LA-UR- 93-747

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE: Report on High Energy Neutron Dosimetry Workshop

AUTHOR(S): Kenneth R. Alvar
Avigdor Gavron

SUBMITTED TO: Workshop at Gaithersburg, MD

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Report on High Energy Neutron Dosimetry Workshop

November 19, 1992 at Gaithersburg, MD

Kenneth R. Alvar and Avigdor Gavron

Los Alamos National Laboratory

Los Alamos, New Mexico

Report prepared for:

United States Department of Energy

Office of Assessment and Support ER-8

Office of Energy Research

Under KC-08-11-02-0

January 27, 1993

Report on DOE High Energy Neutron Dosimetry Workshop
November 19, 1992 at Gaithersburg, MD

Kenneth R. Alvar and Avigdor Gavron
Los Alamos National Laboratory
Los Alamos, New Mexico

The workshop was called to assess the performance of neutron dosimetry per the responses from ten DOE accelerator facilities to an Office of Energy Research questionnaire regarding implementation of a personnel dosimetry requirement in DRAFT DOE 5480.ACC, "Safety of Accelerator Facilities" [August 28, 1992]. The goals of the workshop were to assess the state of dosimetry at high energy accelerators and if such dosimetry requires improvement, to reach consensus on how to proceed with such improvements.

There were 22 attendees, from DOE Programs and contract facilities, DOE, Office of Energy Research (ER), Office of Environmental Safety and Health (EH), Office of Fusion Energy, and the DOE high energy accelerator facilities. A list of attendees and the meeting agenda are attached. Copies of the presentations are also attached.

Introductory remarks were made by **Joseph Maher,** Director of the Office of Assessment and Support, ER-8. He noted that the Workshop should address areas of weakness in high energy neutron dosimetry. While ER-8 is in support of new technical programs, he said that there will be a time of transition as the new administration assumes office and replaces many of the high level administrators.

DeVaughn Nelson made the first presentation that included (1) a summary of the responses to the questionnaire, which he circulated with the DOE draft accelerator safety order, and (2) an overview of recorded personnel doses at DOE supported accelerator facilities. He specifically noted the monitoring requirements of DOE 5080.11 [9g(1)] DOE 5480.25 [9c(4)], DOE 5480.15 and the Radiological Control Manual Chapter 5, Part 1 (512) and Chapter 1, Part 3 (131 and 137).

The number of persons presently monitored at DOE accelerator facilities is approximately 4000 with about 1500 receiving "measurable" exposure. The total collective dose equivalent for all DOE facilities and DOE accelerator facilities is similar. During the period 1982 through 1986 the yearly collective dose equivalent was approximately constant at 8000 person rem for all DOE facilities and 240 person rem for accelerator facilities. After that period the collective dose equivalents leveled off at about 2500 and 150 person rem, respectively. The decrease was due in part to increased ALARA activities and to the reduced workload at some of the higher exposure-producing facilities. The average whole body dose has been on a decreasing trend since 1977. Similarly the distribution of whole body exposures also shows a significant decrease of high individual exposures. No doses in the 3-4 rem range have been reported since 1984 for accelerator facilities. The total exposure at BNL, Fermilab, LLNL, and LANL represent 111 out of 142 person-rem received at all DOE accelerator facilities. The average neutron dose is approximately 25% of the total dose equivalent.

Robert Loesch, DOE Dosimetry and Technology Assessment Branch (EH) spoke next on DOE policy on monitoring and accreditation, especially for neutrons. The present policy requires monitoring when exposures are anticipated to be above 100 mrem per year. Neutron dosimetry is accredited in the range 1 keV to 2 MeV and not above 2 MeV. Mr. Loesch posed several questions related to high energy neutron dosimetry.

1) Do workers receive occupational exposures to neutrons above 2 MeV?

2) What percent of their annual exposure is from neutrons above 2 MeV?

3) If the exposure is significant, is the current dosimetry technology adequate to record the exposure? If it is, there is the need for routine intercomparisons. If not, there is the need for additional research.

Mr. Loesch then presented early results from a dosimeter intercomparison study done at Oak Ridge which included 14 MeV neutron dosimetry. A total of 57 dosimeters were exposed to a 14 MeV neutron beam. The dosimeter types included TLD, albedo, track-etch, film, bubble and combined dosimeters. All except the three bubble dosimeters under-responded on average. However, the individual dosimeter readings varied from less than 20% of the actual value of 163 mrem to over 250% of the actual value. The participants of the intercomparison were informed that this particular exposure was to be 14 MeV neutrons. The conclusion of the report was that few facilities' dosimetry would pass current DOELAP neutron criteria at low energy if the criteria were used for 14 MeV neutrons.

Ken Alvar, Los Alamos National Laboratory, gave a brief overview of high energy neutron dosimetry. NTA film was used for neutron dosimetry in the past and as noted in Fermilab Report FN-510 is still used by most facilities. Several facilities are using CR-39 track-etch technology and there is interest in bubble dosimeters for this application. It is clear that the response with neutron energy from 15 MeV to 100 MeV and higher for the three dosimeters, NTA, CR-39 and bubbles needs to be measured in a systematic and thorough manner.

Data were presented which showed that routine exposures to high energy neutrons can occur at proton accelerators. Accumulated yearly exposure data for the LAMPF site indicates, consistent with other presentations at the workshop, that 20% of the total person exposure is due to neutrons. LAMPF has modelled some beam spill scenarios which indicate the possibilities of high neutron dose rates. The routine exposures as far as can be determined with present dosimetry have been small. Because of the lack of dosimeter response data no further definitive conclusions could be reached.

A number of items which would improve the accuracy of neutron dosimetry were presented. The workshop attendees noted that very little work has been in high energy neutron dosimetry in the last fifteen years.

Avigdor Gavron, Los Alamos National Laboratory, presented the capabilities available at the LAMPF Weapons Neutron Research (WNR) facility for doing high energy neutron dosimetry. Both monenergetic beams and polyenergetic beams are available at WNR and the spectra and fluence for both types are well-known. Energies between 0.1 to 800 MeV are available through the use of reaction kinematics and different beam path locations, filters and time-of-flight. The polyenergetic or "white" beams are characteristic of the neutron leakage spectra through accelerator shielding and represent the spectra for which operational dosimetry is needed. The monenergetic beams are useful for dosimeter and rate meter response determinations. The staff at WNR provide expertise in Monte Carlo and neutron transport calculations.

Joe McDonald, PNL reported on the high energy neutron dosimetry intercomparison carried out in July-August 1992 at the University of Washington neutron therapy cyclotron. The neutron beam came from deuterons bombarding a beryllium target which was thick enough to cause the deuteron beam to lose one-half of its energy traversing the target. The average neutron energy was approximately 20 MeV. Dosimetry was provided through ion chamber measurements by the University staff. Six sets of dosimeters from different facilities were irradiated to 0.53 and 0.98 rad and then read and analyzed by their respective laboratories. For the 0.53 rad exposure the reported results varied from 1.3 to 7.8 rem and for the 0.98 rad exposure from 2.0 to 11.8 rem. Only the TLD results were in the same ratio as the exposures. The NTA ratio was high and the other 3 ratios were lower.

The conclusion of the report was that there was significant differences among the results.

Steve Musolino, of Brookhaven National Laboratory, discussed the results of dose equivalent measurements in experimental halls at the Alternating Gradient Synchrotron at BNL. He used dosimeters from three commercial vendors and some TLD's processed by BNL.

The neutron spectra were not measured but undoubtedly varied with location. The reported results showed wide variation which could be due to different calibrations, different processing, and different energy responses of the dosimeters.

Dave Boehnlein, Fermilab, discussed the Bonner-sphere measurements of the neutron spectra through shielding at various locations at Fermilab. While the relative contributions to dose equivalent from neutrons above 20 MeV varied significantly from location-to-location the site-wide average yielded the statement that neutrons above 2 MeV contribute 50% of the dose equivalent.

After the presentations **DeVaughn Nelson** led the workshop discussions, first on summarizing the present state on high energy neutron dosimetry and secondly on what direction should a new effort take.

The attendees agreed that high energy neutron dosimetry needs to be improved. The attendees agreed with the following statements:

1) Neutron dosimetry above 2 MeV is both imprecise and inaccurate.

2) For current dosimetry

   - The measurement uncertainty is of the order ± 300%.

   - The neutron dosimeters are neutron indicators, not dosimeters.

   - There is little active R&D.

   - Dose is being underestimated.

   - There is limited capability for area surveys with Bonner spheres. Bonner sphere response has not been carefully determined for neutron spectra above 35 MeV.

   - A reliable dosimeter is needed, at least for the range of 20 to 50 MeV.

3) Better personnel dosimeters and area monitors are needed.

4) Dosimeter response is poorly known as a function of neutron energy.

5) It is erroneous to assume that one detector will be appropriate for all spectra.

6) There are no calibration standards for high energy neutron dosimetry.

7) Neutron fields are not well-characterized in accelerator environments.

8) The current process for the characterization of neutron fields and fluence is laborious.

9) Whatever set of neutron quality factors as a function of energy is selected for DOE, they must be used consistently and universally.

10) 14 MeV dosimetry needs improvement.

11) Radiobiology is not within the purview of the workshop.

The discussion then turned to what is needed now for high energy neutron dosimetry:

1) A high energy neutron dosimeter with sensitivity in the range of 20 to 50 mrem.

2) The energy response and lower level of detection for the present dosimeters needs to be determined.

3) Need to do accurate determinations of neutron spectra at various locations for personnel in work areas.

A final group of recommendations were listed:

1) There is a definite need for the determination of the energy response and lower limit of detection for current dosimeters-TLD, NTA film, CR-39 and bubble dosimeters.

2) A committed and available neutron source, such as WNR, is very important for near-and long-term improvement of high energy neutron dosimetry.

3) Standards should be developed for high energy neutron dosimetry as has been done in the past for lower energy neutron dosimetry.

4) There should be a dedicated facility for 14 MeV dosimetry.

In the closing discussion the attendees agreed that Los Alamos National Laboratory (LANL) should develop promptly a proposal for improvement of high energy neutron dosimetry following the recommendations of the workshop. The proposal should include development of the WNR neutron beam facility as a standard source for high energy neutron dosimetry. The LANL attendees agreed to do this and to have the proposal reviewed by a group of workshop attendees. An open invitation was issued by LANL to host the next high energy neutron dosimetry meeting at Los Alamos.

AGENDA FOR HIGH ENERGY NEUTRON DOSIMETRY (HEND) WORKSHOP
NOVEMBER 19, 1992
HOLIDAY INN, GAITHERSBURG, MARYLAND

Thursday, November 19, 1992

12:30 p.m.	Introduction Joseph Maher, Director, Office of Assessment and Support, ER-8, or W. Neill Thomasson, Acting Director, Safety and Health Protection Division, ER-8.1
12:35 p.m.	Considerations for HEND DeVaughn Nelson, Health Physicist, ER-8.1
1:00 p.m.	DOE Policy and Accreditation of HEND Robert Loesch, Health Physicist, EH-411
1:15 p.m.	Overview: Status of HEND Ken Alvar, Section Leader, Measurements Technology Support, LANL
2:00 p.m.	HEND Calibration and Intercomparison Capabilities at WNR Avigdor Gavron, Deputy Group Leader, Neutron and Nuclear Science, LANL
2:45 p.m.	BREAK
3:00 p.m.	Accelerator Personnel Dosimeter Intercomparison Joe McDonald, PNL
3:10 p.m.	Intercomparison of Neutron Dosimetry at the AGS Stephen Musolino, BNL
3:20 p.m.	Neutron Radiation Fields at Fermilab David Boehnlein, FNAL
3:30 p.m.	Workshop Discussions
5:15 p.m.	Consensus Recommendations and Priorities
5:30 p.m.	Adjournment

WORKSHOP ATTENDEES

Joseph Maher, DOE, ER
DeVaughn Nelson, DOE, ER-8
Joe McDonald, PNL
Bob Mundis, LANL
Steve Musolino, BNL
Al Evans, ER-13 Material Science, Basic Energy Sciences
Dave Boehnlein, Fermilab
Henry Kahnhauser, BNL
Ken Alvar, LANL
Avigdor Gavron, LANL
Roger Kloepping, LBL
Marcia Torres, ANL
Ken Kase, SLAC
Geoff Stapleton, SSC
Robert Loesch, EH-41
Peter O'Connell, EH-41
Joe McGrory, ER-23 HE&NP
Norman Rohrig, INEL
Herb Field, Intech
Paul Johnson, LBL, ES&H
Ed Jascewsky, DOE,COO
Robert May, CEBAF
Bill Casson, ORNL
Mark Wilson, DOE, ER-43
Robert Schenker, ANL

High Energy Neutron Dosimetry Workshop

INTRODUCTION

DeVaughn Nelson
Office of Assessment and Support

Thursday, November 19, 1992
Holiday Inn
Gaithersburg, Maryland

STATUS OF HIGH ENERGY NEUTRON DOSIMETRY

- WHAT IS CURRENT STATUS OF HEND?
- WHERE DO WE GO FROM HERE?

SURVEY - 8/28/92

PERSONNEL DOSIMETRY AT ACCELERATOR FACILITIES

Major Questions: Do you currently have documentation in place that would satisfactorily meet the requirements of Paragraph 9.c.(4) of DOE 5480.25 for ER HQ as well as any other HQ safety oversight?

	YES	NO
SSC	--	--
LLNL	X	--
ANL-E	X [Qualified]	--
LANL	X [Qualified]	--
CEBAF	--	--
SLAC	--	X
SNL	X	--
ORNL	X	--
BNL	--	X
FNL	X	--

QUESTIONS 3 & 4	FUTURE ENDEAVORS
SSC	Workshop Consensus for Research
LLNL	---
ANL-E	Spectral Studies/Dosimeter Studies
LANL	Additional R&D
CEBAF	Validation of Proposed Dosimetry
SLAC	Some Research required on TTAP
SNL	---
ORNL	---
BNL	Spectral/Calibration Studies
FNL	Intercomparison/Refinement Studies

DOE MONITORING REQUIREMENTS

- DOE 5480.11 [9g(1) External Radiation]

  "Personnel dosimetry programs shall be adequate to demonstrate compliance with the radiation protection standards provided in paragraph 9b. Personnel dosimeters shall be routinely calibrated and maintained and shall meet he requirements of the DOE Laboratory Accreditation Program (DOELAP) for Personnel Dosimetry as specified in DOE 5480.15."

DOE MONITORING REQUIREMENTS (Continued)

- DOE 5480.25 [9c(4) "Documented Personnel Dosimetry Program"]

  "Have a documented personnel dosimetry program, as required by DOE 5480.11, which follows the practices specified in DOE's Radiological Control Manual, and which specifically addresses those radiations and energies encountered in facility operation that at are not covered by DOE 5480.15."

- DOE RADIOLOGICAL CONTROL MANUAL - Chap 5: Part 1, External Dosimetry

511 Requirements

1. Personnel dosimetry shall be required for personnel who are expected to receive an annual external whole body dose greater than 100 mrem or an annual dose to the extremities, lens of the eye or skin greater than 10 percent of the corresponding limits specified in Table 2-1. Neutron dosimetry shall be provided when a person is likely to exceed 100 mrem annually from neutrons.

Neutron Quality Factor

DOE MONITORING REQUIREMENTS (Continued)

512 Technical Requirements for External Dosimetry

1. DOE 5480.15 specifies the requirements for accreditation of personnel external dosimetry monitoring programs by the DOE Laboratory Accreditation Program (DOELAP). A technical basis document shall be developed for the external dosimetry program Personnel external dosimeters include but are not limited to TLDs, Track etch dosimeters and neutron sensitive film.

DOE MONITORING REQUIREMENTS (Continued)

2. The technical basis document shall also address dosimeters monitoring radiation outside the scope of DOELAP, such as dosimetry associated with high-energy accelerators and extremity dosimeters.

3. Facilities should participate in intercomparison studies for external dosimetry programs.

CHAPTER 1 EXCELLENCE IN RADIOLOGICAL CONTROL

PART 3 Improving Radiological Performance

137 Neutron Exposures

Neutron exposures have the following characteristics which require attention:

- The specific biological effects of neutrons are not as well understood as the effects of gammas.

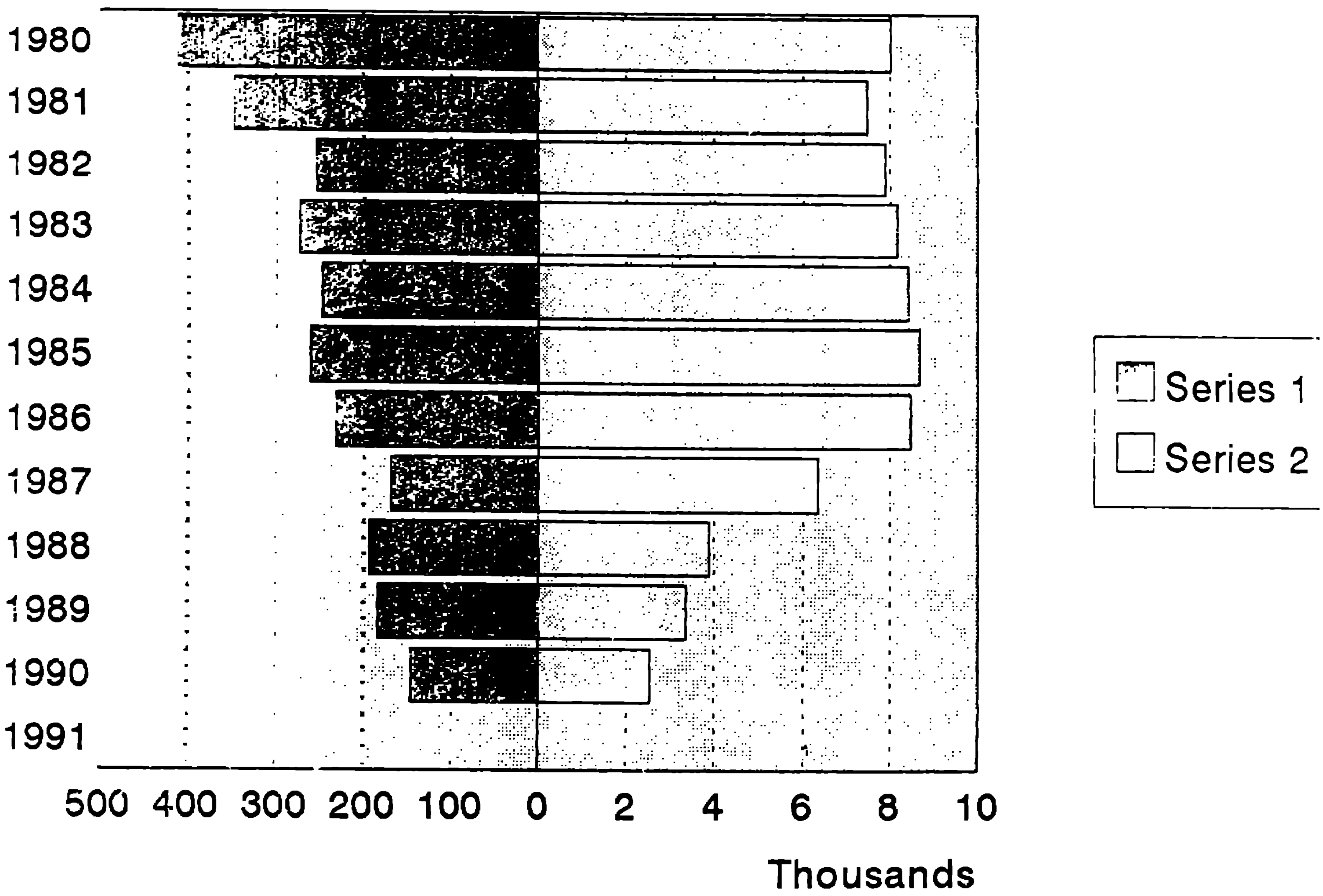
Distribution of WB Doses Greater than 1 rem at DOE AFs, 1974-1991

Year	Number of Persons Receiving Dose Equivalent in Each Dose Equivalent Range (rem)				
	1-2	2-3	3-4	4-5	5-6
1974	192	90	44	20	1
1975	176	72	45	19	
1976	142	40	28	2	
1977	153	61	24	7	
1978	127	25	13	2	
1979	95	24	8	1	
1980	70	11	2		
1981	53	12	1		
1982	31	2	1		
1983	42	10	3		
1984	40	7	1		
1985	42	10			
1986	26	7			
1987	27	1			
1988	28	3			
1989	24	2			
1990	3				
1991	5				

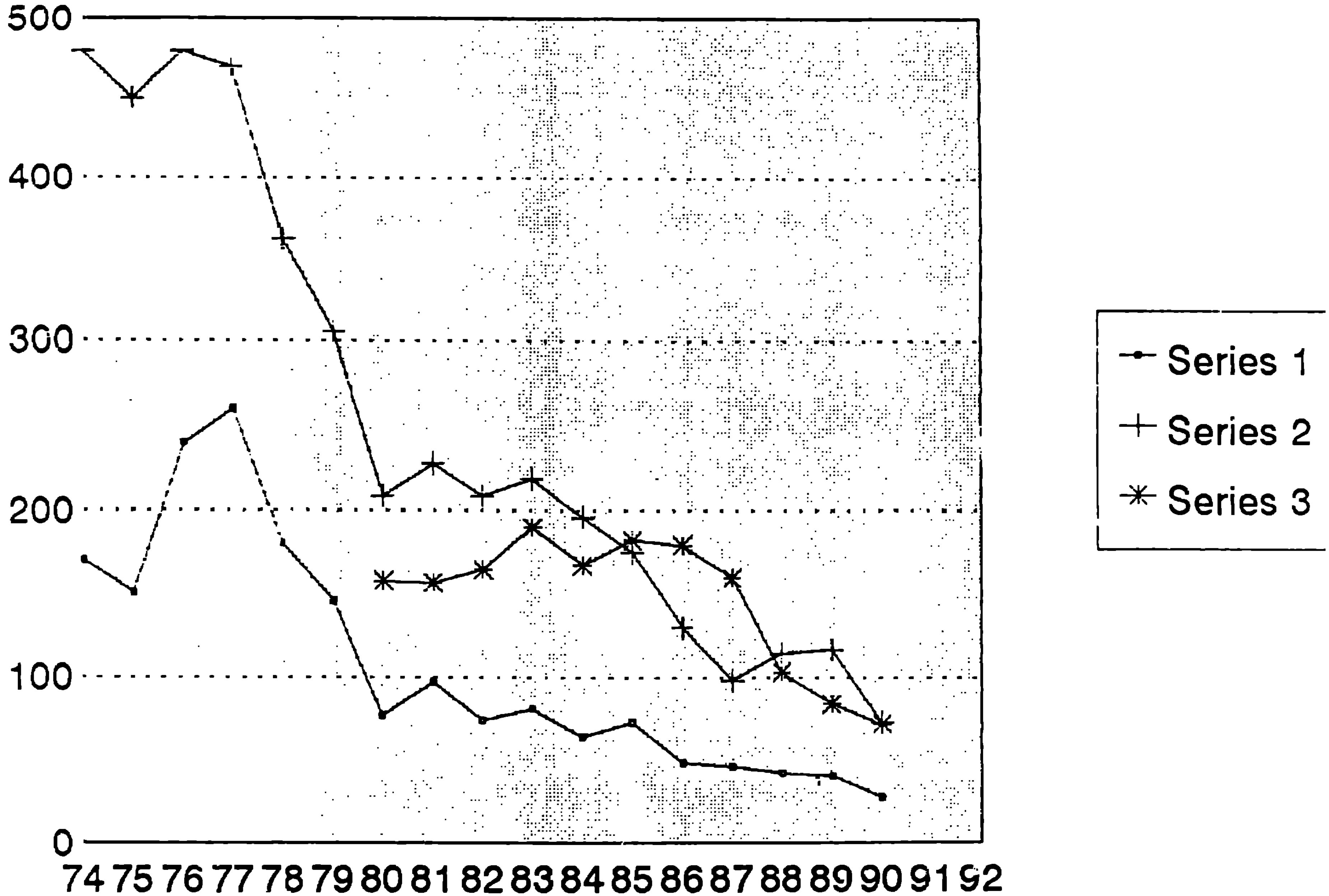
Table 1. Average Penetrating and Neutron Doses at Accelerator Facilities, 1990

Organization	Average Penetrating Dose (mrem)	Average Neutron Dose (mrem)	Records
Pacific Northwest Lab.	10	5	8
Brookhaven National Lab.	51	10	830
Chicago Subcontractors	74	< 1	14
Fermilab	12	1	2821
Lawrence Berkeley Laboratory	45	12	262
Lawrence Livermore National Laboratory	1	< 1	124
Los Alamos National Laboratory	54	21	830
Mason & Hanger-Amarillo	8	< 1	33
Mass. Inst. of Tech.	26	0	121
Sandia National Laboratory	6	< 1	408
Stanford Linear Acc. Center	7	< 1	496

Collective Dose Equivalent for All DOE Facilities & Accelerators



Average Whole-Body Dose to Monitored and Measurably Exposed Persons at DOE AFs



Year	1-2	2-3	3-4	4-5	5-6
1974	192	90	44	20	1
1975	176	72	45	19	
1976	142	40	28	2	
1977	153	61	24	7	
1978	127	25	13	2	
1979	95	24	8	1	
1980	70	11	2		
1981	53	12	1		
1982	31	2	1		
1983	42	10	3		
1984	40	7	1		
1985	42	10			
1986	26	7			
1987	27	1			
1988	28	3			
1989	24	2			
1990	3				
1991	5				

Table 1. Average Penetrating and Neutron Doses at Accelerator Facilities, 1990

Organization	Average Penetrating Dose (mrem)	Average Neutron Dose (mrem)	Records
Pacific Northwest Lab.	10	5	8
Brookhaven National Lab.	51	10	830
Chicago Subcontractors	74	< 1	14
Fermilab	12	1	2821
Lawrence Berkeley Laboratory	45	12	262
Lawrence Livermore National Laboratory	1	< 1	124
Los Alamos National Laboratory	54	21	830
Mason & Hanger-Amarillo	8	< 1	33
Mass. Inst. of Tech.	26	0	121
Sandia National Laboratory	6	< 1	408
Stanford Linear Acc. Center	7	< 1	496

TABLE 2. Distribution of Penetrating Doses by Organization and Dose-Equivalent Range for Workers at Accelerator Facilities, 1990

Number of Persons	Receiving Penetrating Doses in each Dose-Equivalent Range (rem)								
Organization	< Meas.	Meas.-< 0.10	0.10-0.25	0.25-0.50	0.50-0.75	0.75-1.0	1.0-2.0	2.0-3.0	Total Persons	Total Person rem
Pacific NW Lab	5	3							8	< 1
BNL	455	251	72	41	6	4	1		830	42
Chicago Subcon.	9	3	1			1			14	1
Fermilab	1936	803	72	8	1	1			2821	34
LBL	3	241	14	3			1		262	12
LLNL	121	3							124	< 1
LANL	578	146	44	31	19	11	1		830	45
M&H-Amarillo	25	8							33	< 1
MIT	79	35	5		1	1			121	3
SNL	332	74	2						408	2
SLAC	420	69	7						496	4
TOTAL	3963	1636	217	83	27	18	3		5947	142

TABLE 3. Distribution of Neutron Doses by Organization and Dose-Equivalent Range for Workers at Accelerator Facilities, 1990

	Number of Persons Receiving Neutron Doses in each Dose-Equivalent Range (rem)									
Organization	< Meas.	Meas.- < 0.10	0.10- 0.25	0.25- 0.50	0.50- 0.75	0.75- 1.0	1.0- 2.0	2.0- 3.0	Total Persons	Total Person rem
Pacific NW Lab.	6	2							8	< 1
BNL	762	34	18	9		1			830	8
Chicago Subcon.	14								14	< 1
Fermilab	2731	85	5						2821	3
LBL	214	46	1				1		262	3
LLNL	123	1							124	< 1
LANL	644	123	46	17					830	17
MH--Amarillo	33								33	< 1
MIT	121								121	< 1
SNL	408								408	< 1
SLAC	491	5							496	< 1
TOTAL	5553	296	70	26		1	1		5947	32

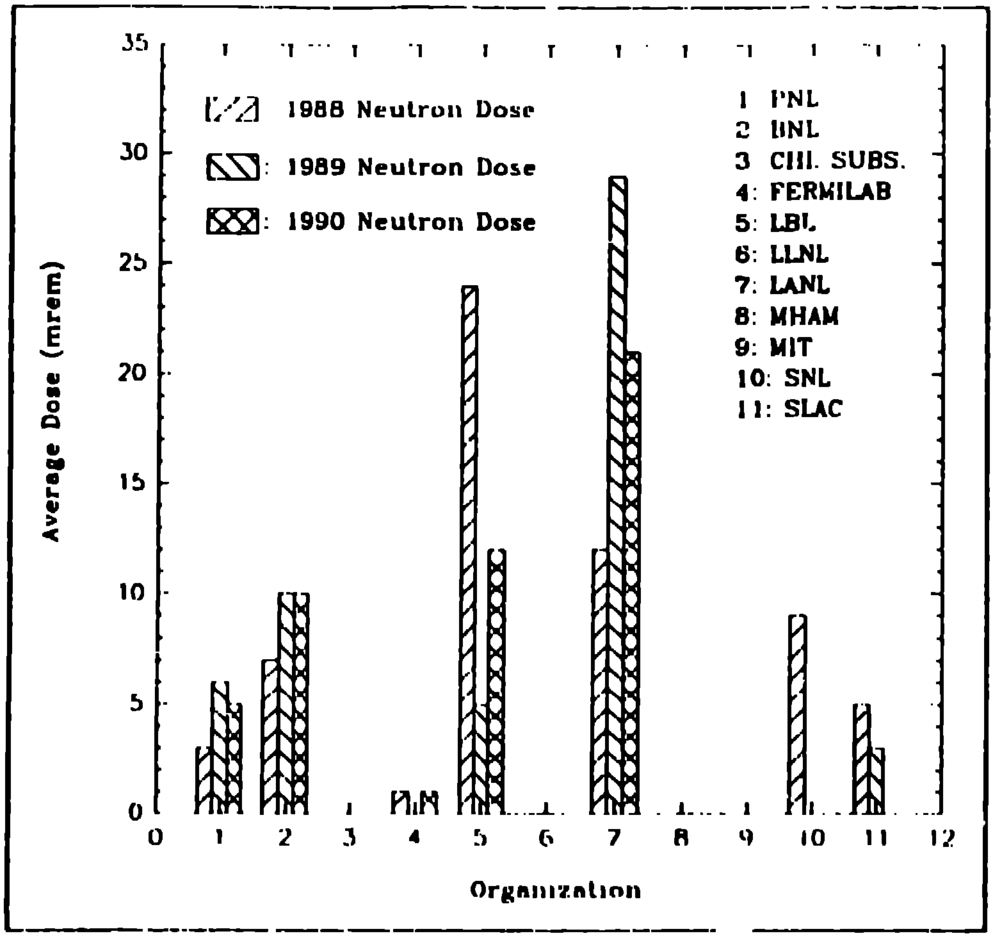


Figure 1. Average neutron doses at acclerator facilities, 1988-1990.

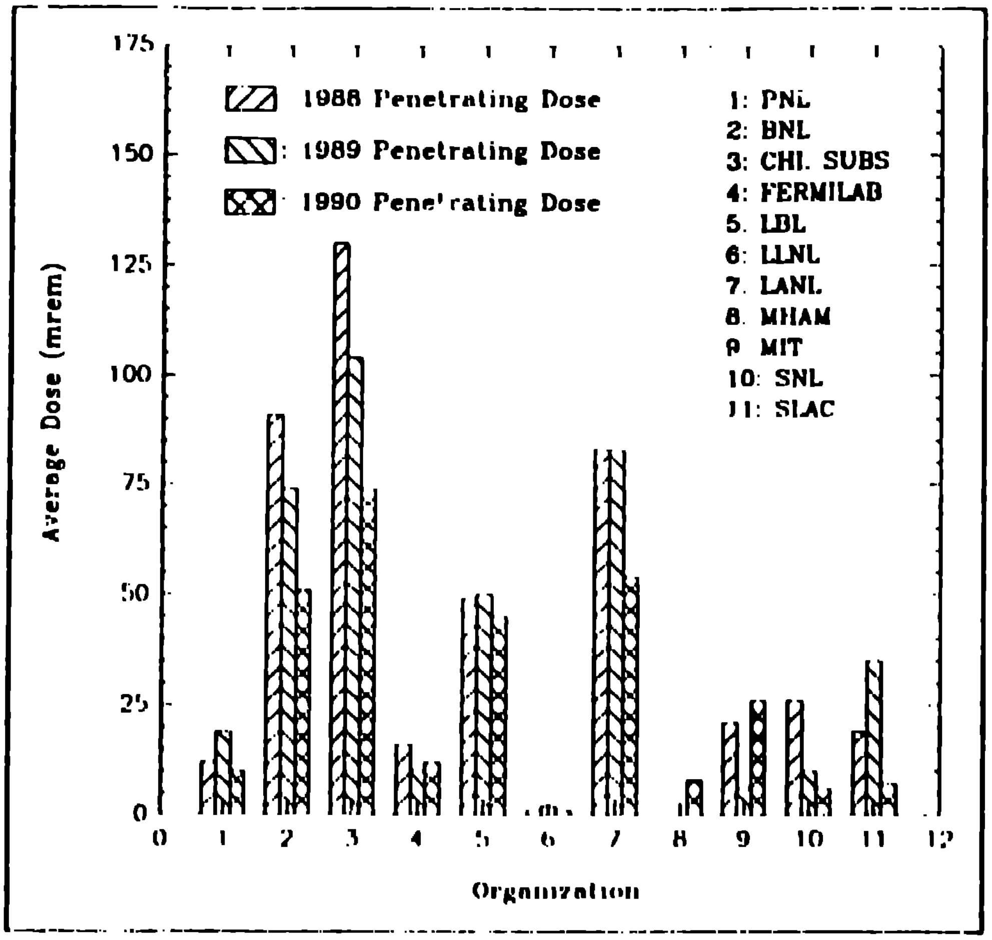


Figure 2. Average penetrating doses at accelerator facilities, 1988-1990.

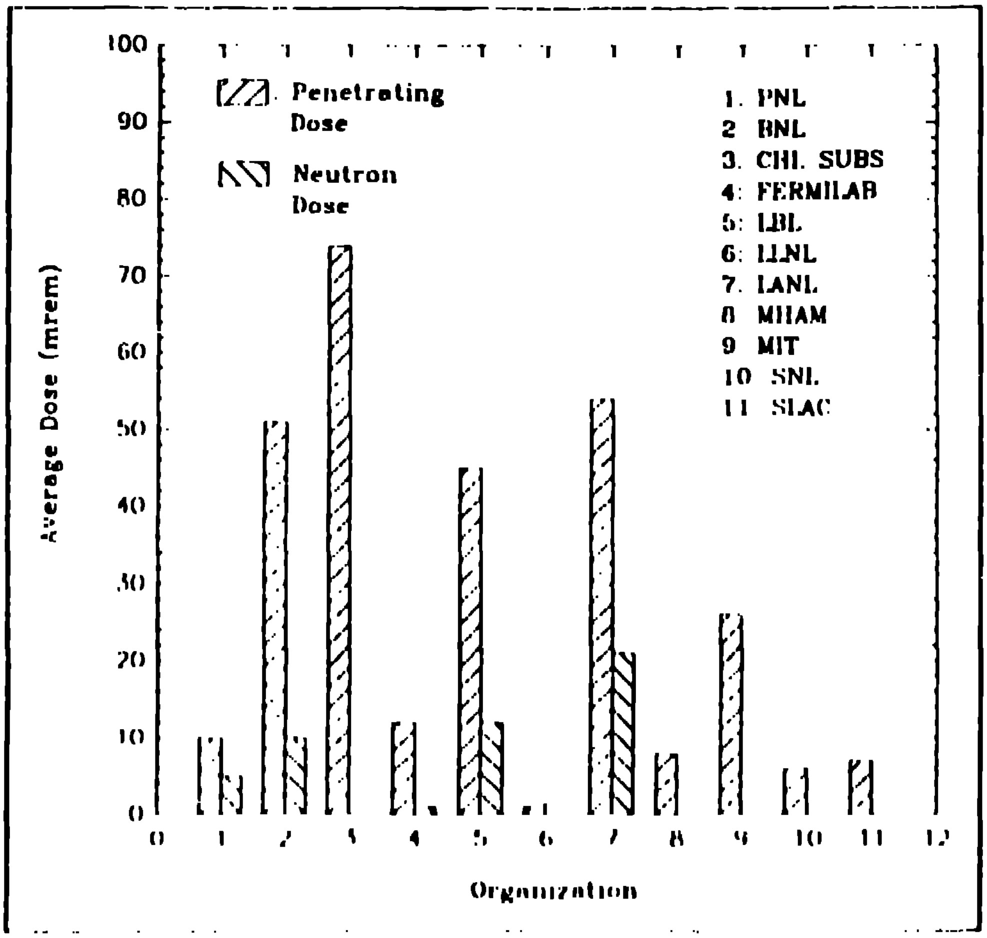


Figure 3. Average penetrating and neutron doses at accelerator facilities, 1990.

DOE POLICY AND ACCREDITATION OF HIGH ENERGY NEUTRON DOSIMETRY

ROBERT M. LOESCH
Dosimetry and Technology Assessment Branch
Office of Health
November 1992

DOE Policy
Monitoring and Accreditation

- 100 mrem threshold for monitoring
- DOELAP Accreditation
  - Applicable range: 1 keV - 2 MeV
  - Threshold met at energies $<$ 2 MeV

DOE Policy

Questions on Occupational Exposures

- Do workers receive occupational exposures to high energy (i.e. >2 MeV) neutrons?
- What percent of their annual exposure is attributable to high energy neutrons?
- If significant, is current dosimetry technology adequate?
  - No - need for additional research
  - Yes - need for routine intercomparisons

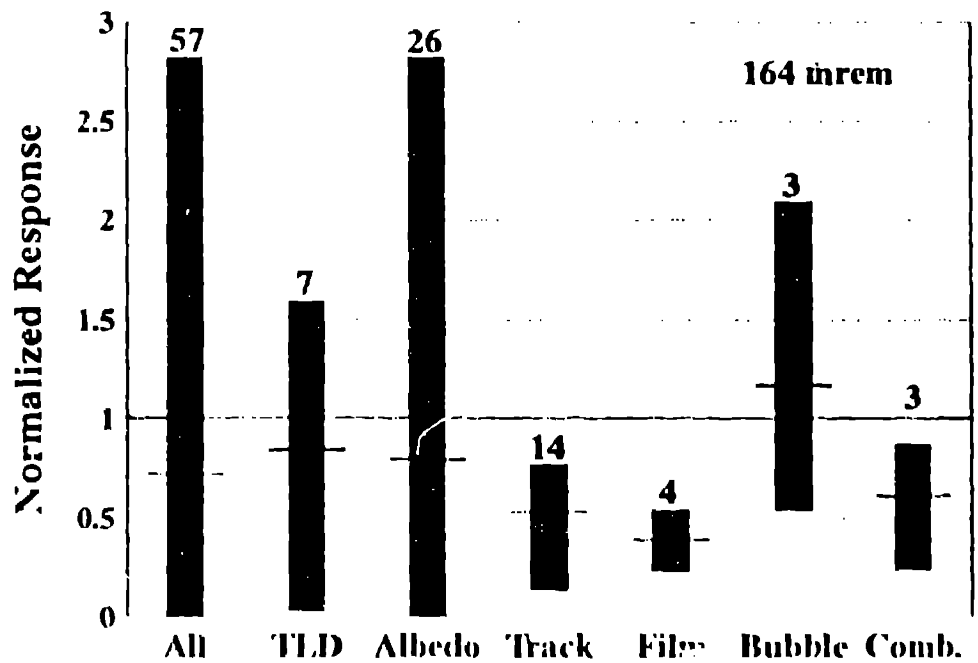
Accelerator Intercomparison Program

Purpose and Overview

- Purpose: To evaluate the performance of high energy neutron dosimetry at accelerator facilities
- Neutron dosimeters (> 2 Mev)
- Feasibility study report completed
- Initial feasibility test in progress
- Oak Ridge PDIS-16, Run 7

Accelerator Intercomparison Program

Results of PDIS-16 to 14 MeV Neutrons



Oak Ridge PDIS-16 Results

Overall Observations

- Participants informed exposure was to 14 MeV neutrons
- Overwhelming tendency towards serious underresponse
- Track and film believed to have superior response at higher energies
- Bubble detector average good but SD and individual poor
- Very few could pass DOELAP criteria at 14 MeV

HIGH ENERGY DOSIMETRY

Kenneth R. Alvar, Ph.D.

Health Physics Measurements Group, HS-4

LOS ALAMOS NATIONAL LABORATORY

DOE Accelerators (Energy >50MeV)

Accelerator	*Laboratory*	*Maximum Energy*
Intense Pulsed Neutron Source	ANL	450 MeV p
Bates	MIT	500 MeV e^-
AGS	BNL	24 GeV p
CEBAF	CEBAF	4 GeV e^-
Fermi Lab	Batavia	800 GeV p
LAMPF	LANL	800 MeV p
Bevalac	LBL	2 GeV p
88" Cyclotron	LBL	60 MeV p
Linac	LLNL	100 MeV e^-
ATA	LLNL	50 Mev e^-
ORELA	ORNL	170 MeV e^-
SLAC	Stanford	51 GeV e^-

Los Alamos

HIGH ENERGY DOSIMETRY

Definition: Dosimetry for dose caused by particles and photon radiation with energies above 20 MeV.

Assumption: We understand and can properly measure dose equivalent caused by particles and photons with energies below 20 MeV.

"If a tree falls in the forest and no one is there to hear it, does it make a noise?"

"If our dosimeters are <u>not</u> sensitive to dose caused by higher energy particles, do we get any dose from this flux?"

DOSIMETRY IN THE PAST

Mainly NTA for Neutron Dosimetry

DOSIMETRY IN THE PRESENT

Mainly NTA for Neutron Dosimetry

External Dosimeters in Used at DOE Accelerator Facilities*

	DOSIMETERS	
LAB	PHOTON	NEUTRON
ANL	TLD	NTA, CR-39
Bates	TLD	
BNL	Film (Kodak Type II)	NTA, Lexan
CEBAF	TLD	
FNAL	Film (Kodak Type II)	NTA,CR-39, Polycarbonate
LAMPF	TLD	NTA
LBL	Film (Kodak Type II)	NTA, CR-39
LLNL	TLD	CR-39
ORNL	TLD	
SLAC	TLD	
SNL	TLD	

* Coulson, et al., Report FN-510

What's the Problem?

1) The dose equivalents when measured are normally small because the flux is low. Neutrons are the major contributor to dose.

2) For example, measurements by Fermilab and TRIUMF indicate that there is a high percentage of dose equivalent caused by neutrons above 20 MeV transported through shielding.

3) Uncertainties in these measurements are large. From an ALARA point-of-view we need to do better.

4) If you don't measure it, is it there? Need to explicitly measure the neutron dose to prevent surprises.

Occupational exposure to high energy (>20 MeV) neutrons occurs at DOE Accelerators

Calibration at these higher energies needs to be improved

High Energy Neutron Exposure Can Occur By

- Routine, low level exposure
- Accident-related exposure, possibly high level
- Unshielded beam exposures
- Partially shielded beam exposures
- Mixture of shielded and unshielded exposures

Neutron Dose Rate at LAMPF D Line Parking Lot

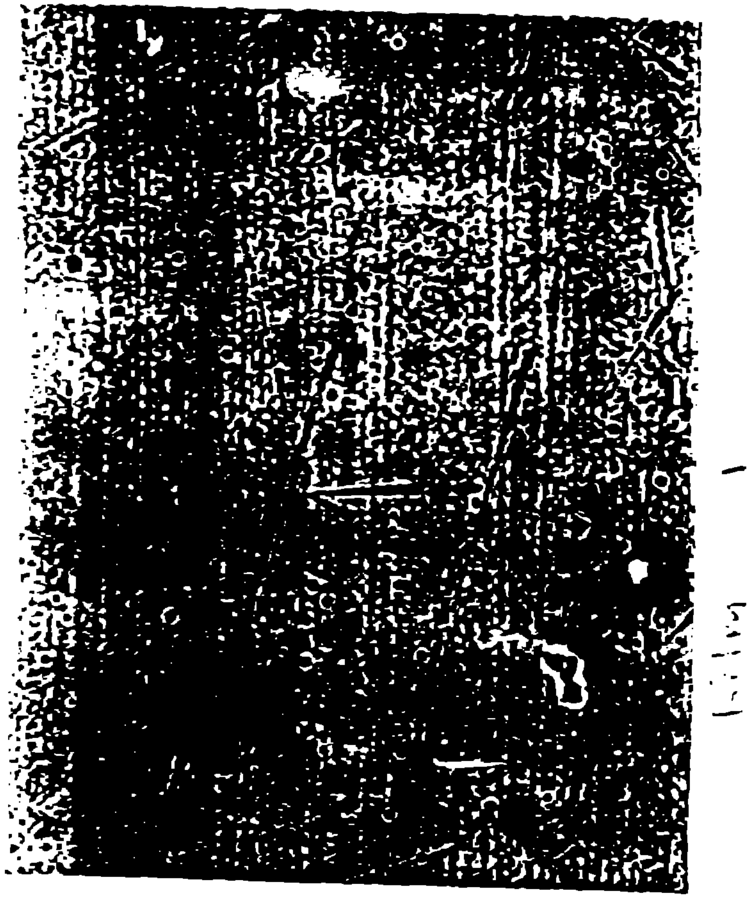
Operation	*Dose rate*
Normal use	< 1 mrem/hr
Beam tune up ≤ 20 nA beam loss	< 80 mrem/hr
Worst case accident 500 μA point spill	< 10 rem/hr at exclusion area fence for one hour

Neutron Dose Rate at LAMPF ER-1, 0.1μA Beam on Carbon Block

Shielding	*Dose rate mrem/hr*	*Relative Neutron Dose Equivalent E_n >25 MeV*
5.5 ft. magnitite concrete	620	67%
5.5 ft. magnetite concrete and 3 ft. iron	75	53%

NTA Film Indicates Presence of High Energy Neutron Dose Component

Film 1	Exposure to 600 MeV "white" neutron beam
Film 2	Routine film

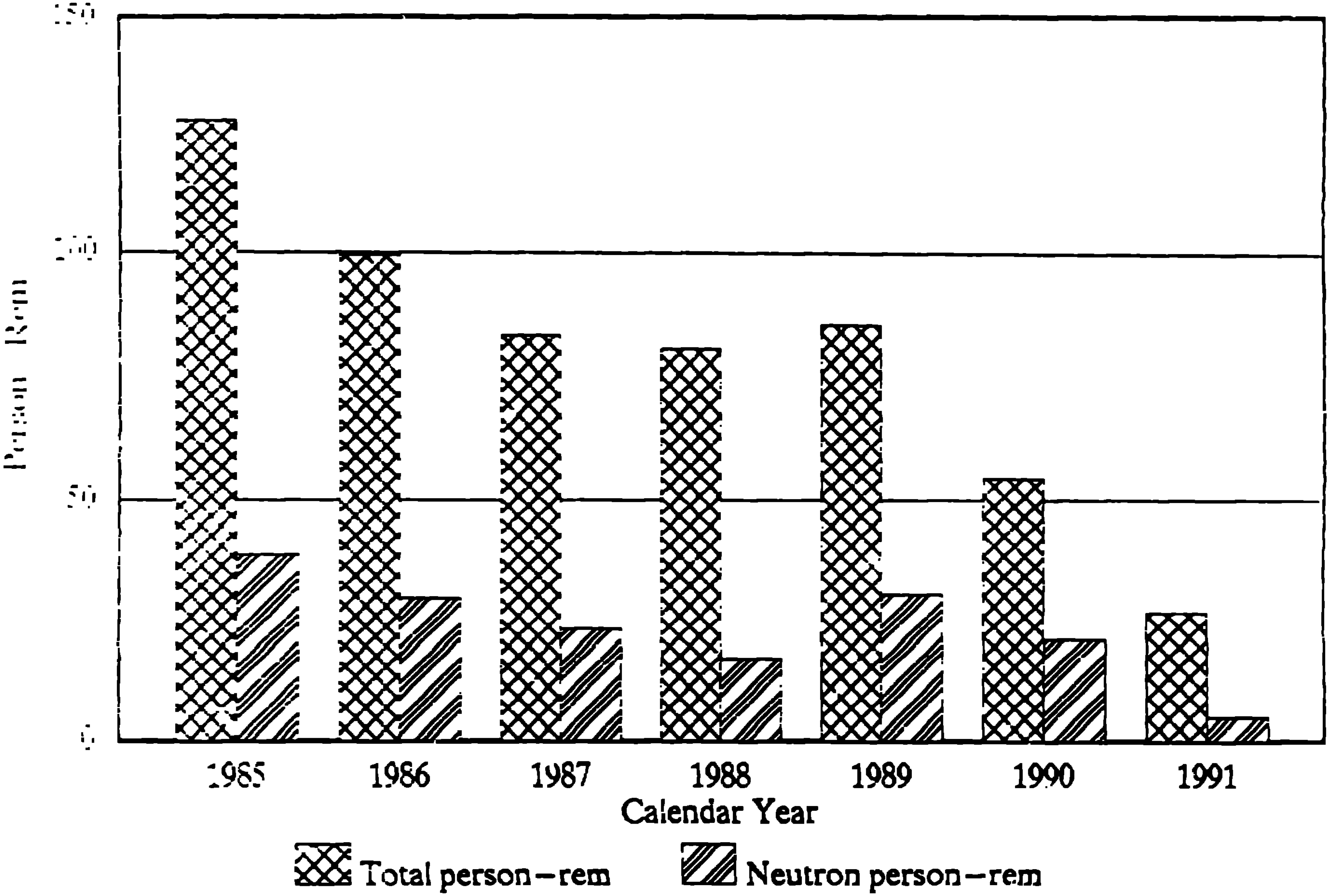


650 M.V 440x

440x

TA-53 EXPOSURE HISTORY

Total n + g, and n only.



Reports of High Energy Neutron Exposures at Fermi Lab

Location	*Relative Contribution to dose by neutrons E_n >25 MeV*
Debuncher ring at AP3C	93.6%
MC, catwalk above target pile	37%
Debuncher ring at AP10	14%
PC extension roof DS (1)	12%

A. J. Elwyn, Fermi Lab R. P. Note 93, Characteristics of Neutron Radiation Fields Outside of Shielding, October 1991

International Accelerator Facilities with High Energy Neutron Leakage Through Shielding

- Triumpf, Canada, 500 MeV p
  - Neutron leakage spectra through shielding
  - Some locations have 50% of the neutron flux with E_n >20 MeV
- KEK, Japan, 12 GeV p
  - Neutron leakage spectra through shielding
  - 50% of dose equivalent for E_n >50 MeV

Requirements for a High Energy Neutron Dosimetry Facility

- **Well-characterized high energy neutron beams - fluence, energy spectrum, dose, dose equivalent.**

- **Flexibility to approximate "real world" exposures - fluence rates, energy spectra.**

- **Polyenergetic and monoenergetic neutron beam capabilities.**

- **Calculational and experimental support.**

- **Availability to DOE and non-DOE users.**

What should be done next?

Need coordinated program

- LET measurements vs E_n Monoenergetic and white spectra
- Revise fluence-to-dose calculations with new cross-section data and updated nuclear reaction models
- Response vs E_n measurements for NTA, CR-39, and Bubble Dosimeters. Monoenergetic and white spectra
- Neutron spectroscopy measurements, especially for leakage spectra.
- High energy neutron dosimeter developments
- Further dosimetry inter-comparisons benchmark measurements
- Other items

Selected Bibliography

Reviews

Swanson, W.P. and Thomas, R.H. (1990) "Dosimetry for Radiological Protection at High-Energy Particle Accelerators." The Dosimetry of Ionizing Radiation, Volume 3, Kase, K.R.; Bjärngard, B.E.; and Attix, F.H., editors, pp. 1-162

Patterson, H.W. and Thomas, R.H. (1973) Accelerator Health Physics Academic Press, Inc., New York

Coulson, L.V.; Elwyn, A.J.; and Freeman, W.S. (1989) "Accelerator Health Physics at DOE Laboratories: A Characterization "Fermi" National Accelerator Laboratory Report FN-510

Neutron Spectra Measurements

Cossairt, J.D.; Elwyn, A.J.; Freeman, W.S.; Salsbury, W.C.; and Yurista, P.M. (1988) "Measurements of Neutrons in Enclosures and Outside of Shielding at the TEVATRON" Proceedings of the 22nd Mid-year Topical Meeting of the Health Physics Society, San Antonio, Texas, December 4-8, 1988

Moritz, L.E., (1989) "Measurement of Neutron Leakage Spectra at a 500 MeV Proton Accelerator" Health Physics 56, 287-296

Moritz, L.E.; Suzuki, T.; Noguichi, M.; Oki, Y.; Miura, S.; Tawara, H.; Ban, S.; Hirayoma, H.; and Kondo K. (1990) "Characteristics of the Neutron Field in the KEK Counter Hall" Health Physics 58, 487-492

Mundis, R.L. and Howe, M.L.; (1987) "Neutron Spectrum Measurements in ER-1, July 22, 1987" Los Alamos National Laboratory Memo. HSE-11-87-153 (September 4, 1987)

Muon Dosimetry

Höfert, M. (1987) "Dosemeter Response to Muons." Radiation Protection Dosimetry 20, 149-154

NTA and CR-39

Greenhouse, N.A.; deCastro, T.M.; McCaslin, J.B.; Smith, F.A.; Sun, R.K.; and Hankins, D.E. "An Evaluation of NTA Film in an Accelerator Environment and Comparisons with CR-39" Radiation Protection Dosimetry 20, 143-147

Bubble Dosimeters

Ing, H. and Birnboim, H.C. (1984) "A Bubble-Damage Polymer Detector for Neutrons" Nuclear Tracks and Radiation Measurements, Vol. 8, pp. 285-288

Roy, S.C.; Apfel, R.E.; and Lo, Y-C (1987) "Superheated Drop Detector: A Potential Tool in Neutron Research" Nuclear Instruments and Methods A255, pp. 199-206

Schwartz, R.B.; and Hunt, J.B.; (1990) "Measurement of the Energy Response of Super Heated Drop Neutron Detectors: Radiation Protection Dosimetry 34, pp. 377-380

Ipe, N.E.; Donahue, R.J.; and Busick, D.D.; (1990). "The Active Personnel Dosimeter - Apfel Enterprises Super Heated Drop Detector. "Radiation Protection Dosimetry 34, pp. 157-160

NTA Film

Mallett, M.W.; Vasilik, D.G.; Littlejohn, G.J.; and Cortez, J.R. (1990) "High Energy Neutron Dosimetry at the Clinton P. Anderson Meson Physics Facility, Los Alamos National Laboratory Report LA-11740-MS

CR-39

Griffith, R.V. and Tommasino, L. (1990) "Etch Track Detectors in Radiation Dosimetry" The Dosimetry of Ionizing Radiation, Volume 3, kase, K. R.; Bjärngard, B. E.; and Attix, F. H. editors, pp. 323-426

Neutron Beam Capabilities at WNR

Presented by Avigdor Gavron,
P-17, Neutron and Nuclear Science Group

Los Alamos National Laboratory

<u>The Neutron and Nuclear Science Group-</u>

- Operates WNR*
- Calibrates its energy and fluence
- Performs experiments in Neutron and Nuclear Science - Basic, Applied, Weapons.
- Uses results for
  1. Nuclear Data Requirements
  2. Simulation input
- Develops advanced, special requirement simulation calculations.

Use **us** for the solution!

WNR is only facility *in the world* which has standard, reproducible and well characterized high energy neutron beams.

* Weapons Neutron Research facility.

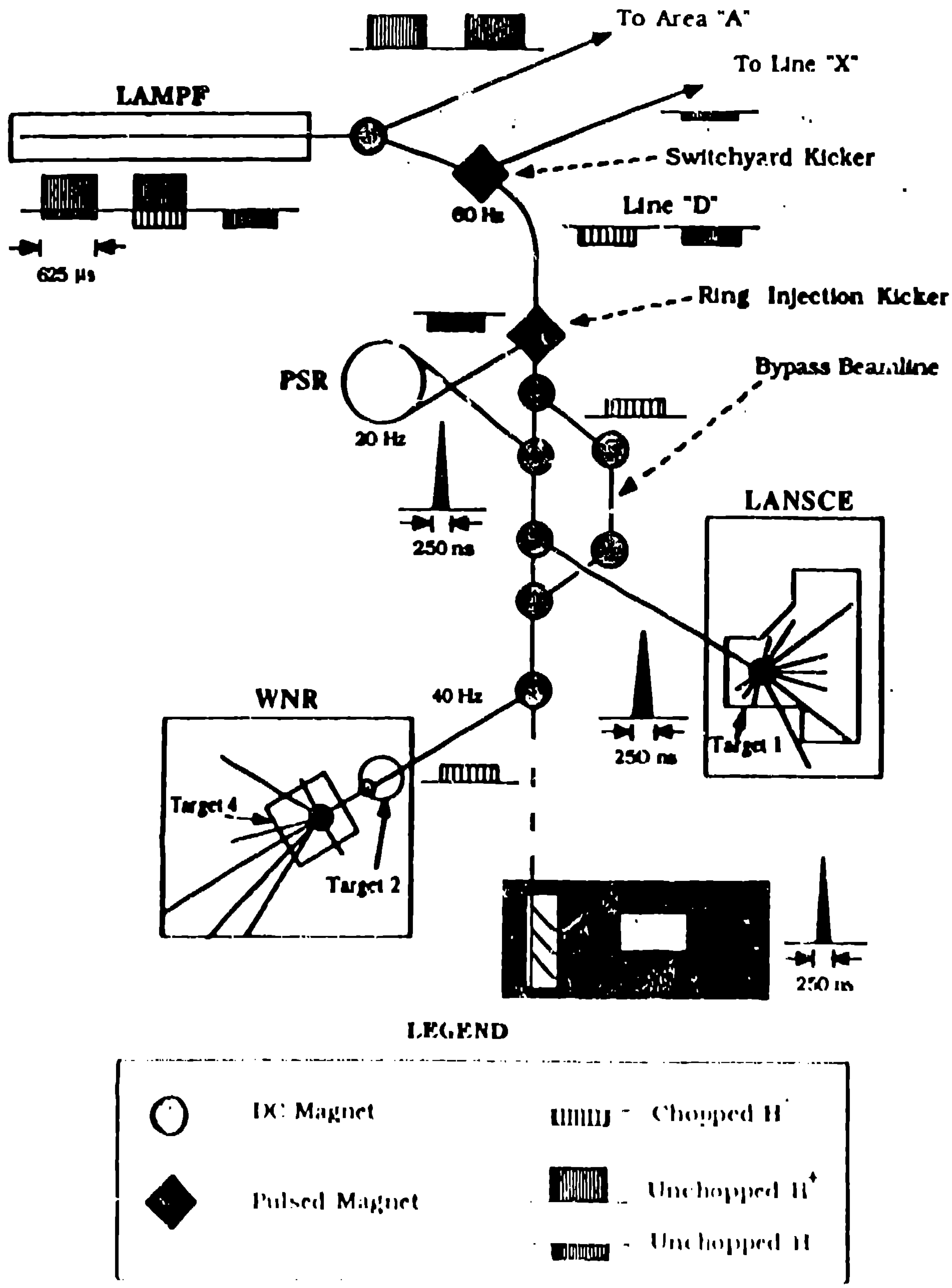
The WNR facility:

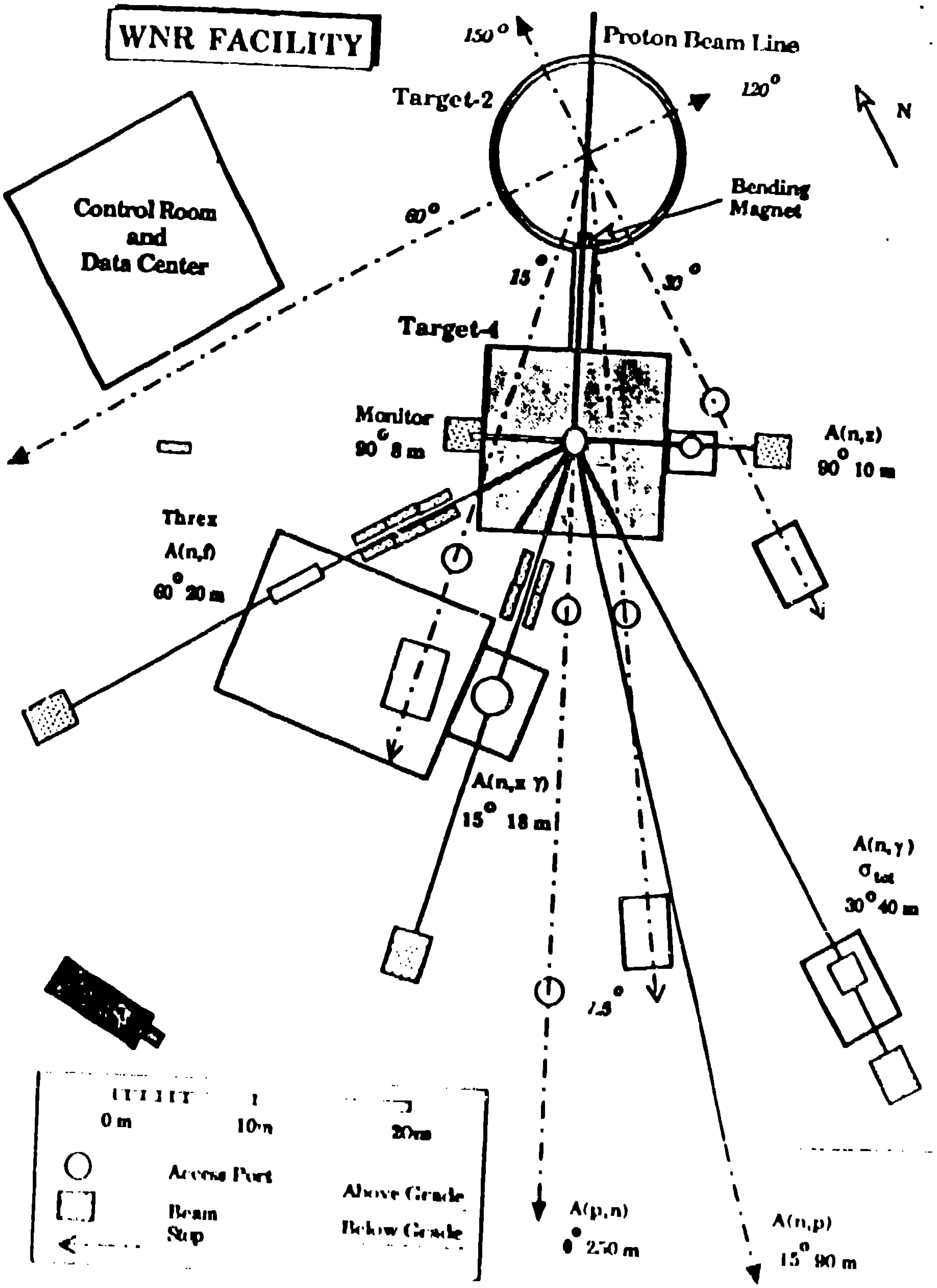
- Well shielded
- Well collimated
- Spectrum and fluence meticulously determined

Achieved by:

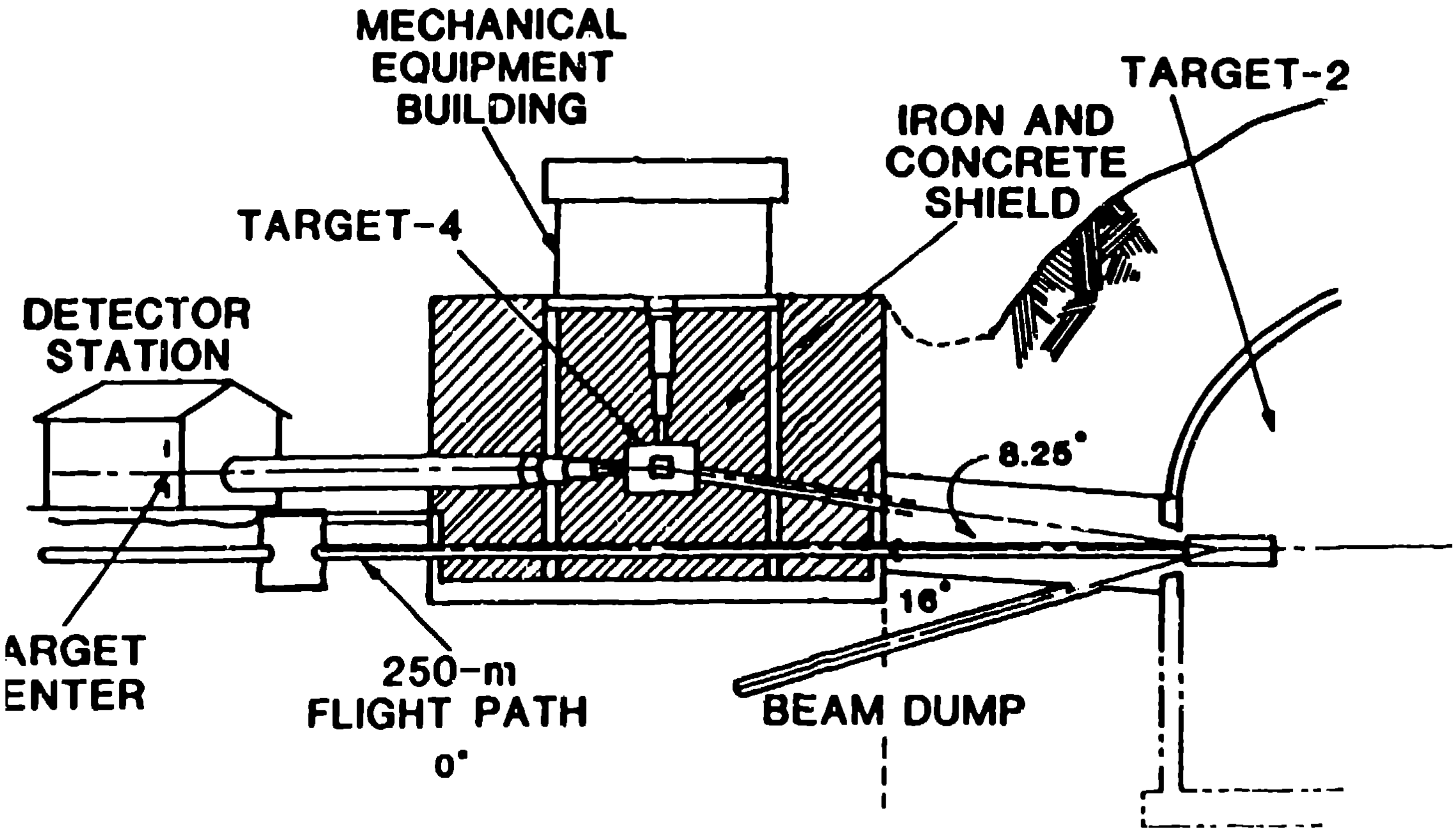
1. Thick concrete/magnetite building to house source ("crypt")
2. Ten ton shutter - Fe, some W and Cu to stop neutron beam and serve as collimator.
3. Magnets to sweep away charged particles.
4. High intensity enables use of long flight paths which leads to accurate energy and fluence determination
5. Detector/irradiation stations.

LAMPF LANSCE AND WNR BEAM TRANSPORT

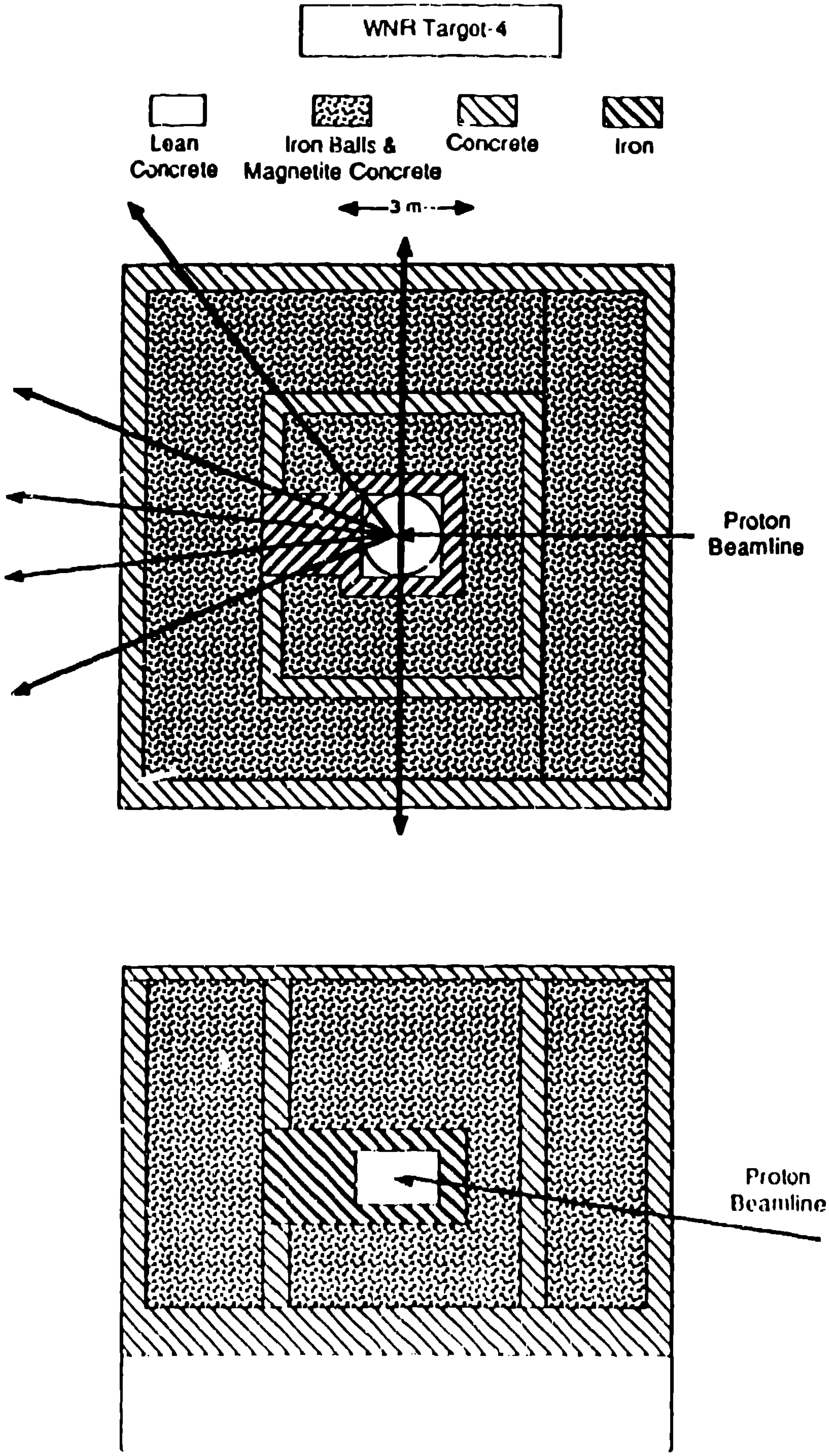


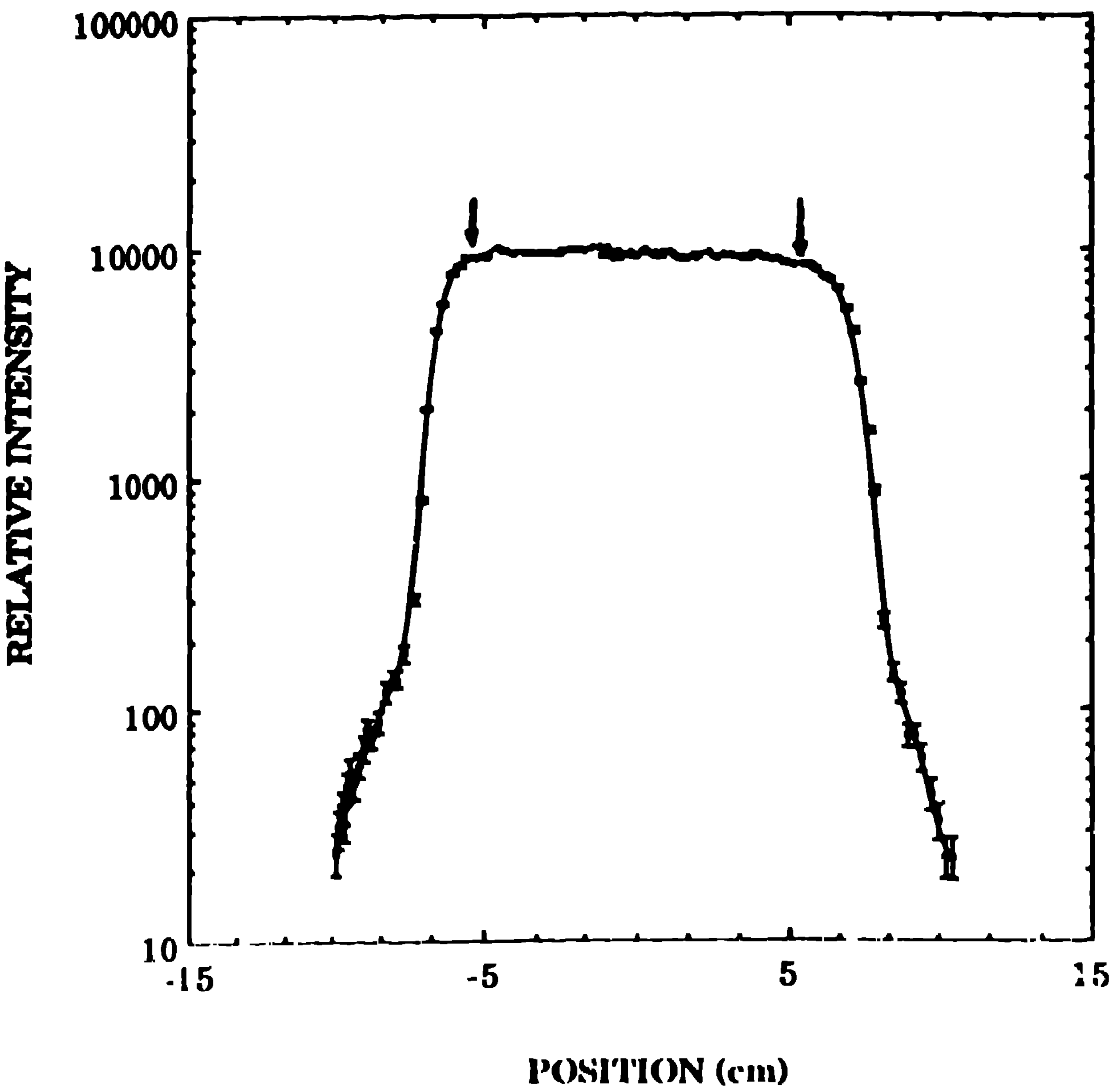


WNR FACILITY
Proton Beam Line
150°
120°
Target-2
N
Control Room
and
Data Center
60°
Bending
Magnet
15°
30°
Target-4
Monitor
90° 8 m
A(n,z)
90° 10 m
Threx
A(n,f)
60° 20 m
A(n,x γ)
15° 18 m
A(n,γ)
σ_{tot}
30° 40 m
15°
0 m
10 m
20 m
Access Port
Beam
Stop
Above Grade
Below Grade
A(p,n)
0° 250 m
A(n,p)
15° 90 m



MECHANICAL
EQUIPMENT
BUILDING
TARGET-2
IRON AND
CONCRETE
SHIELD
TARGET-4
DETECTOR
STATION
8.25°
16°
ARGET
ENTER
250-m
FLIGHT PATH
0°
BEAM DUMP


WNR Target-4
Lean Concrete
Iron Balls & Magnetite Concrete
Concrete
Iron
3 m
Proton Beamline
Proton Beamline



Neutron beam profile at the 22-m fission chamber location.
Fission foils are 10.2-cm diam.,frames are 15.24-cm diam.,

WNR Beams:

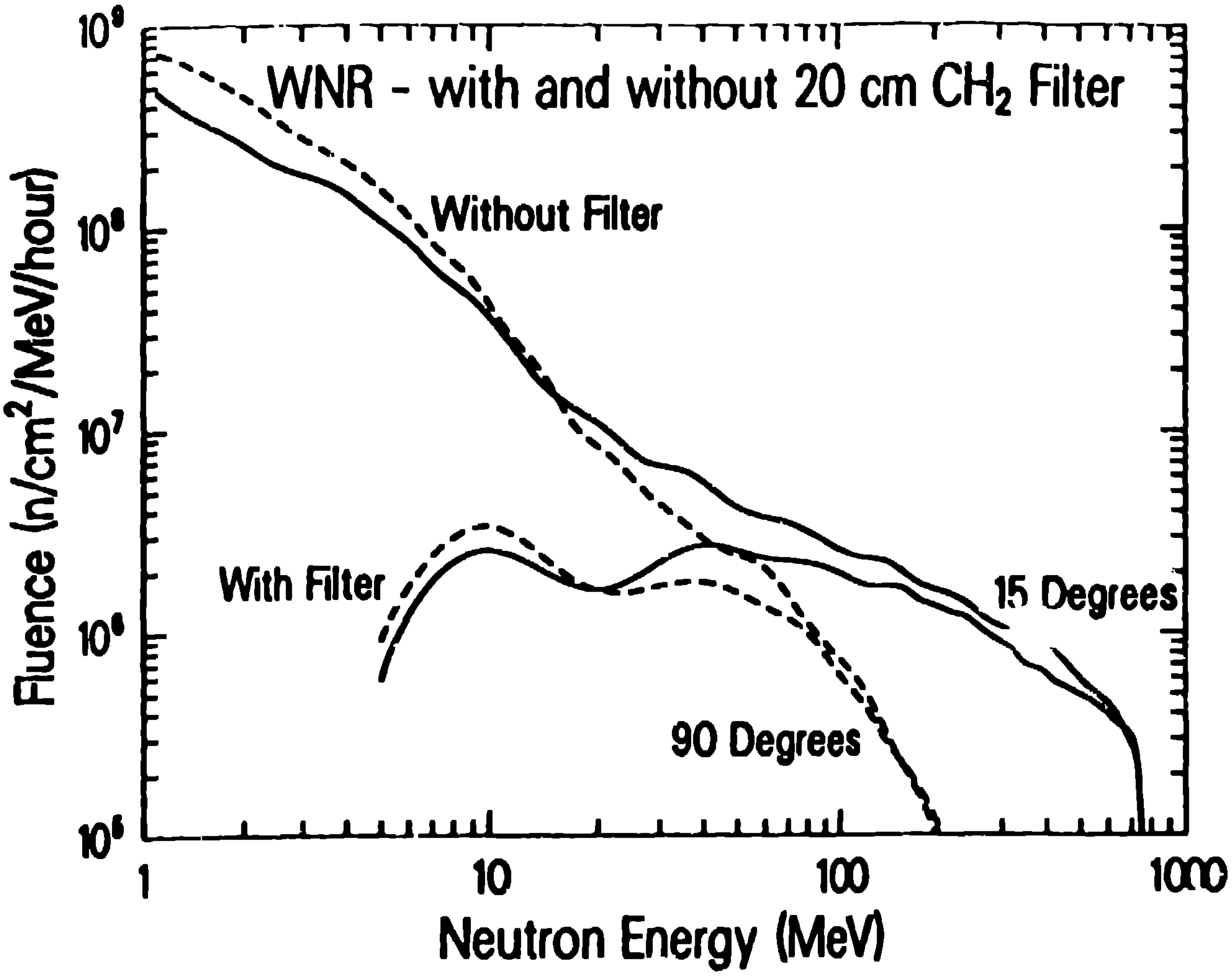
1. "White" Beams: Energies between 0.1 and ~800 MeV.

   a. Variation of maximum energy with angle.

   b. Lower energies can be cut with CH_2 filter.

   c. Time-of-Flight used in *real time* applications to determine response as a function of energy.

These white spectra are characteristic of what may be expected from an accidental spill at a high energy accelerator, through some shielding.



Dose-equivalent at 20 meters, 1 hour irradiation, "regular" beam conditions.

Angle	With CH_2 filter	Without CH_2 filter
15 Deg	20 rem	87 rem
90 Deg	5 rem	95 rem

Options to increase dose rate:

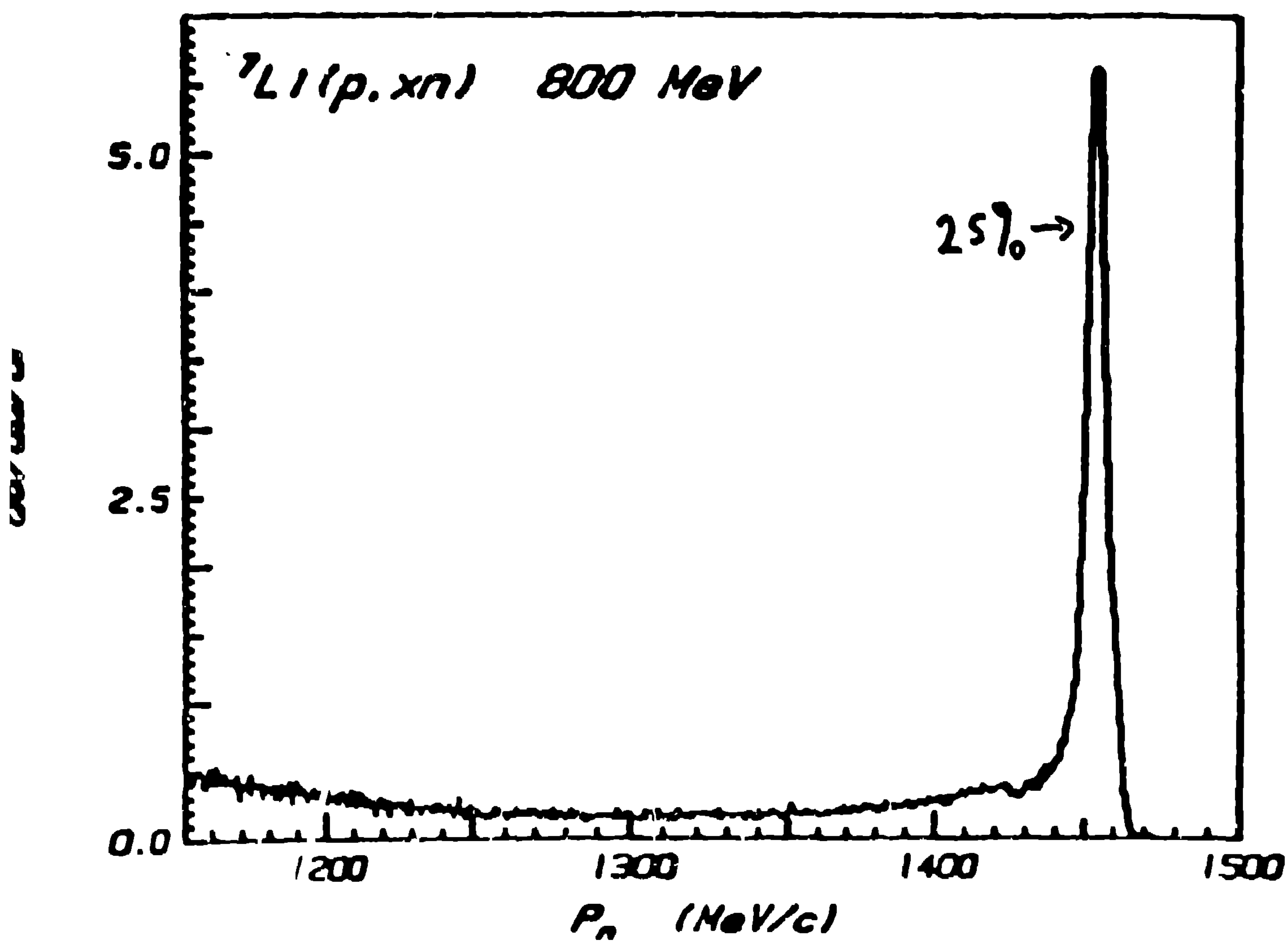
1. Increase proton beam intensity.
2. Move irradiation position to smaller distance from target.

2. Quasi-monoenergetic beams, using the $^7Li(p,n)$ reaction. This utilizes the "Target 2" facility in which

1) different targets can be exposed to the proton beam.

2) proton energies can be varied between 100 and 800 MeV,

providing additional flexibility.



7Li(p.xn) 800 MeV
25% →
5.0
2.5
0.0
1200
1300
1400
1500
Pn (MeV/c)

WNR Summary

Neutron beams are available with energies up to 800 MeV. These can be "white", tailored to specific energy limits by changing angle and filter. They can be quasi-monoenergetic by changing beam energy to "target 2".

They are well characterized*!

*Presently, below 200 MeV.

WNR facilities and Neutron and Nuclear Science group expertise are available for -

1. Characterization of neutron beams: WNR beams are well characterized below 200 MeV. Additional experimental program involving fission cross section measurements necessary to characterize beams up to 800 MeV.
2. Exposure of dosimeters and radiation protection detectors to these beams.
3. Advanced program to address issues of improved determination of quality factors at high neutron energies.

Accelerator Personnel Dosimeter Intercomparison

Joe McDonald

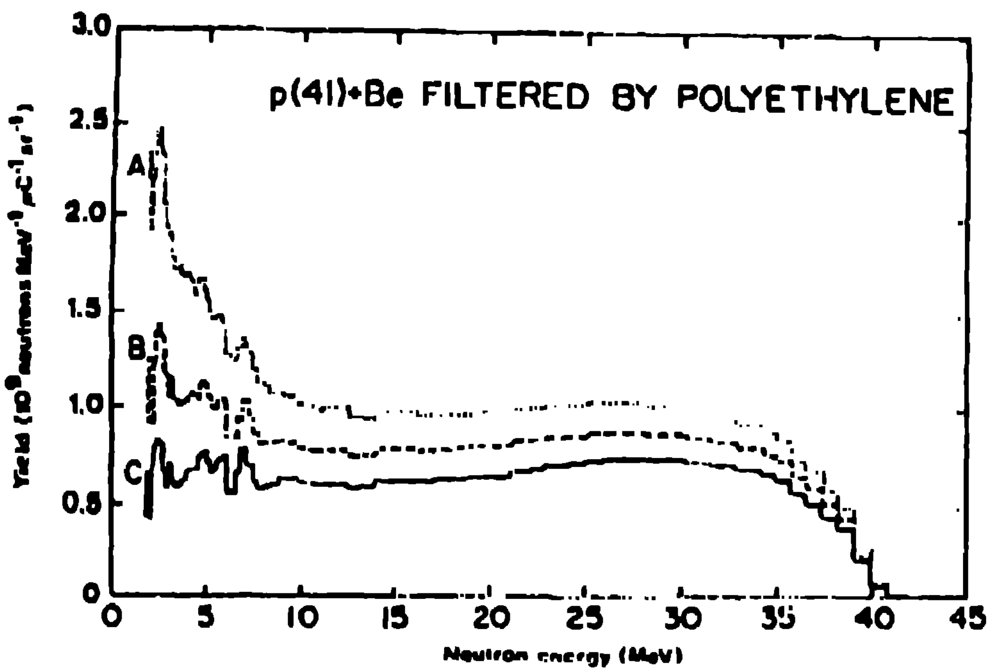
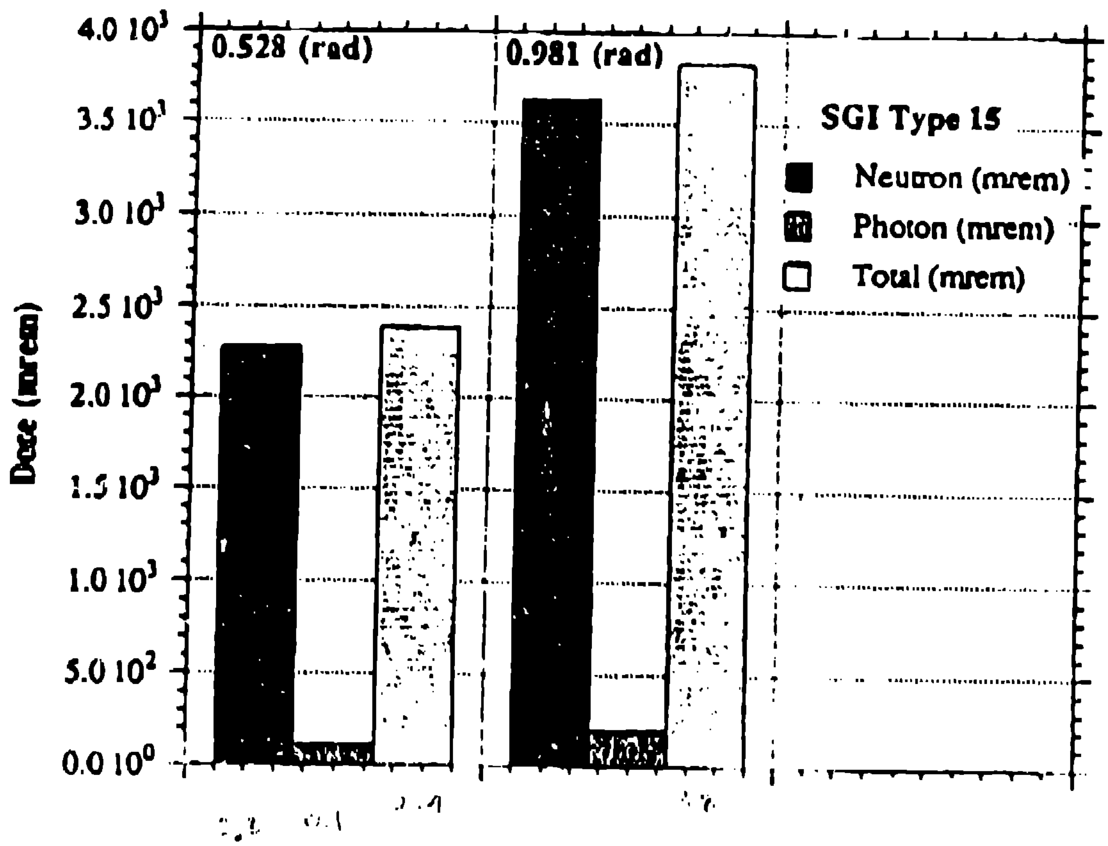
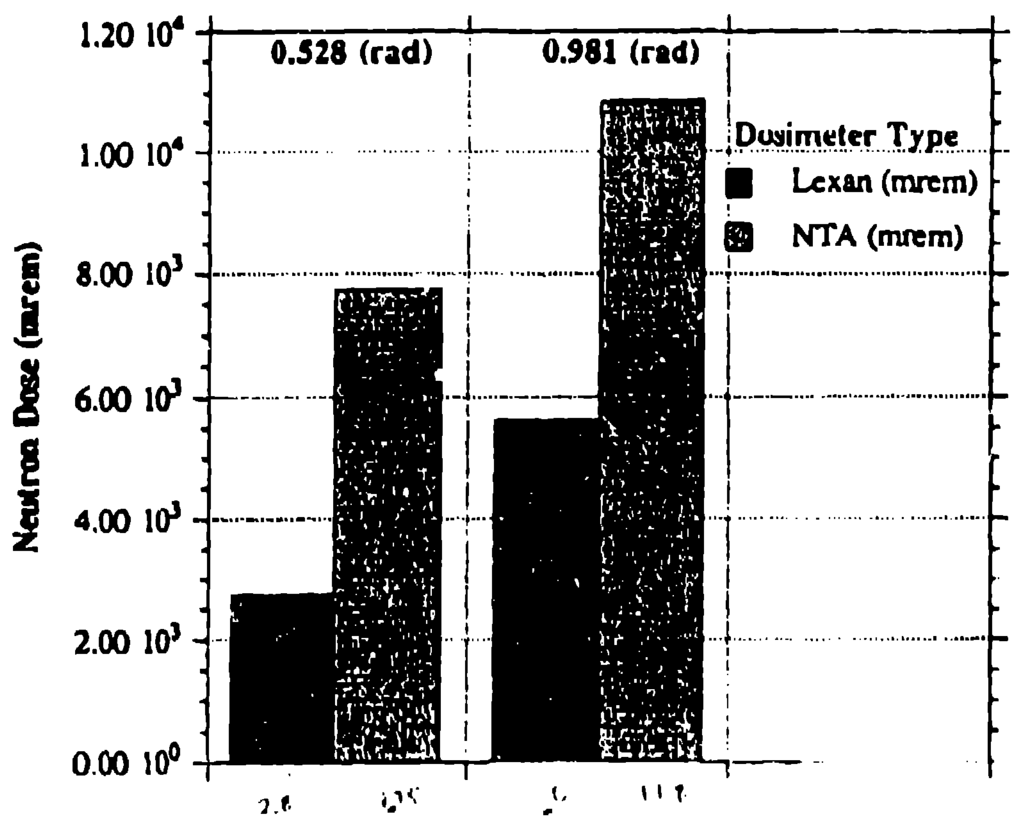


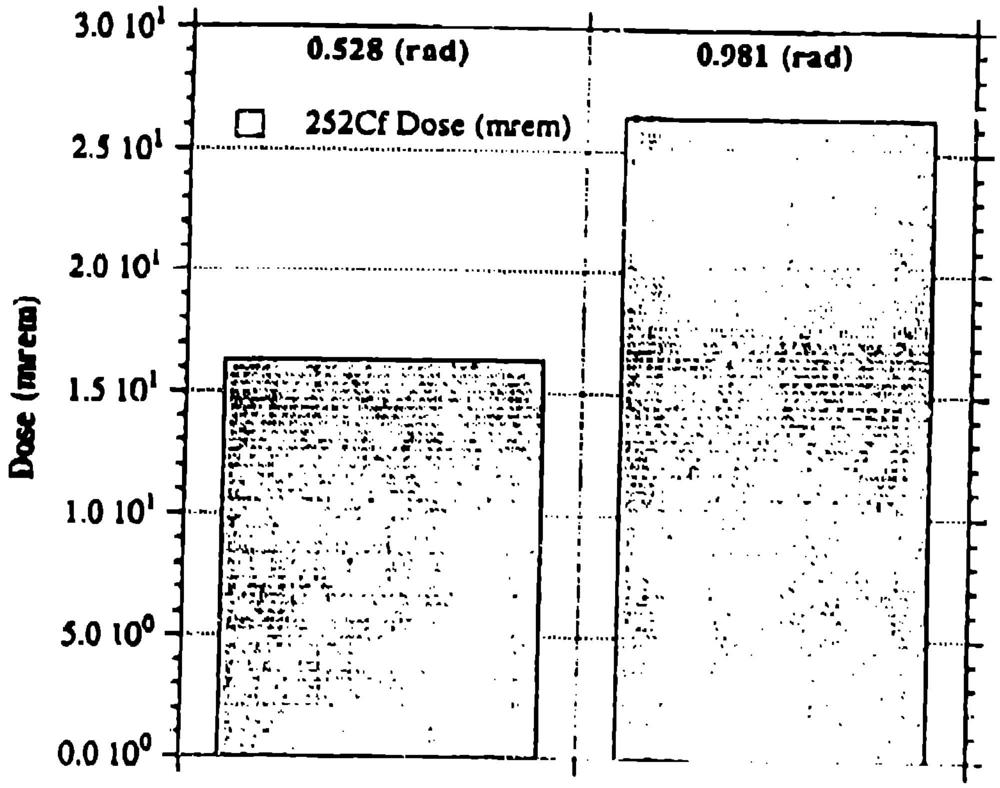
Figure 1. Neutron Energy Spectra for 41 MeV protons on Beryllium Filtered by Polyethylene of Thicknesses, 2 cm (Curve A), 4 cm (Curve B) and 6 cm (Curve C).



0.528 (rad)
0.981 (rad)
SGI Type 15
Neutron (mrem)
Photon (mrem)
Total (mrem)
Dose (mrem)
4.0 10³
3.5 10³
3.0 10³
2.5 10³
2.0 10³
1.5 10³
1.0 10³
5.0 10²
0.0 10⁰



0.528 (rad)
0.981 (rad)
Dosimeter Type
Lexan (mrem)
NTA (mrem)
Neutron Dose (mrem)
1.20 10⁴
1.00 10⁴
8.00 10³
6.00 10³
4.00 10³
2.00 10³
0.00 10⁰



3.0 10¹
2.5 10¹
2.0 10¹
1.5 10¹
1.0 10¹
5.0 10⁰
0.0 10⁰
Dose (mrem)
0.528 (rad)
0.981 (rad)
252Cf Dose (mrem)

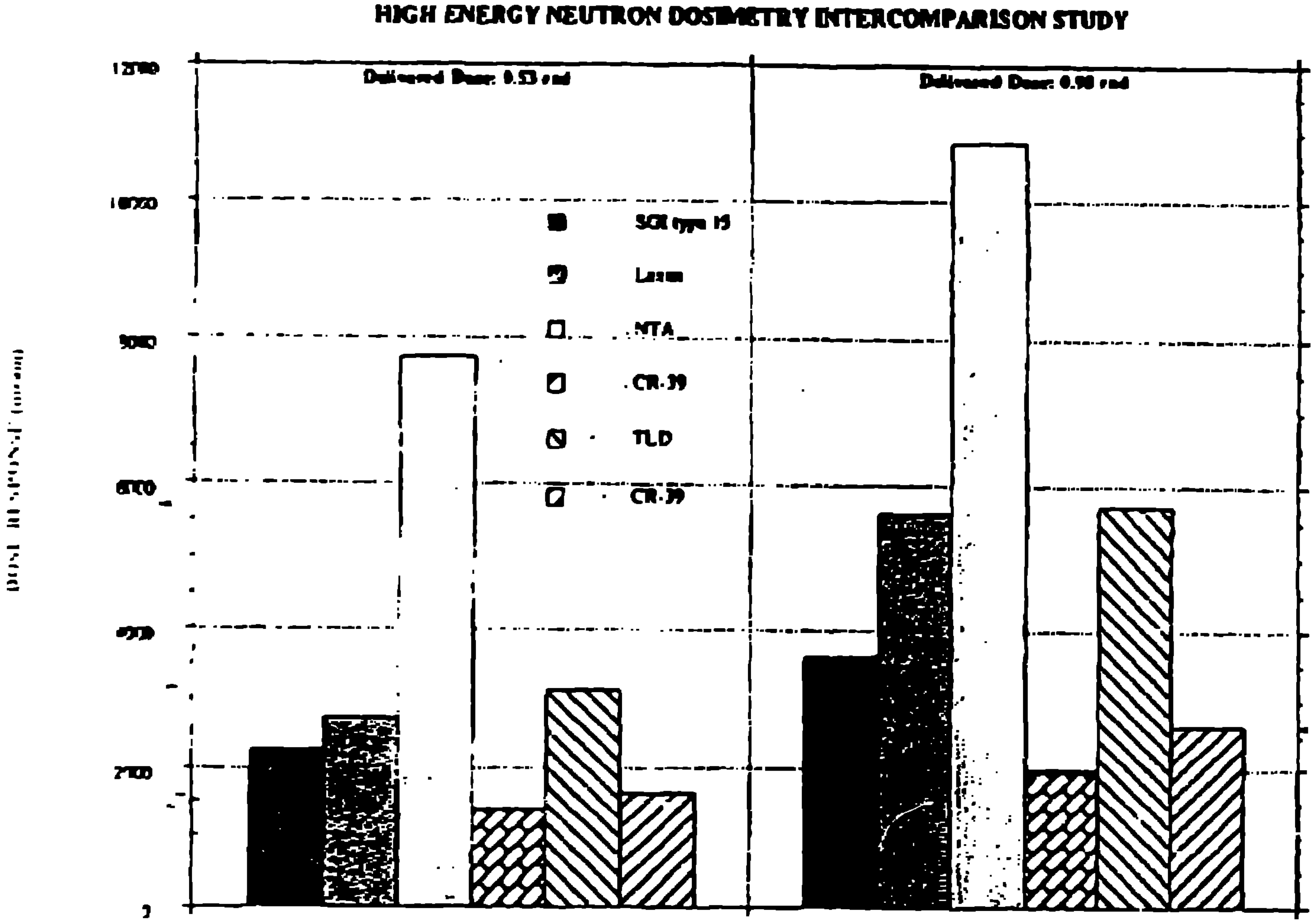
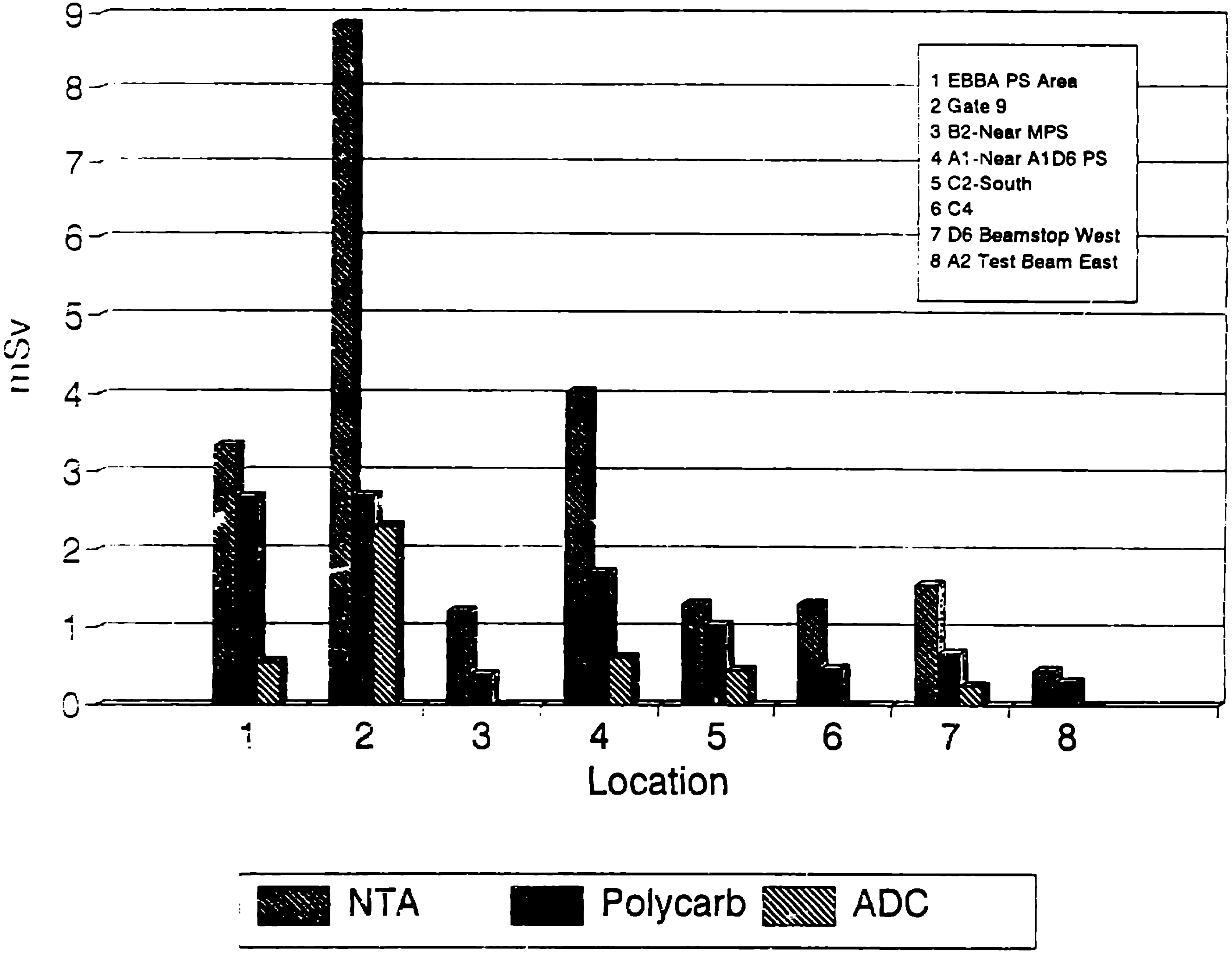
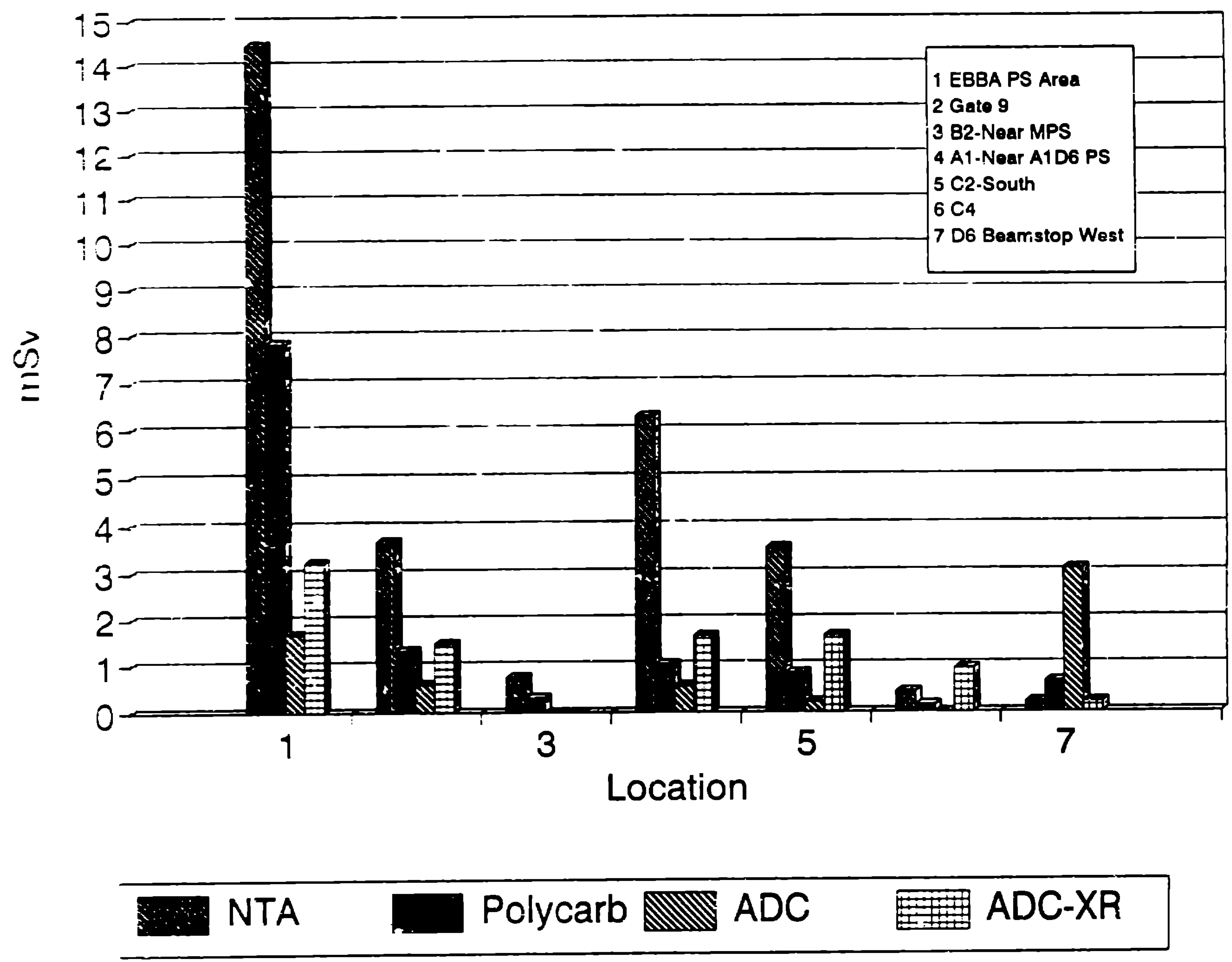


Figure 6. Intercomparison of results for 0.528 and 0.981 rad.

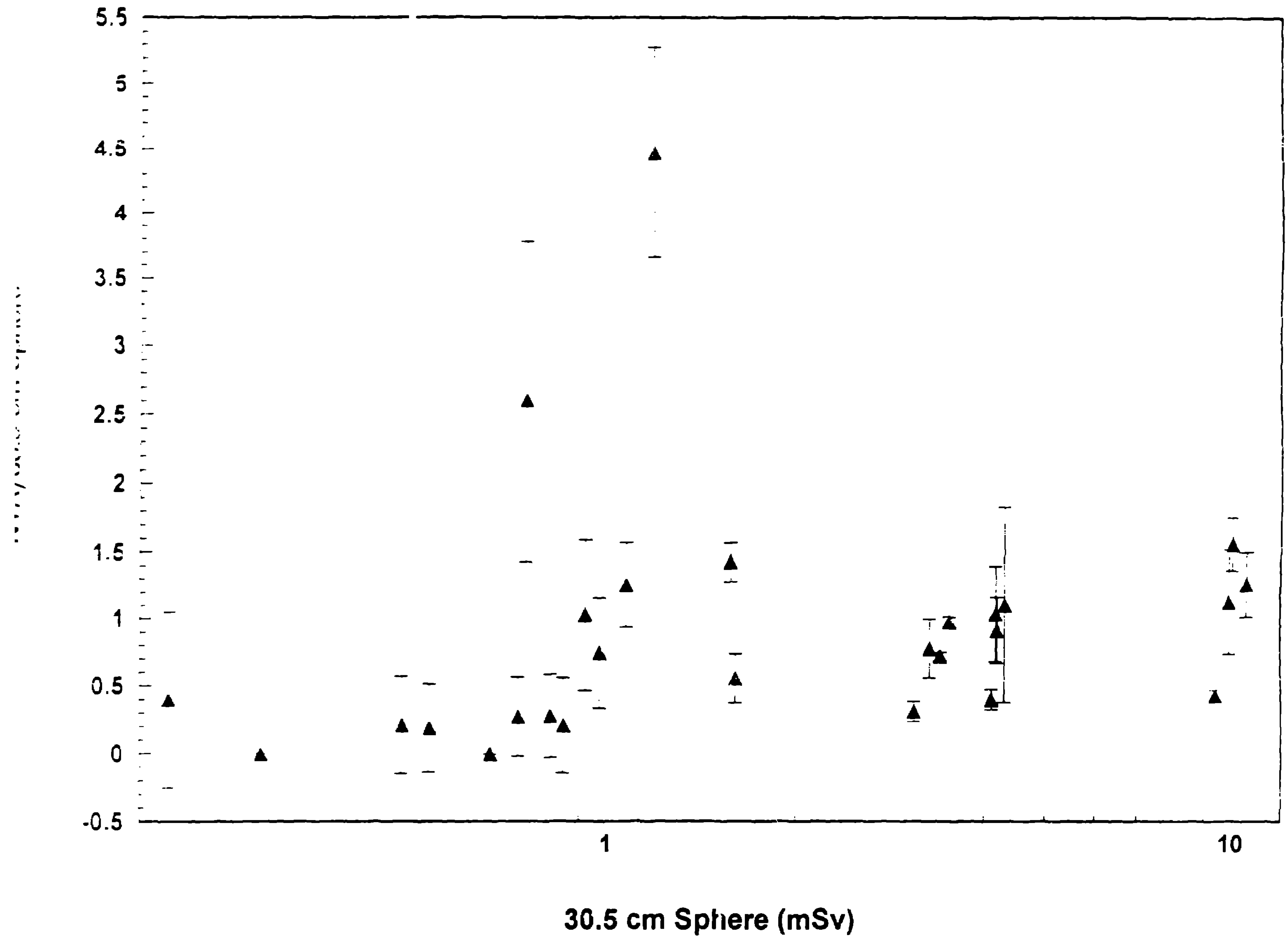
Intercomparison of Neutron Dosimetry at the AGS

Stephen Musolino

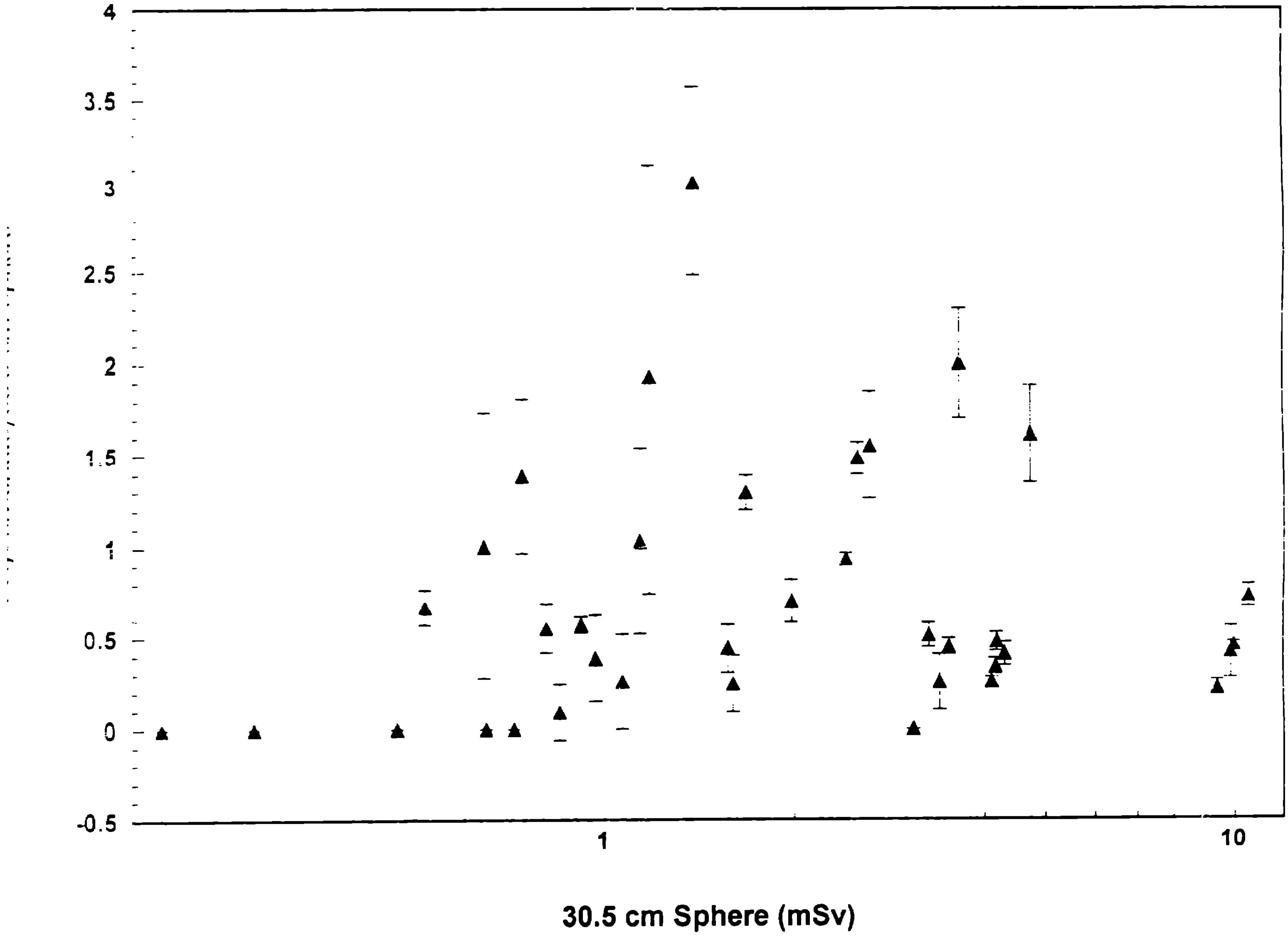

9
8
7
6
5
4
3
2
1
0
mSv
1 EBBA PS Area
2 Gate 9
3 B2-Near MPS
4 A1-Near A1D6 PS
5 C2-South
6 C4
7 D6 Beamstop West
8 A2 Test Beam East
1
2
3
4
5
6
7
8
Location
NTA
Polycarb
ADC



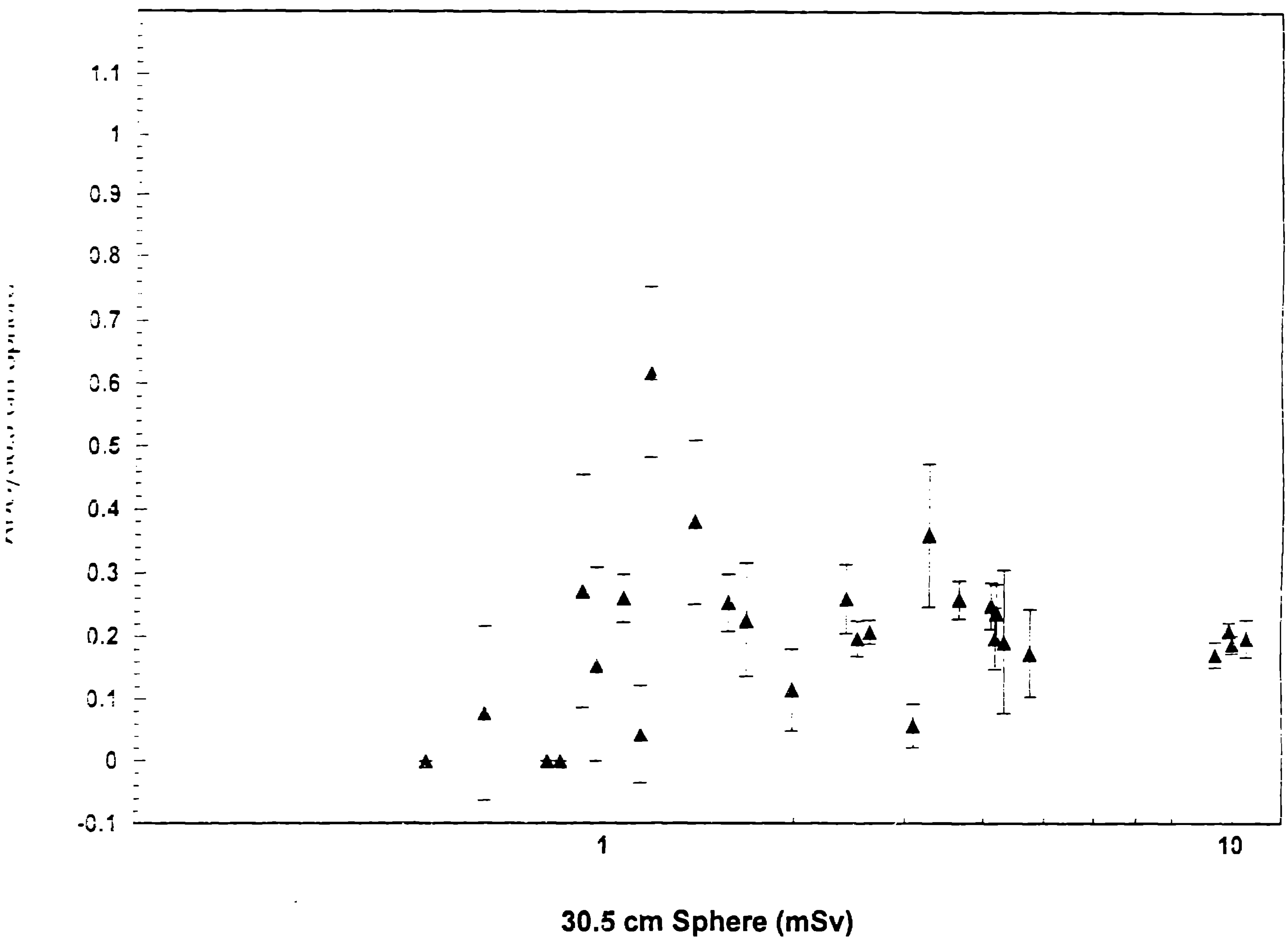
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
mSv
1 EBBA PS Area
2 Gate 9
3 B2-Near MPS
4 A1-Near A1D6 PS
5 C2-South
6 C4
7 D6 Beamstop West
1
3
5
7
Location
NTA
Polycarb
ADC
ADC-XR



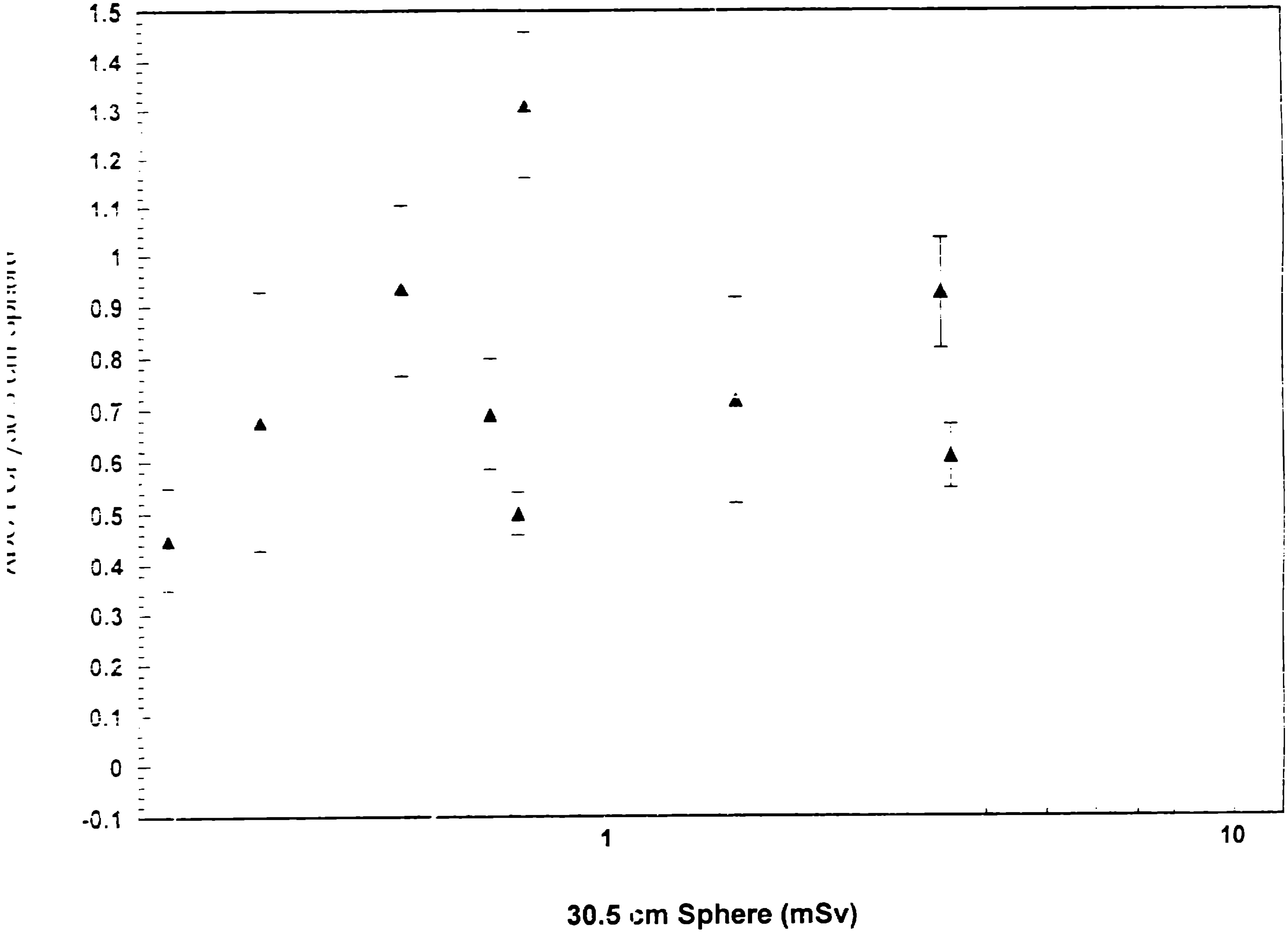
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
1
10
30.5 cm Sphere (mSv)

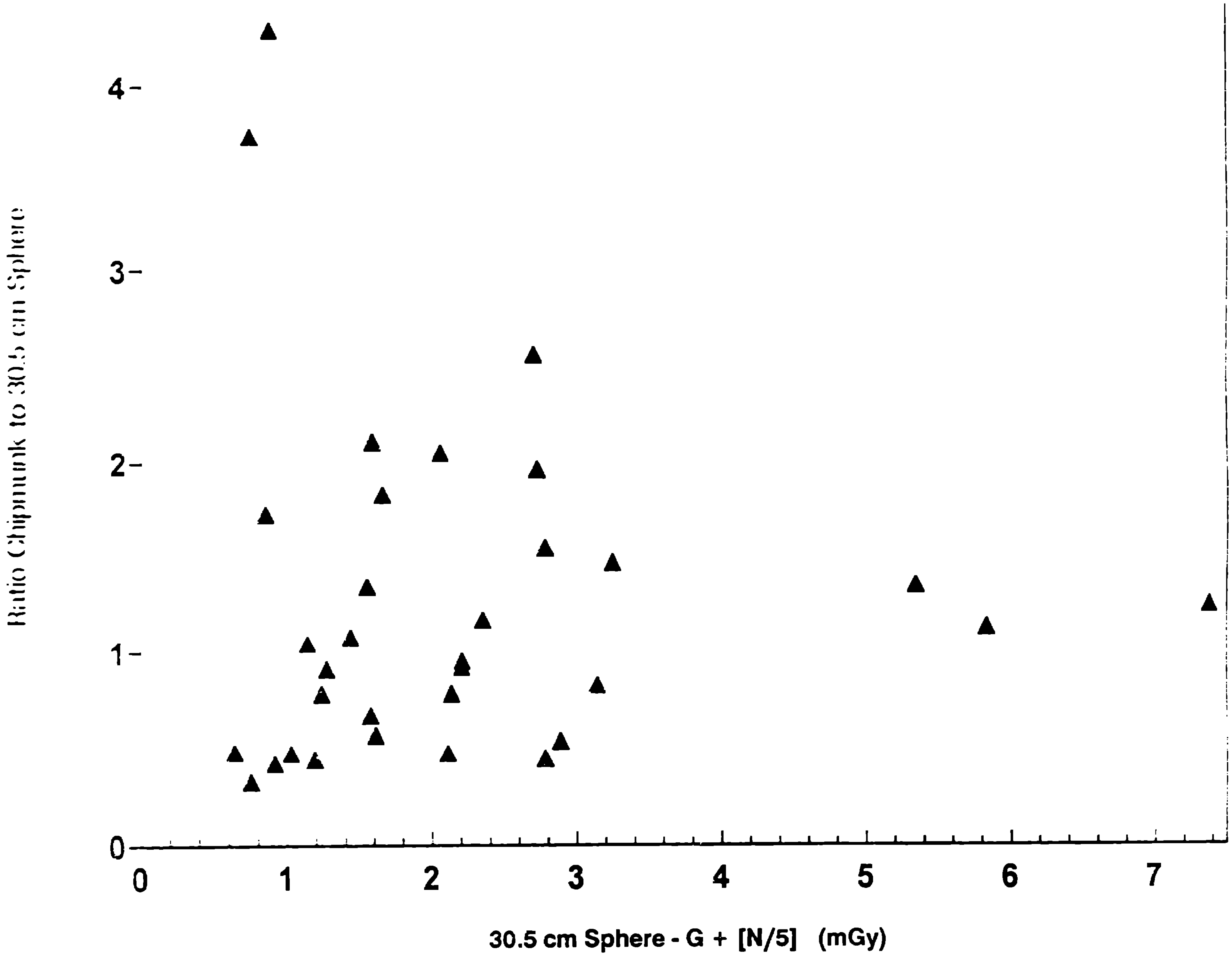


4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
1
10
30.5 cm Sphere (mSv)

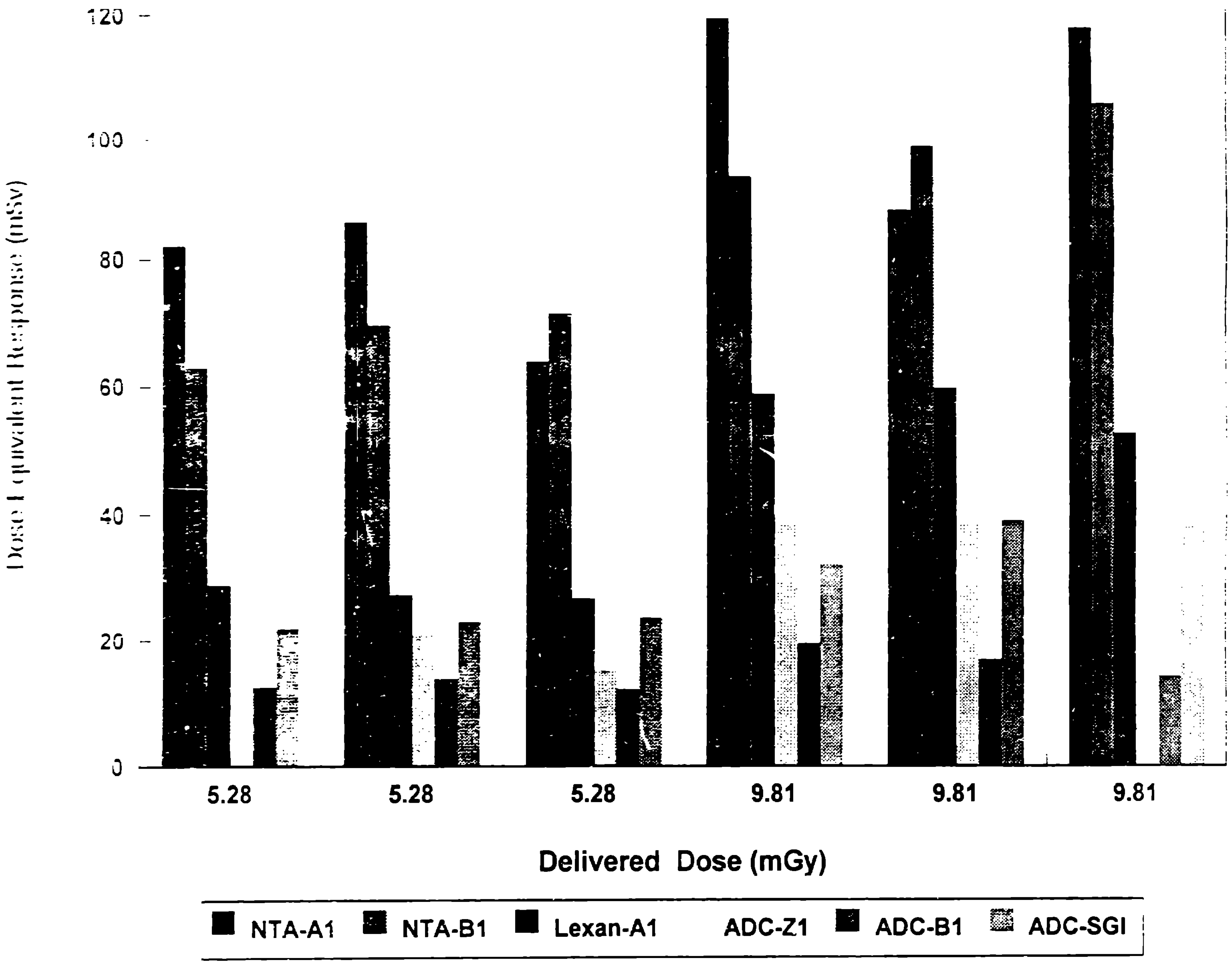


1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
1
10
30.5 cm Sphere (mSv)


1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
1
10
30.5 cm Sphere (mSv)



Ratio Chipmunk to 30.5 cm Sphere
0
1
2
3
4
5
6
7
30.5 cm Sphere - G + [N/5] (mGy)



Dose Equivalent Response (mSv)
0
20
40
60
80
100
120
5.28
5.28
5.28
9.81
9.81
9.81
Delivered Dose (mGy)
NTA-A1
NTA-B1
Lexan-A1
ADC-Z1
ADC-B1
ADC-SGI

Neutron Radiation Fields at Fermilab

David Boehnlein

Neutron Measurements at Fermilab

- J. Cossairt, A. Elwyn, W. Freeman, W. Salisbury, P. Yurista
- Multisphere technique used for measurements
  - 7 sphere sizes + bare detector
  - LiI(Eu) "phoswich" or LiF TLD
  - Neutrons detected through thermal capture reaction
- Spectra measured at 14 sites outside of shielding

Data Analysis

- 1/E dependence assumed for spectra
- 3 unfolding programs used
  - BUNKI
  - LOUHI
  - SWIFT
- Macroscopic agreement for low resolution spectra
- Integral properties are independent of the unfolding program
  - Average total fluence
  - Average dose equivalent
  - Average quality factor

Sample Spectra and Geometries

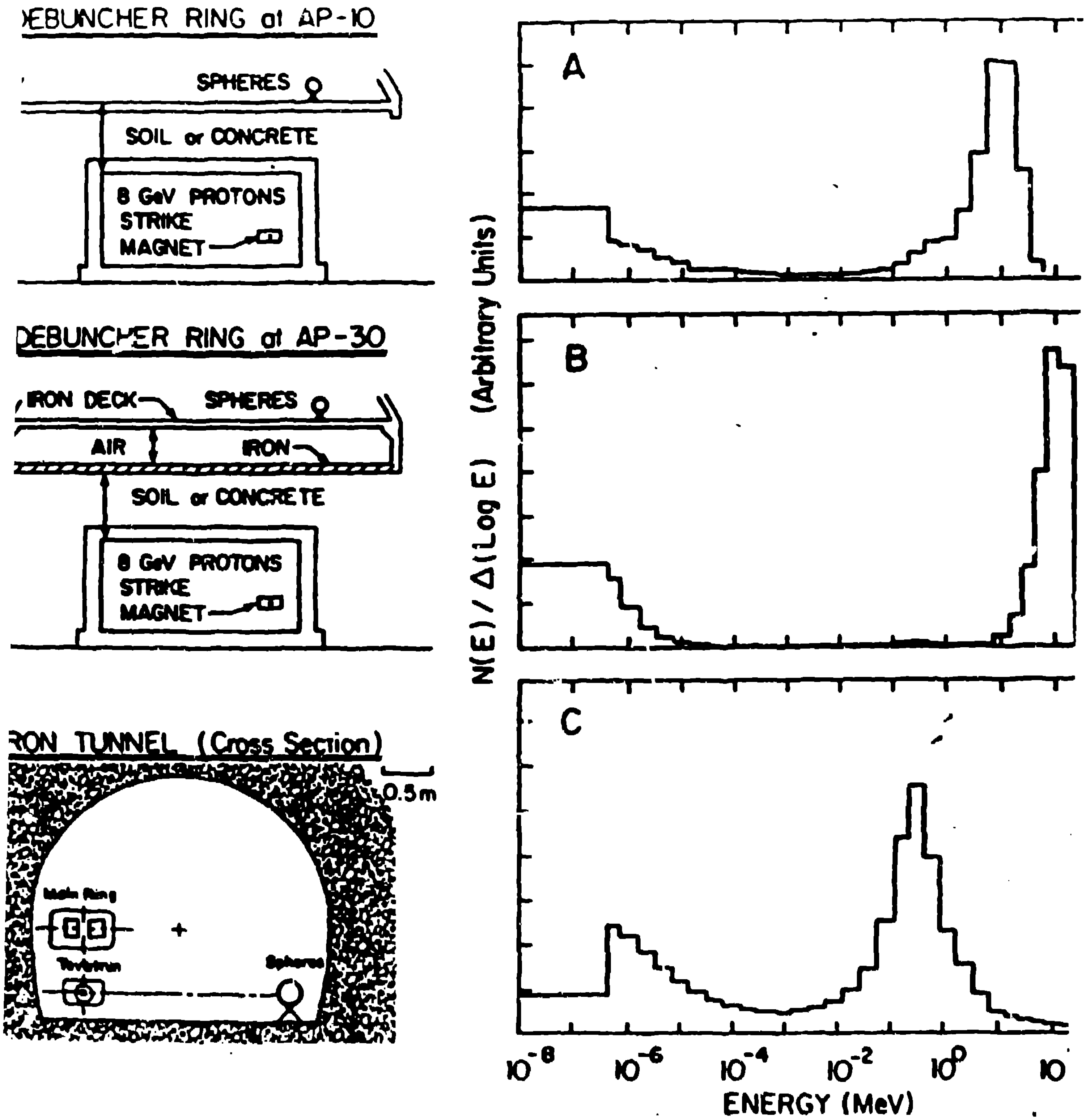


Figure 1. Shielding geometries (left) and corresponding unfolded neutron energy spectra (right) for situations A, B, and C. The abscissa is in arbitrary units of fluence per logarithmic energy interval.

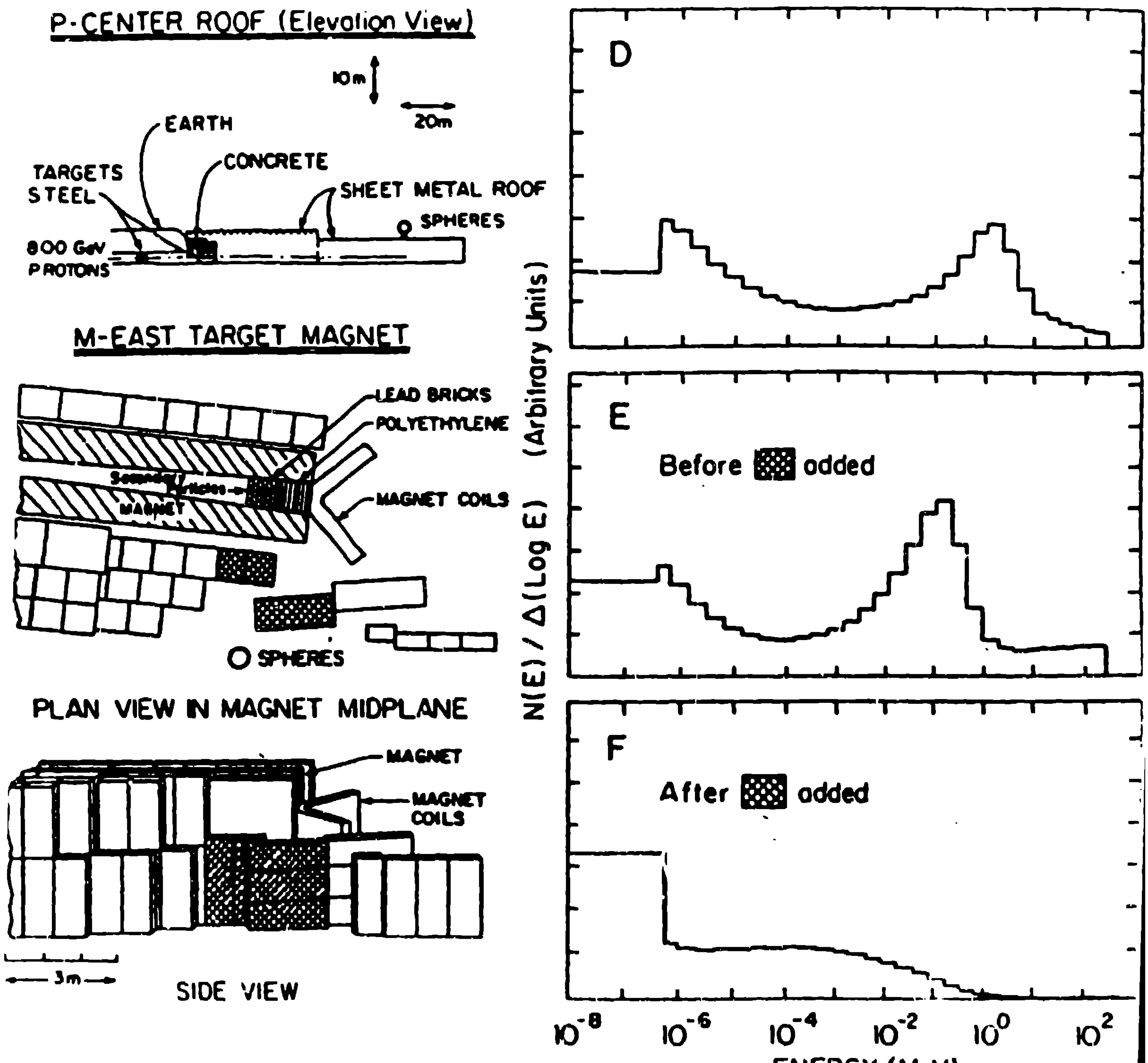


Figure 2. Shielding geometries (left) and corresponding unfolded neutron energy spectra (right) for situations D, E, and F. The abscissa is in arbitrary units of fluence per logarithmic energy interval.

Average Integral Quantities

- Average total Fluence
- Average dose equivalent
- Average quality factor = 5.3 +/- 1.6

AN ADAPTIVE FEEDBACK CONTROLLER FOR TRANSVERSE ANGLE AND POSITION JITTER CORRECTION IN LINEAR PARTICLE BEAM ACCELERATORS

D. S. Barr
Los Alamos National Laboratory, Los Alamos, NM 87545

ABSTRACT

It is desired to design a position and angle jitter control system for pulsed linear accelerators that will increase the accuracy of correction over that achieved by currently used standard feedback jitter control systems. Interpulse or pulse-to-pulse correction is performed using the average value of each macropulse. The configuration of such a system resembles that of a standard feedback correction system with the addition of an adaptive controller that dynamically adjusts the gain-phase contour of the feedback electronics. The adaptive controller makes changes to the analog feedback system between macropulses. A simulation of such a system using real measured jitter data from the Stanford Linear Collider was shown to decrease the average rms jitter by over two and a half times. The system also increased and stabilized the correction at high frequencies; a typical problem with standard feedback systems.

INTRODUCTION

A basic feedback configuration used for jitter control is shown in Fig. 1. Figure 2 shows an adaptive version of the same system. This type of system is known as a self-tuning regulator (STR). The processor is the intelligent part of the system which controls H in such a way as to decrease the rms system output error. The processor uses past jitter values in its determination of H. It analyzes past errors and periodically updates H thus exploiting short and long term trends in the jitter. H will usually be in the form of a standard feedback filter. The fast loop operates in real time, while the slow loop does not.

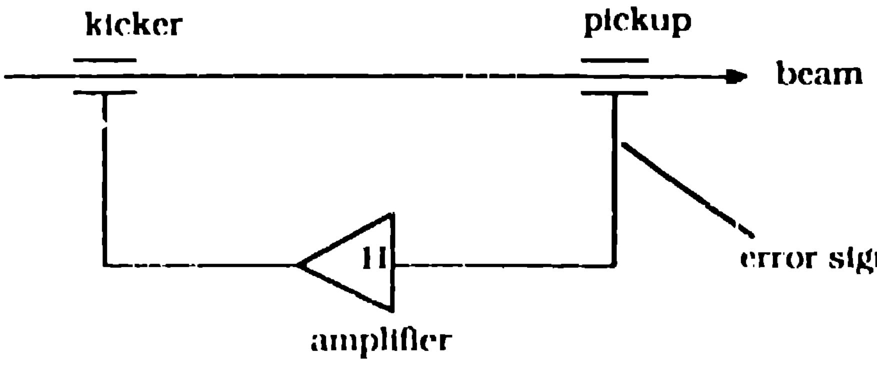


Fig. 1 - Simple feedback system

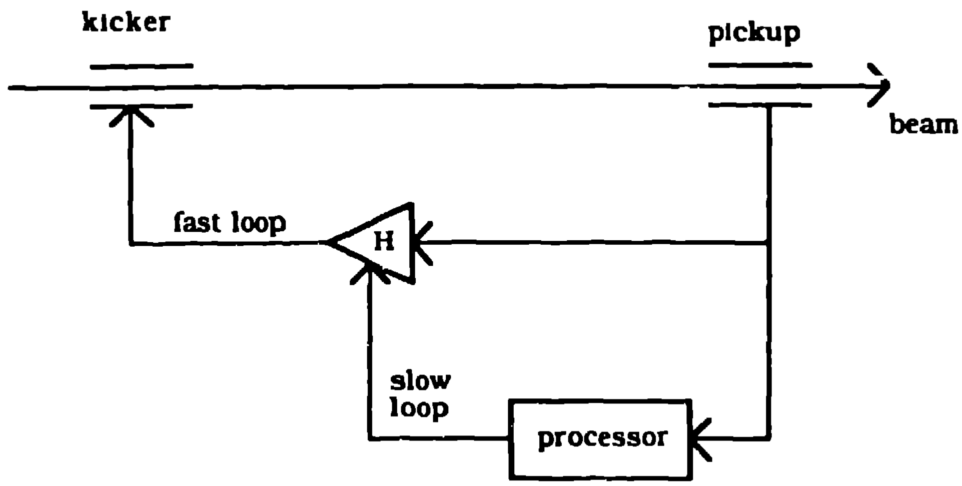


Fig. 2 - STR feedback system

The area of the beam which is to be corrected is setup as follows. First define the transfer matrix or r-matrix for the x-plane transport through a beam element as follows:

$$\begin{pmatrix} x_1 \\ x_1' \end{pmatrix} = \begin{pmatrix} (x|x_0) & (x|x_0') \\ (x'|x_0) & (x'|x_0') \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \end{pmatrix} . \quad (1)$$

In this equation, x_0 is the input beam position in the horizontal plane, and x_0' is the input horizontal beam trajectory angle. x_1 is the output beam position in the horizontal plane, and x_0' is the output horizontal beam trajectory angle. It is assumed that a point in a particle beam transport can be found such that [1]

$$R_{22} = \frac{\Delta \dot{x}_1}{\Delta \dot{x}_0} = 0 . \quad (2)$$

At this point in the beam, x'_1 depends only on the input beam position (δ is assumed to be zero in the horizontal case). The beam position is measured using a BPM (beam position monitor). Correction can be done by simply changing the upstream beam angle. Since the output angle at the BPM only depends on the input position, this configuration can effectively be used to correct beam angle jitter using a single BPM and a single deflector. The assumption given in equation (2) is made in order to simplify the correction model. After the mechanics of this simple model are mastered, it is relatively straightforward to design a system that corrects both position and angle jitter in both the horizontal and vertical planes.

A typical beam setup for standard feedback control of angle jitter is shown in Fig. 3. This will be used as the model for correction

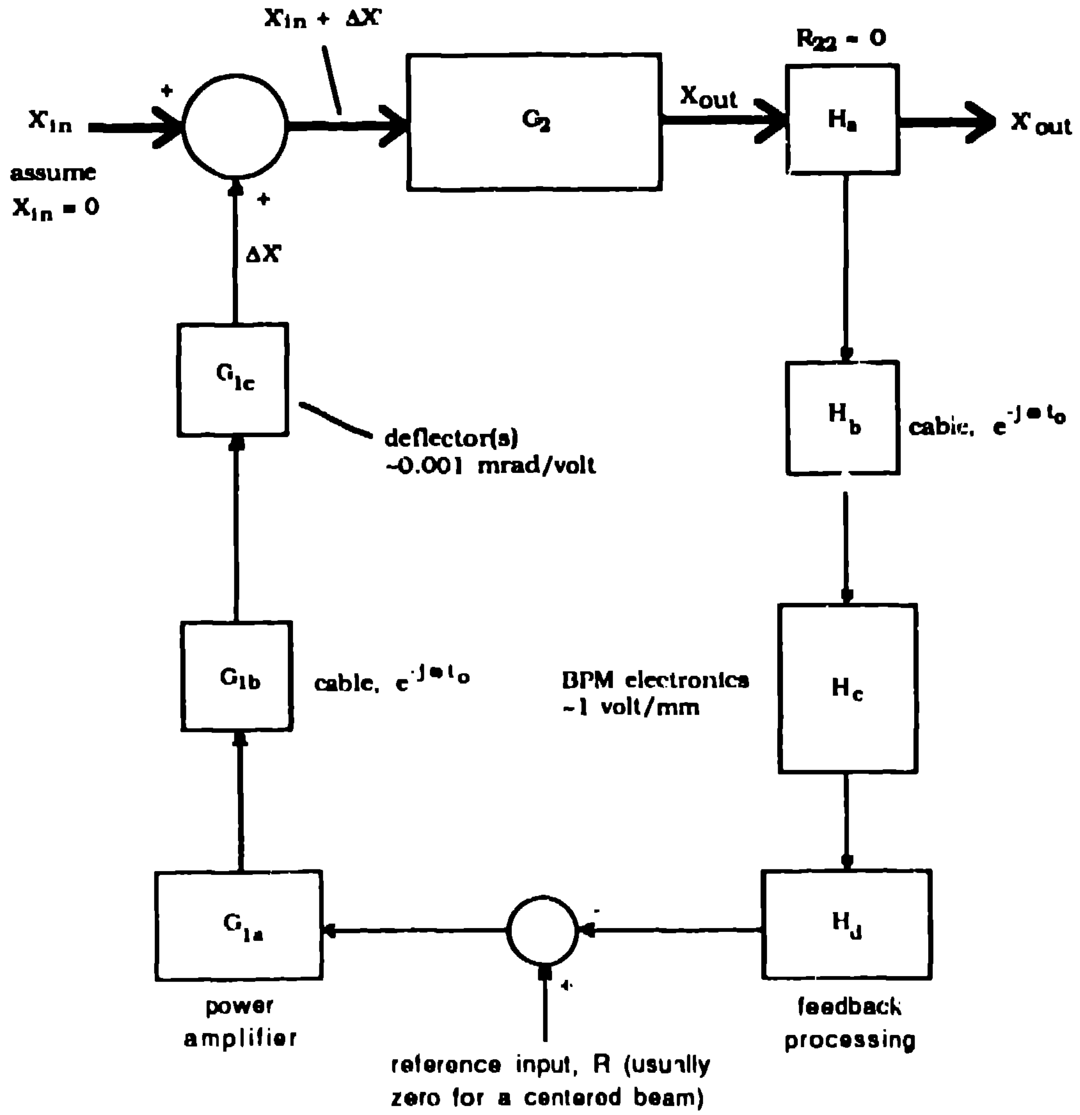


Fig. 3 - Feedback setup for simple angle jitter control

Select $G_2(\omega)$ as a drift. Other possibilities for $G_2(\omega)$ are possible, but a drift makes the derivation easier. So

$$G_2(\omega) = 1 \text{ mm/mrad} \quad . \tag{3}$$

Also, as typical values, let

$$G_{1a}(\omega) = 1000 \text{ volts/volts} \tag{4}$$

$$G_{1b}(\omega) = e^{j\omega t_0} \tag{5}$$

$$G_{1c}(\omega) = 0.001 \text{ mrad/volt} \quad . \tag{6}$$

Now,

$$G_1(\omega) = G_{1a}(\omega)G_{1b}(\omega)G_{1c}(\omega) = e^{-j\omega t_0} \quad . \tag{7}$$

As well choose

$$H_a(\omega) = 1 \text{ mm/mm} \tag{8}$$

$$H_b(\omega) = G_{1b}(\omega) = e^{-j\omega t_0} \tag{9}$$

$$H_c(\omega) = 1 \text{ volt/mm} \tag{10}$$

$$H(\omega) = H_a(\omega)H_b(\omega)H_c(\omega)H_d(\omega) \quad . \tag{11}$$

So,

$$H(\omega) = e^{-j\omega t_0}\, H_d(\omega) \quad . \tag{12}$$

The corner frequency poles for $G_{1a}(\omega)$, $G_{1c}(\omega)$, $H_a(\omega)$, and $H_c(\omega)$ will easily be much higher than that for $H_d(\omega)$, and therefore will be neglected. As a typical figure, the value for β in the cable will be taken as 0.85. A total of 500 feet of cable will be assumed. This is a typical length from a beamline to a control room and back. The value for t_0 can be calculated since the β of the of the cable is known.

$$t_0 = \frac{\ell}{\beta c} = 298.8 \text{ nsec} \tag{13}$$

where ℓ is the length of the cable and c is the speed of light in a vacuum (3.0×10^8 m/s). For one section of cable, ℓ=250 feet. For the round trip the delay due to the cable is 597.6 nsec ~ 0.6 µsec. This time is insignificant compared to the repetition rate of the beam (for the SLC data it is 60 Hz). Since correction is done once per macropulse, a new correction value will always be applied on the next pulse.

To analyze the feedback loop, start with the output transfer function. The value for R will be taken as zero since it is desired to center the beam with zero beam trajectory angle in both the horizontal and vertical planes. From Fig. 3 (with R=0),

$$X_{out}(\omega) = \frac{G_2(\omega)X'_{in}(\omega)}{1 + G_1(\omega)G_2(\omega)H(\omega)} \quad . \tag{14}$$

Using Eqs. (3), (7), and (12), this is now

$$X_{out}(\omega) = \frac{X'_{in}(\omega)}{1 + e^{-2j\omega t_0}\, H_d(\omega)} \quad . \tag{15}$$

The open-loop transfer function is

$$G(\omega)H(\omega) = G_1(\omega)G_2(\omega)H(\omega) = e^{-2j\omega t_0}\, H_d(\omega) \quad . \tag{16}$$

The last step is the design of $H_d(\omega)$. Pick an open-loop transfer function of the form

$$G(s)H(s) = \frac{K\,(s+z_1)(s+z_2)\ \dots\ (s+z_{m-a})}{s^{\ell}(s+p_1)(s+p_2)\ \dots\ (s+p_{n-a-\ell})} \tag{17}$$

where $\ell \geq 0$, and $-z_i$ and $-p_i$ are the nonzero finite zeroes and poles of $G(s)H(s)$. This is known as a *type-ℓ system*. Commonly used feedback systems include types 0,1, and 2. The higher numbered system types increase the accuracy of feedback systems in correcting complicated input functions (such as ramps and parabolas), but at the expense of bandwidth. Since bandwidth is very important in the beam jitter case, and the expense in bandwidth is high, type 0 systems are usually used. The value of K is made as large as possible in order to decrease the jitter as much as possible. These systems have some problems tracking complex input signals, but the increased bandwidth and gain (K) make the tradeoff worthwhile.

Now using ω-notation ($s=j\omega$), equation (17), and $\ell=0$,

$$H_d(\omega) = \frac{K\,(j\omega+z_1)(j\omega+z_2)\ \dots\ (j\omega+z_{m-a})}{(j\omega)^0\,(j\omega+p_1)(j\omega+p_2)\ \dots\ (j\omega+p_{n-a})} \quad . \tag{18}$$

Filters with more than one pole are usually unstable for reasonable bandwidths (in the present case) since the phase shift is larger. These can be used if the bandwidth is decreased, but in this case is not worth the loss of bandwidth. In addition, multiple poles increase the number of independent variables which drastically slows down the adaptive routines discussed later. Equation (18) simplifies to

$$H_d(\omega) = \frac{K}{1 + j\omega/p_1} \quad . \tag{19}$$

The open-loop transfer function can be found by using Eqs. (16) and (19).

SELF-TUNING REGULATORS

The basic self tuning regulator setup was given in Fig. 2. The processor is the intelligent part of the system which controls H in such a way as to decrease the rms system output error and achieve the highest possible bandwidth. Effectively the gain-phase contour of H will be altered depending on past values of the amplitude error function. In this role, H and the associated processor can be considered a self tuning regulator.

The main problem with the standard STR system is stability analysis. Typically the overall system stability is difficult to investigate and must be done after the fact. That problem is solved here by using an H for which the stability can be easily analyzed.

The standard feedback filter (H_d in Fig. 3) has a transfer function found in Eq. (19). This filter has two variable parameters, K and p_1. K is the gain and p_1 is the corner frequency or 3 dB point of the filter pole. Many filters are possible as the values for Kp_1 are allowed to vary. Logically, for any given filter, different input signals should give different values for rms system output error. Also, logically, for any given input signal, different filters should give different values for rms system output error. Thus for different types of beam jitter, different feedback filters should work better than others. It should therefore be possible to improve on the standard feedback system by including an $H_d(\omega)$ that adapts itself to changing jitter characteristics.

The interesting part of this technique is the design of the adaptive routine. This is the routine which analyzes past jitter and determines the new filter parameters. It also includes a criteria for stability. The routine works as follows. First, a performance criteria must be chosen to which a control law should conform. The one used here is the minimum mean-square output error. The idea is to minimize

$$\sigma_f = \left[\int_{t_0-\tau}^{t_0} \varepsilon^2(t)\, dt \right]^{\frac{1}{2}} \qquad (20)$$

where ε is the output error measured at the BPM, t_0 is the current time, and τ is the amount of time the integration should be carried into the past. This serves as a "forgetting" factor, and allows some degree of control over how much the remote past affects the current measurements. Values for K and p_1 must be found which minimize σ_f. The forgetting factor can be implemented by taking only the desired number of macropulses from the recent past.

A mathematical technique must be chosen to minimize $\sigma_f(K,p_1)$. There are many possible mathematical methods that can be used. Two of the most promising were used. They are the conjugate gradient method and the simplex method.

STR CORRECTION MODEL

It is now desired to create a discrete version of Fig.3 in order to simulate the jitter control system by computer. Figures 4 and 5 show the discrete model. The delay in the feedback return path is included to simulate the delay incurred between the deflector and the BPM as well as the cable delays. In Fig. 4, u[n] is $x'_{in}[n]$ and e[n] is $x'_{out}[n]$.

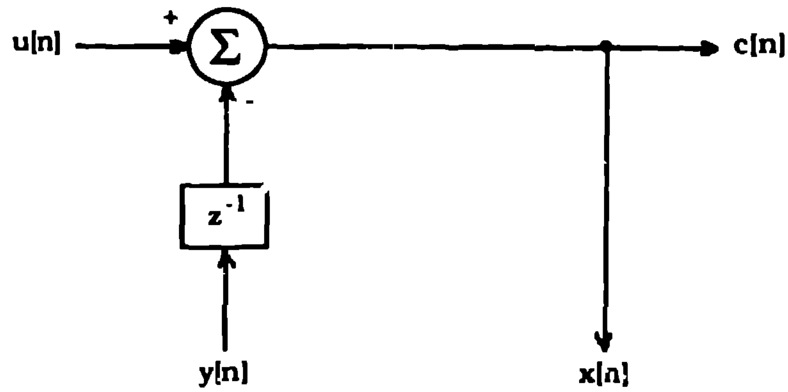


Fig. 4 - Discrete beamline model

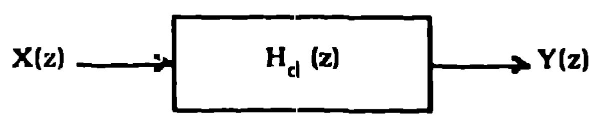


Fig. 5 - Discrete feedback filter

In order to simulate the STR feedback correction as a discrete system, the differential equation that this represents must be solved numerically. Many types of solutions are possible. The technique used here is the backward difference. It is equivalent to numerically taking a derivative according to Eq. (21). [2]

$$\frac{d}{dt}y(t) = \frac{y(t) - y(t-T)}{T} \quad . \tag{21}$$

The transform is accomplished by the following substitution

$$s = j\omega = \frac{1 - z^{-1}}{T} \quad . \tag{22}$$

This is used in Eq. (19) to obtain the discrete filter. The sampling time T is the inverse of the macropulse repetition rate.

$$H_d(z) = H_d(s)\big|_{s=(1-z^{-1})/T} = \frac{\alpha K z}{z(\alpha+1) - 1} \tag{23}$$

where $\alpha = Tp_1$. After manipulation

$$y[n] = \frac{\alpha K}{\alpha+1}x[n] + \frac{1}{\alpha+1}y[n-1] \quad . \tag{24}$$

Now using Fig. 3 in conjunction with Figs. 4 and 5, the system can be modeled. After substitution and simplification,

$$c[n] = u[n] + \frac{1 - \alpha K}{\alpha + 1} c[n-1] - \frac{1}{\alpha + 1} u[n-1] \quad . \tag{25}$$

It is now desired to perform a stability analysis of the feedback system. The test used was a discrete version of the Routh-Hurwitz criterion called Jury's stability test[2]. The results of the test are given below:

$$\alpha(K+1) > 0 \tag{26}$$

$$\alpha(K-1) < 2 \quad . \tag{27}$$

Equations (26) and (27) must both be met for the feedback system to be stable. The values chosen for the SLC data in the standard feedback case were K=9.9 and p_1=10.8 Hz. These values gave stable results while working well. They were chosen using the power spectral density of the actual data.

The performance criterion for adaptation is the rms output of the system. Thus the error is given by

$$E = \left[\sum_{n=1}^{N} c^2[n] \right]^{\frac{1}{2}} \tag{28}$$

where N is the number of data points in the sample and c[n] is found in Eq. (25). Equation (28) is taken from Eq. (20).

The mathematical techniques used were the conjugate gradient method[1,3,4,5] and the simplex method[5]. Details on these methods can be found in the respective references. The techniques were modified to perform constrained optimization using the stability criterion as the constraint

RESULTS

In this section, the results of the simulated beam runs using the real beam jitter data will be given. Two types of output are used to measure the results of the simulations. The first is a table listing the jitter reduction that each technique provides over the case of no correction at all. The second are plots of jitter correction versus frequency. This gives an indication of the bandwidth of each correction system. These plots are generated by dividing the spectral density plot of each output by the spectral density of the driving function or raw jitter data. They will be displayed on a semi-log graph. No correction would correspond to zero dB, while jitter reduction would be negative dB, and jitter enhancement would be positive dB.

All jitter data is in the form of beam position versus time. The data includes only one data point per macropulse. Note that the ability to apply position correction, directly implies the ability to apply angle correction. As stated earlier, locations in the beamline can be found where beam angle (in either transverse plane) depends only on beam position. Thus beam position data can be effectively used to model correction schemes for both position and angle jitter. Note that correction of angle jitter can take place elsewhere, but this would require two sets of BPMs and deflectors. The data used in the simulation was not collected at a location such that the condition given in equation (2) was satisfied. It is assumed however, that the frequency makeup of the jitter will stay constant until arriving at a location where equation (2) holds. Thus, even though the absolute values of the jitter data may change as the beam passes downstream, the relative values of the jitter compared to itself will stay the same. This justifies the use of the simple model (Figure 3).

The interpulse data consists of various sequences of 220 consecutive macropulses acquired from the Stanford Linear Collider (SLC) located at the Stanford Linear Accelerator Center (SLAC) in Palo Alto, California. Each macropulse was passed through an analog low-pass filter before digitization in order to get its average value. The first 100 of the data points were used as a training set. The first point of the remaining data was then processed using Eq. (25), and the error measured using the actual data point. The feedback filter was then updated and the next point was processed. The process was continued with the remaining data points. The update was possible due to the length of time between each macropulse. The beam repetition rate was 60 Hz. It is assumed that an update can be accomplished in this time scale. As long as the adaptive algorithm is not extremely complicated, it can always be hardwired and hopefully quick enough. In the worst case scenario, the update takes too long and is only accomplished every other macropulse. If this situation were to arise, the simulation could be easily altered to reflect it.

The data was taken at three BPMs at different locations in the beamline. The locations correspond to different particle energies. The energies are 1.2 GeV, 17 Gev, and 42 GeV. The higher energies are found farther along in the accelerator. The accelerator was also run at different values of charge. These values were (in units of e^{+09} e^- particles per macropulse): 13, 18, 30, 36, 40, and 45. There is also x and y position data. The actual values analyzed are given in Table I. At higher charge (36, 40, and 45), problems occurred in the standard feedback correction system for medium (17 GeV) and high (42 GeV) energies in the x-plane only. Slight problems occurred in the y-plane at medium energy at higher charges. These effects were probably due to longitudinal wakefields at high charge, which incur a head-tail distortion at later stages of the beam in the horizontal plane (high energy). The problems in the vertical plane were probably due to some form of transverse plane coupling.

The analysis results are also given in Table I. Certain cases caused problems for the standard feedback system (in particular, case x4). The STR feedback system was able to deal with these problems much better.

TABLE I

STANDARD FEEDBACK AND STR FEEDBACK JITTER REDUCTION

Data	Energy (GeV)	Charge (e^9 e^-/pulse)	Standard Feedback R_{orig}	Standard Feedback R_{fbd}	STR Feedback R_{orig}	STR Feedback R_{fbd}
x1	1.2	13	-18.94	0.00	-28.73	-9.79
x2	1.2	45	-17.36	0.00	-25.75	-8.39
x3	42	13	-14.88	0.00	-19.82	-4.93
x4	42	45	4.39	0.00	-1.78	-6.17
y1	1.2	13	-20.43	0.00	-36.13	-15.70
y2	1.2	45	-20.47	0.00	-37.05	-16.58

y3	42	13	-16.01	0.00	-22.91	-6.90
y4	42	45	-16.73	0.00	-23.39	-6.67
x5	17	40	2.98	0.00	-4.06	-7.05
x6	17	30	-4.09	0.00	-10.89	-6.80
x7	17	45	3.40	0.00	-2.27	-5.67
x8	42	30	-9.60	0.00	-14.64	-5.04
x9	42	40	5.04	0.00	-1.39	-6.44
y5	17	45	-1.82	0.00	-7.85	-6.03
y6	17	40	-3.95	0.00	-12.16	-8.21

The values for R_{orig} are the rms jitter reduction amounts over those with no correction applied (given in dB).

$$R_{orig} = 20 \cdot \log_{10}\left(\frac{\text{rms jitter}_{w/correction}}{\text{rms jitter}_{w/o\ correction}}\right) \tag{29}$$

The values for R_{feed} are the rms jitter reduction amounts over those for the standard feedback system (also given in dB).

$$R_{feed} = 20 \cdot \log_{10}\left(\frac{\text{rms jitter}_{w/correction}}{\text{rms jitter}_{standard\ feedback}}\right) \tag{30}$$

The average value of R_{feed} for the STR feedback system is –8.02 dB.

Figure 6 shows a typical jitter correction versus frequency graph from the standard feedback system while Fig. 7 shows this graph from the STR feedback routine. The STR feedback system shows an improvement over the standard feedback system as seen in Fig. 7. The STR system does amplify the jitter slightly at high frequencies, but not as much as the standard feedback case.

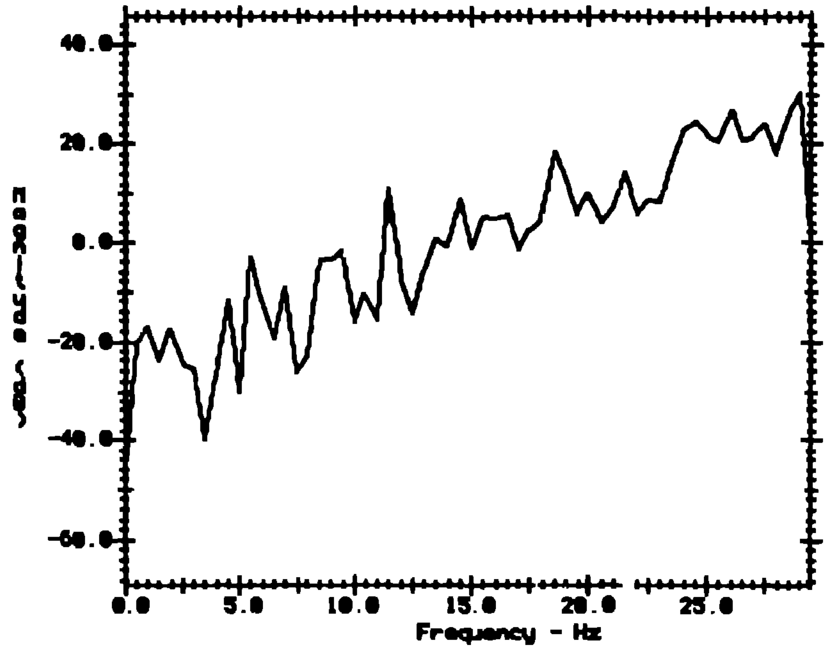


Fig. 6 - Jitter Correction Versus Frequency for Standard Feedback Case

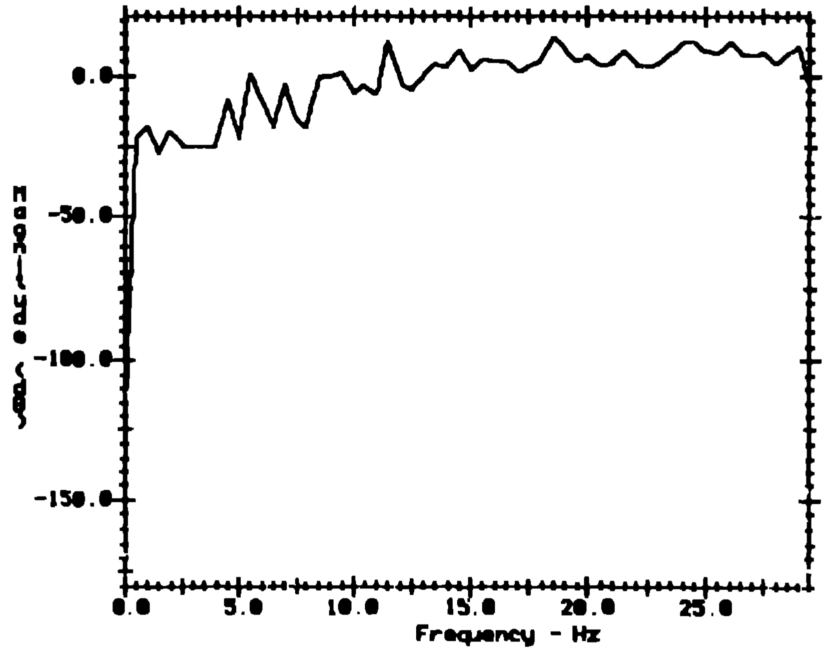


Fig. 7 - Jitter Correction Versus Frequency for STR Feedback Case

CONCLUSION

The STR feedback system worked exceptionally well. Jitter correction was shown to decrease the average rms jitter by over two and a half times over that of a standard feedback system. By comparing the jitter correction versus frequency graphs for the standard feedback system with those of the STR feedback system, one can see that the STR technique does not experience the extreme amplification of jitter at high frequencies. The minimization of the rms output error has effectively stabilized the correction-versus-bandwidth plot for these systems. Finally, the STR feedback system always worked well and could be added without too many problems to many existing accelerator correction systems.

REFERENCES

1. C. Fortgang, Private Communication, 1989
2. C.L. Phillips, H.T. Nagle, Jr., Digital Control System Analysis and Design (Prentice-Hall, Inc., Englewood Cliffs, N.J.,1984), pp. 329, 198.
3. L.S. Ladson, S.K. Mitter, A.D. Warren, IEEE Trans. on Automatic Control, Vol. 12, No. 2, 132 (1967)
4. B. Pagurek, C.M. Woodside, Automatica, Vol. 4, 337 (1968)
5. W.H. Press, B.P. Flannery, S.A. Teukolsky, W.T. Vetterling, Numerical Recipes: The Art of Scientific Computing, (Cambridge Univ. Press, Cambridge, England, 1986), p. 301.