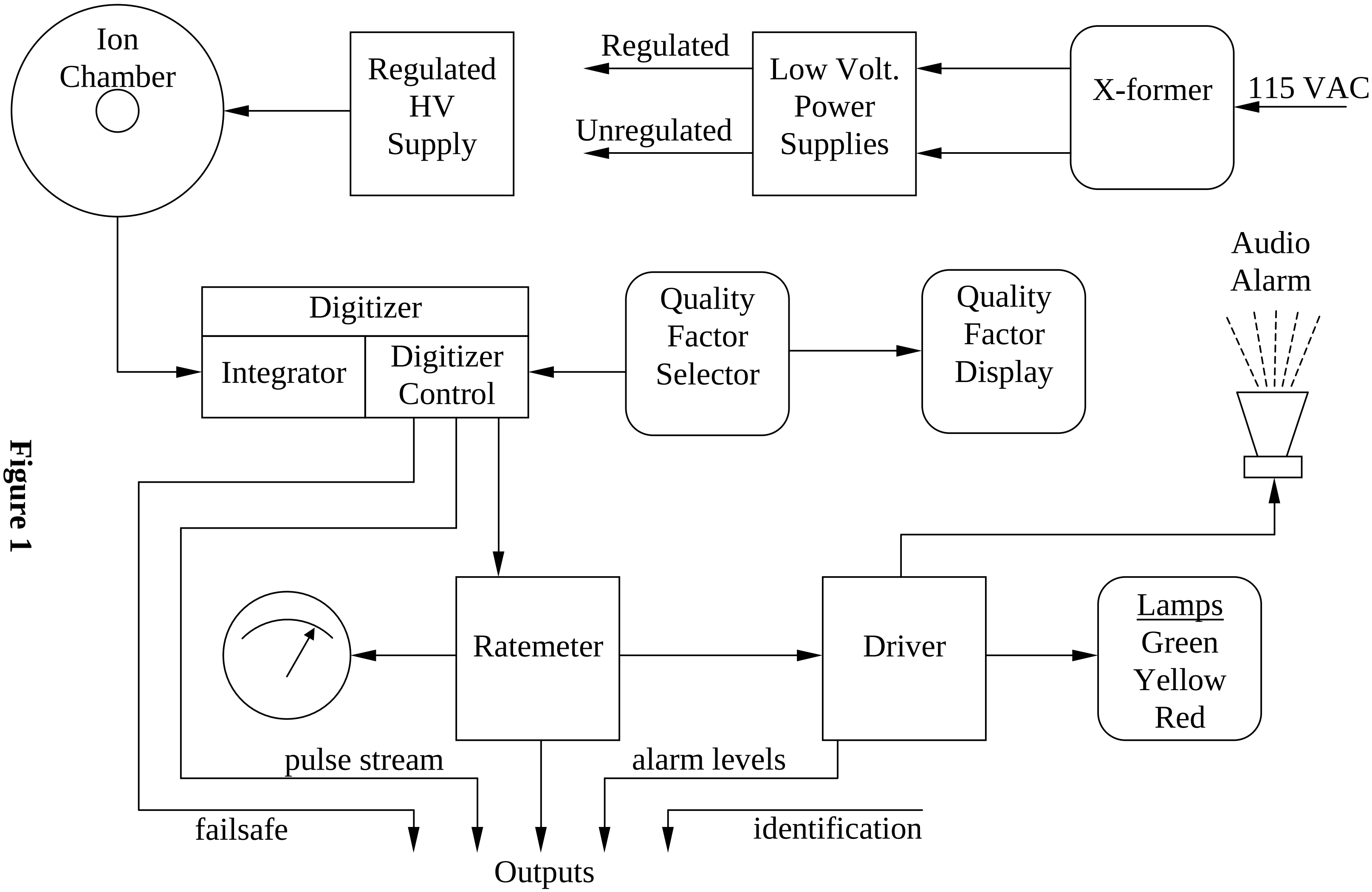
3. Freeman, W.S., et al., "The Response of a Fermilab-Designed Ion Chamber in Pulsed Fields", Fermilab TM 1512 - Fermilab, USA (1988)

List of Figures:

Figure 1



Chipmunk IV Block Diagram

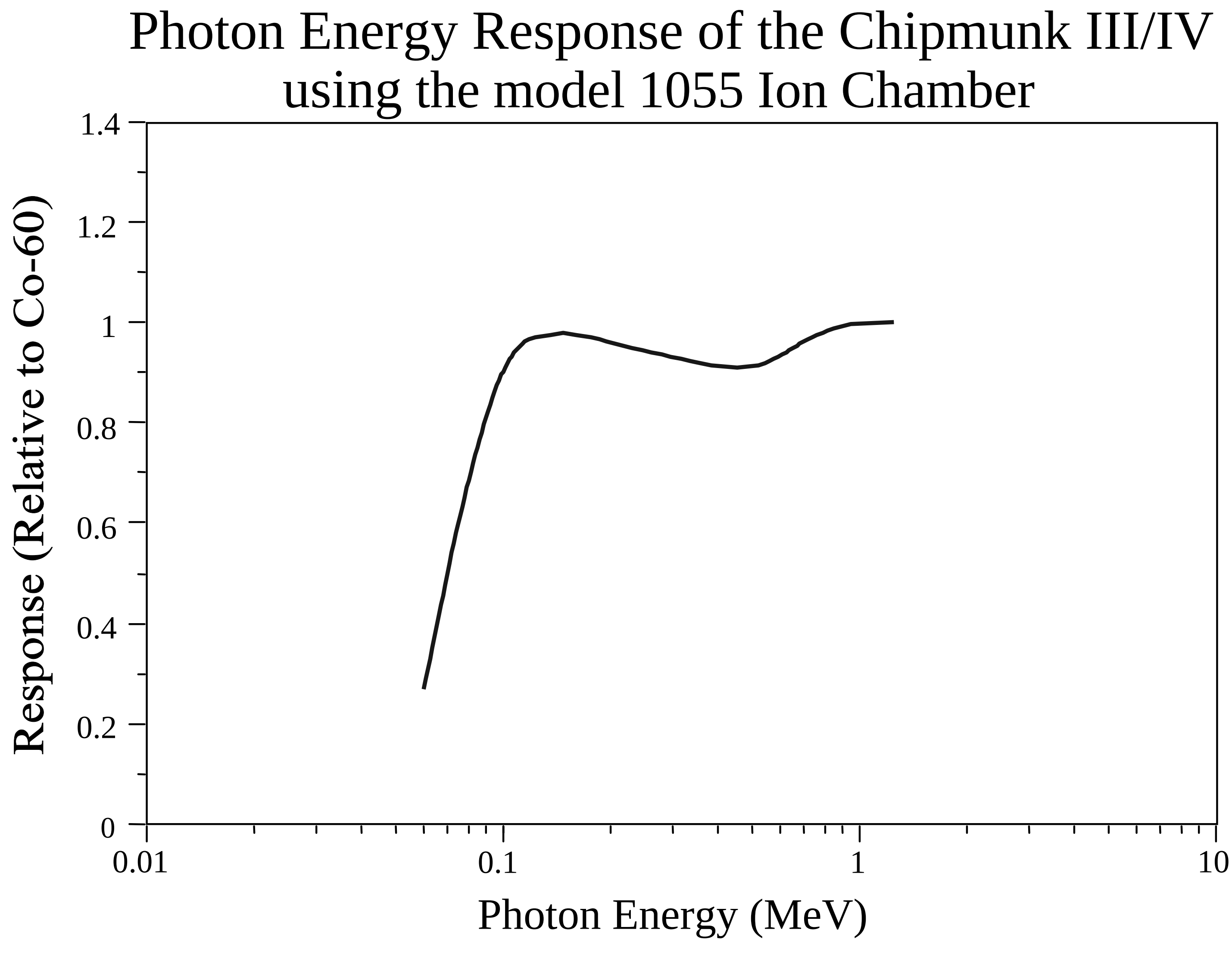
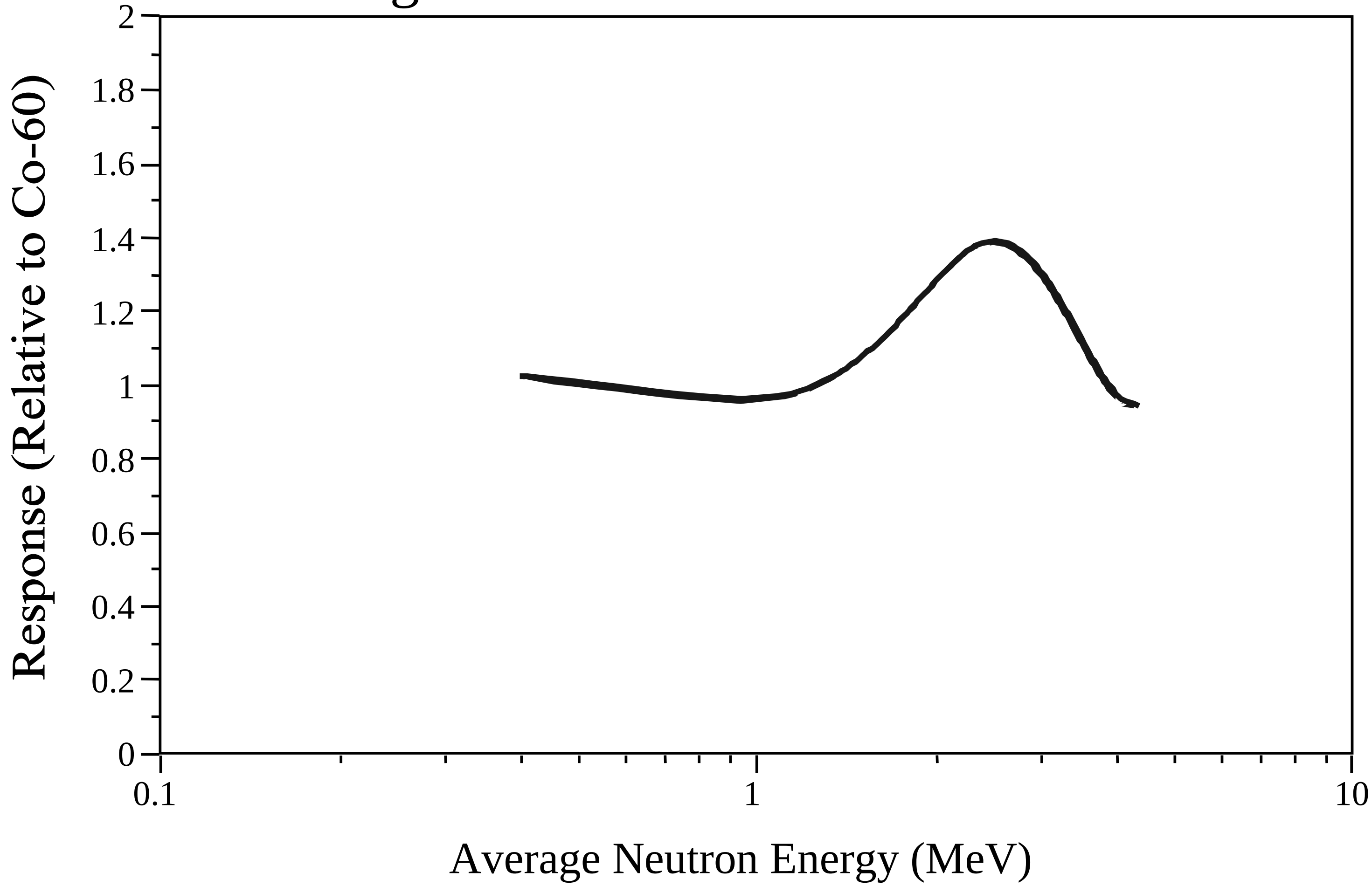

Photon Energy Response of the Chipmunk III/IV
using the model 1055 Ion Chamber
Response (Relative to Co-60)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.01
0.1
1
10
Photon Energy (MeV)

Figure 2

Figure 3

Fast Neutron Energy Response of the Chipmunk III/IV using the model 1055 Ion Chamber



Chipmunk Ion Chamber Pulsed Photon Field
Collection Efficiency from TM1512

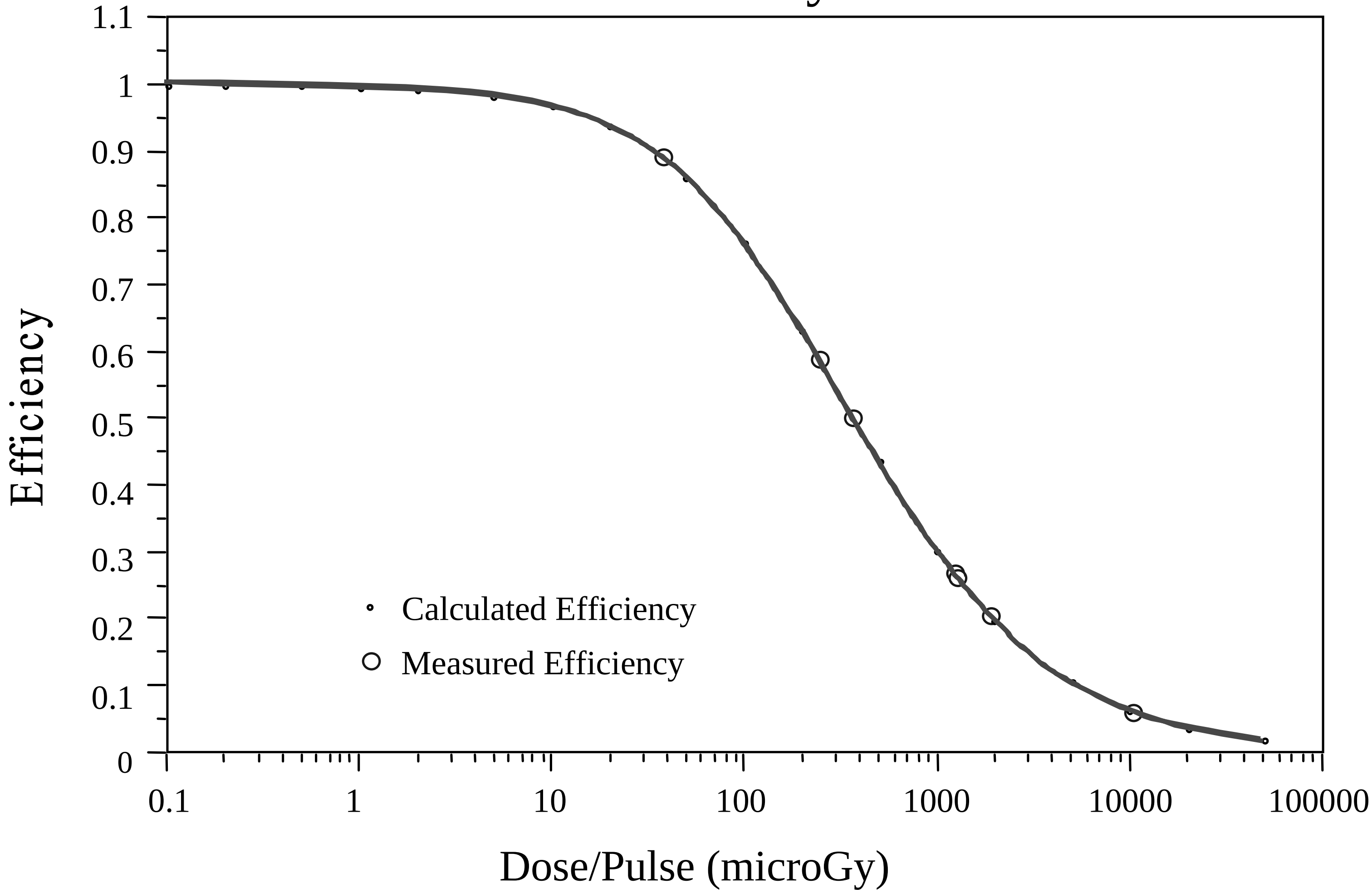
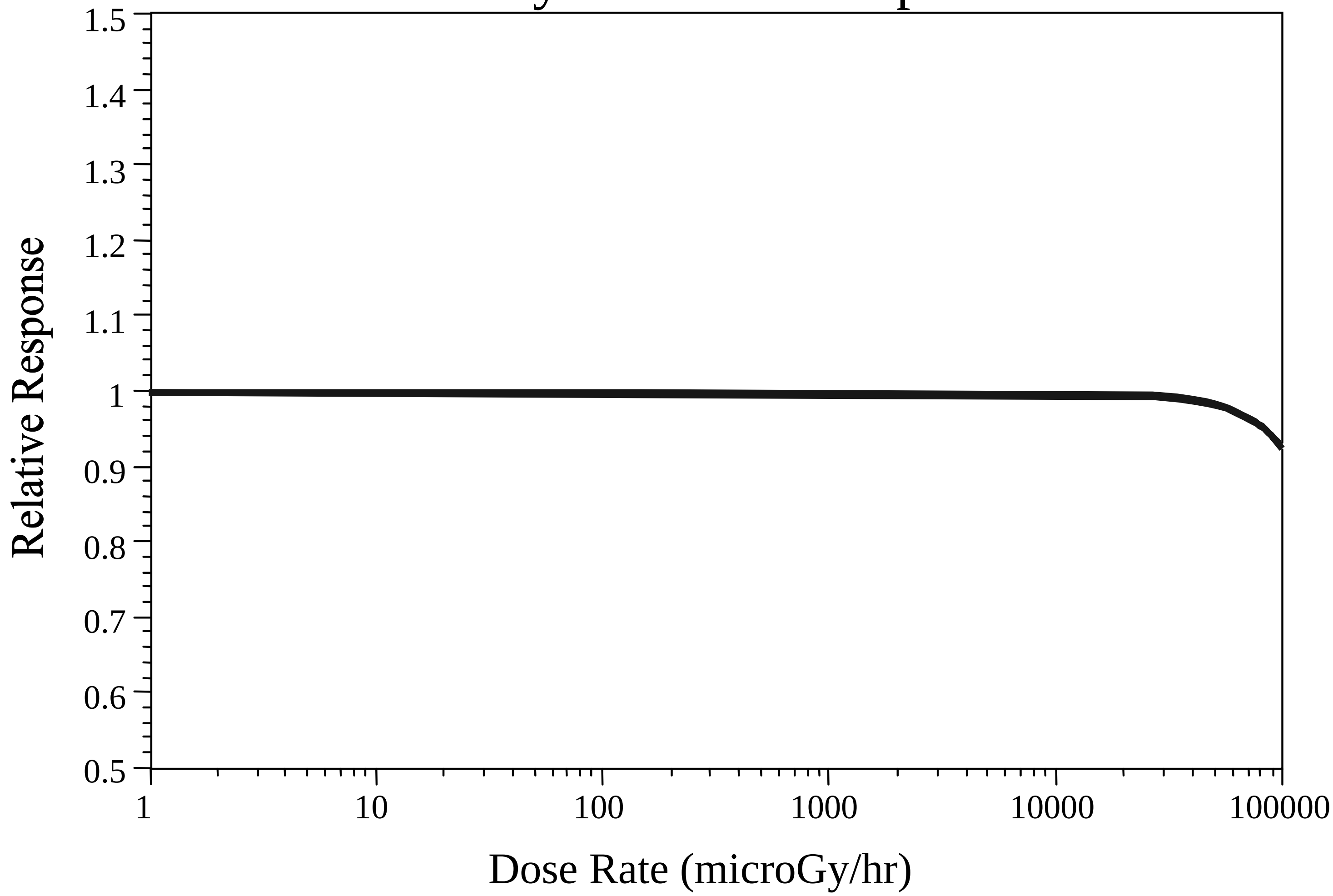


Figure 4

Figure 5

Chipmunk IV Pulse Stream Output
Linearity at Room Temperature



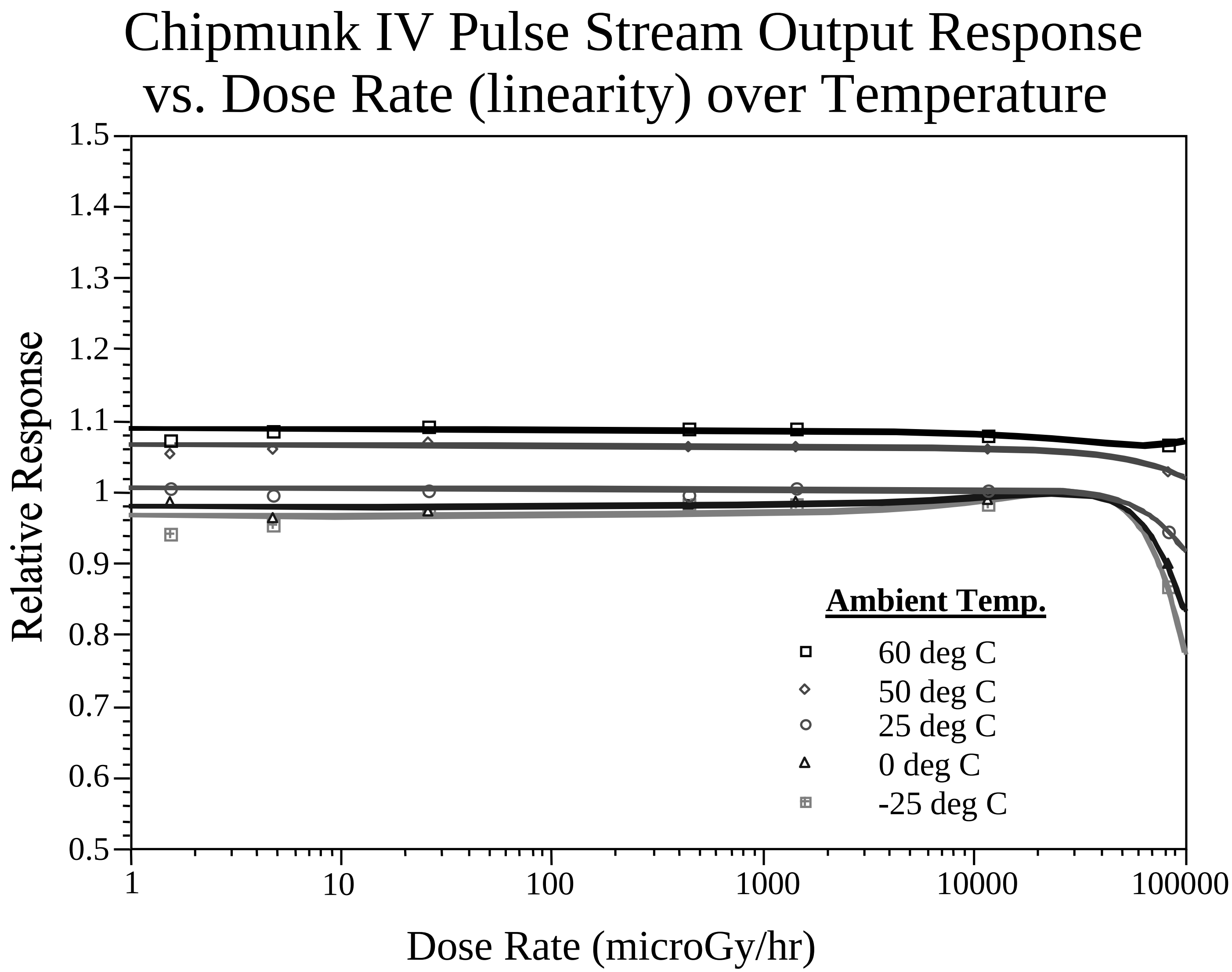

Chipmunk IV Pulse Stream Output Response
vs. Dose Rate (linearity) over Temperature
Relative Response
Dose Rate (microGy/hr)
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
1
10
100
1000
10000
100000
Ambient Temp.
60 deg C
50 deg C
25 deg C
0 deg C
-25 deg C

Figure 6

Chipmunk IV, Representative Background Count Interval vs. Temperature Profile

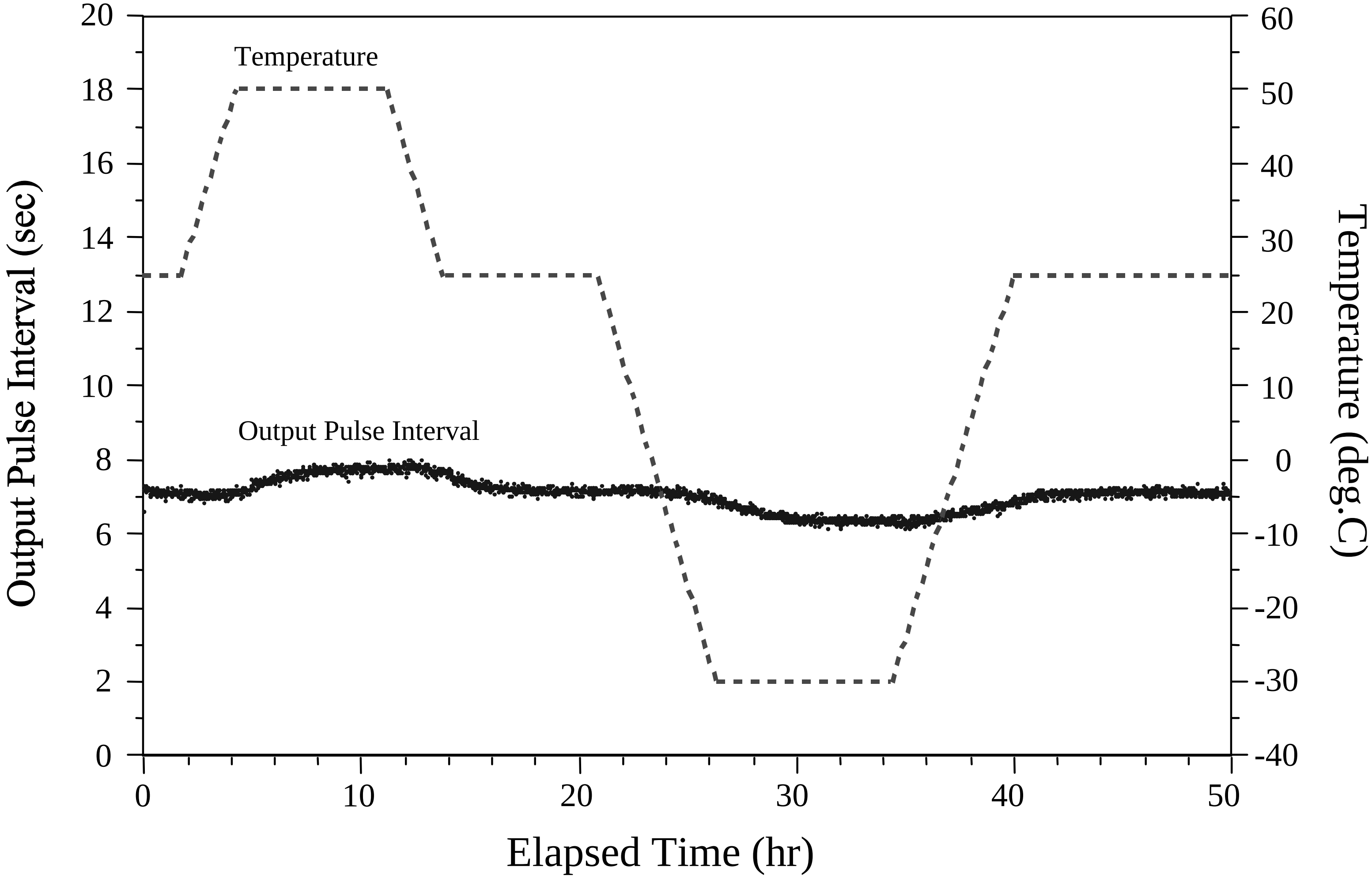


Figure 7

Table 1

Effects of Humidity Change on Digitizer Counting Rate

Dose Rate	Digitizer Counting Rate Change	
	From 40% to 90% RH	From 95% to 40% RH
Background	0.49% change	0.55% change
100 microGy/hr	0.12% change	0.10% change