THE UNIVERSITY OF MICHIGAN
COLLEGE OF LITERATURE, SCIENCE, AND THE ARTS
Department of Physics

Technical Report No. 32

THE USE OF IONIZATION CALORIMETERS IN HIGH ENERGY NEUTRON EXPERIMENTS AT PARTICLE ACCELERATORS

Lawrence W. Jones

ORA Project 03106

under contract with:

NATIONAL SCIENCE FOUNDATION

and

DEPARTMENT OF THE NAVY
OFFICE OF NAVAL RESEARCH
WASHINGTON, D.C.

CONTRACT NO. Nonr-1224(23)
NR-022-274

administered through:

OFFICE OF RESEARCH ADMINISTRATION ANN ARBOR

July 1968

(Submitted to the Versailles International Symposium on Nuclear Electronics)

The Use of Ionization Calorimeters in High Energy Neutron Experiments at Particle Accelerators

Lawrence W. Jones
University of Michigan, Ann Arbor, Michigan 48104
July 1968

ABSTRACT

Ionization calorimeters, or total absorption spectrometers, have enjoyed widespread use by cosmic ray physicists as energy-sensitive detectors for hadron events. We have successfully employed similar detectors of smaller scale in experiments on neutron total cross sections at particle accelerators. A description of these detectors and a discussion of other applications is presented.

I. Introduction and Background

The ionization calorimeter, or total absorption spectrometer, is a device for the determination of energies of hadrons. Consisting of alternate layers of absorbers and ionization detectors, it has been used over the last decade primarily in cosmic ray experiments in the energy range of 100 - 1000 GeV. Gas-filled ionization chambers and proportional counters have been used as ionization detectors in many calorimeters designed for cosmic ray research, although several calorimeters have been constructed using liquid or plastic scintillators. The most commonly used absorber material is iron. The calorimeter may be used to determine the energy whether or not an incident hadron suffers a nuclear interaction before entering the calorimeter, so long as all of the energy of the hadron or its reaction products is dumped in the calorimeter. In principle the ionization calorimeter is very analogous to corresponding counters of lead and scintillator which have commonly been used in electron and photon energy-sensitive counters. An excellent review paper has appeared recently by Murzin[1] summarizing and referencing the extensive cosmic ray literature in this field.

In operation, the sum of the pulse heights of the sampling ionization detectors is proportional to the kinetic energy of the incident hadron to an uncertainty of about ±20%. An incident hadron interacts in the absorber producing a cascade of (predominately) pions which propagate generally in the direction of the incident particle. In each generation, about one third of the pions are neutral and initiate electromagnetic showers. Most of the energy of the incident hadron thus is dissipated through e.m. showers ultimately, and thus lost by ionization of the electrons.

In order to appreciate the magnitudes of parameters involved, consider a calorimeter with layers of ionization detectors spaced by t g cm^{-2} of absorber. The average (<u>not</u> the minimum) ionization of a relativistic particle in the absorber corresponds to (dE/dt) MeV g^{-1} cm^2. If the i^{th} detector detects n_i relativistic particles, the energy of the hadron is given simply by

$$E = \sum_{i=1}^{N} n_i \times t_i \times (dE/dt). \qquad (1)$$

The pulse height (or perhaps area) is generally calibrated with muons, so that $n_i = V_i/V_o$ where V_o is the average pulse height voltage for a relativistic muon in the detector. Hence,

$$E = \frac{(dE/dt)}{V_o} \sum_{i=1}^{N} V_i t_i \qquad (2)$$

If all absorbers t_i are the same,

$$E = \frac{(dE/dt)t}{V_o} \sum_{i=1}^{N} V_i \qquad (3)$$

and the summed voltage output is directly proportional to the energy. These convenient expressions are modified in practice by several smaller factors. First the absorber thickness t_i should be taken centered on the ionization detector rather than between two detectors. Second if the total thickness of the calorimeter is less than several attenuation mean free paths λ (the mean free path in iron is 200 g cm^{-2}) the last detector output should be weighted by a factor reflecting the energy dissipated beyond; e.g.,

$$E = K \left\{ \sum_{i=1}^{N} V_i + \int_{o}^{\infty} V_N e^{-t/\lambda} \, dt \right\} ,$$

$$E = K \left\{ \sum_{i=1}^{N-1} V_i + \lambda V_N \right\} . \qquad (4)$$

Third, the "visible energy" seen by the ionization detectors is an underestimate because (i) some energy is used to overcome nuclear binding (8 MeV/nucleon) in heavier nuclei and some escapes the calorimeter as muons and neutrinos, (ii) the detector (e.g., plastic scintillator) usually has an atomic number significantly different than the absorber so that the development of e.m. showers is quite different therein, and (iii) if the detector is a plastic scintillator, slower, more heavily ionizing nucleons produce pulses less than proportional to their energy loss relative to relativistic particles. Each of these effects may be about 10% for incident hadrons of about 100 GeV, so that Equation (3) should be multiplied by a coefficient of about 1.3.

II. Cosmic Ray Experience

It is important to note that no direct calibration of an ionization calorimeter has been published. Huggett[2] has carried out calibration runs at the Brookhaven A.G.S. in momentum analyzed beams up to 30 GeV/c with a small calorimeter.

In 1966-67 our group employed a calorimeter of 1065 g cm^{-2} in a cosmic ray search for quarks, and a separate study of the properties of that calorimeter has been reported.[3] The calorimeter is illustrated in Figure 1. The main conclusions are noted below.

The attenuation mean free path of the ionization was 200 g cm^{-2} in iron, and within statistics was not a function of incident energy from 75 to 750 GeV. This figure is <u>not</u> the interaction mean free path of hadron in iron (which is about 100 g cm^{-2}). From this attenuation length, approximate values for the initial ionization can be deduced. Assuming an ionization build-up in less than 200 g cm^{-2}, Equation (1) can be written

$$E = n_o(dE/dt) \int_0^\infty \exp\,(-t/\lambda)dt,$$

$$E = \lambda n_o(dE/dt).$$

For iron, $dE/dt \cong 1.7$ MeV g^{-1} cm^2, so that

$$n_o = E\,(\text{GeV}) \,/\, 0.34.$$

As an example, a 200 GeV proton beam entering an iron wall would produce an ionization of about 600 x the ionization of the protons at a depth of the order of 100 g cm^{-2} in the iron. (This corresponds to an energy release of about 8 GeV cm^{-1} per proton or about 1000 joules per cm for a beam of 10^{12} protons.)

Our experience also confirmed the observations of Murzin and others that the ionization profile for particular events fluctuates quite wildly. Examples of several events are given in Figure 2. It is thus very misleading to take the ionization from only one or two detectors under a fixed absorber as a significant index of energy. By way of contrast, the average pulse height of the counters at different depths for collections of events of similar energy are shown in Figure 3.

On the other hand, for events of greater than 100 GeV, it appears that detectors spaced closer than about 1/3 λ do not materially improve the energy resolution. It does seem plausible that much closer spacing of detectors is desirable at low energies (e.g., 10 GeV) where the number of nuclear interactions becomes statistically small. In this case spacings of 1 to 3 radiation lengths (15 - 40 g cm^{-2} of iron) may be optimal, so as to sample each e.m. shower adequately.

It is clear that the calorimeter operates as well for hadrons over a range of incident angles, as long as the elements (absorbers and detectors) are parallel planar. The only limitations are the overall lateral extent, and the poorer sampling of a cascade when the real pathlength through the absorber becomes comparable to or greater than λ.

The lateral spreading of an energetic cascade is reported[1] to be ±1.8 cm (r.m.s.) so that most of the ionization would be contained in a cylinder about 10 cm diameter.

The relative resolution of the calorimeter is expected to be better at higher energies for at least two reasons: (i) there are statistically a larger number of hadronic interactions so that the sampling is better, and (ii) the fraction of the energy going into nuclear binding and into slow nuclear fragments decreases.

In spite of this, we have successfully utilized a calorimeter at current accelerator energies.

III. Accelerator Experience

In an experiment on neutron total cross sections at the Brookhaven Alternating Gradient Synchrotron, a small ionization calorimeter was built as the neutron detector.[4] This experiment is shown schematically in Figure 4. The total calorimeter thickness was about 400 g cm^{-2} of iron in the form of bricks 5.08 x 10.16 x 20.32 cm^3. There were originally 10 counter layers, each about 25 cm high and wider than the iron with each pair spaced by a wall of iron bricks 30.5 cm wide and higher than the counters. Thus the total effective area of the calorimeter was about 25 x 30 cm^2 normal to the beam and the total length along the beam axis was about 70 cm. In practice, alternate counters were connected in parallel on either side of the apparatus, however one set proved to be unstable and was disconnected leaving 5 counters spaced by about 80 g cm^{-2} of iron between each pair as noted in Figure 4. No loss of resolution was apparent on making this change. Only the incident neutrons interacting in the initial 5 cm slab of iron were counted, and a requirement that the pulse height in the counter S_1 (following the iron) be at least 3 times minimum was set. The energy discrimination of the system (involving the A.G.S. neutron spectrum as well as the calorimeter response) was empirically determined from integral discriminator curves taken at different peak proton energies. The system was typically operated at a point on the discriminator curve where a drop in the A.G.S. proton energy (effectively the peak neutron energy) of 4 GeV (14%) decreased the calorimeter counting rate relative to an energy insensitive neutron monitor by a factor of 4 to 6. At this point on the discriminator curve the neutron counting rate was 2% to 5% of its plateau value. While an absolute efficiency was not determined, the 40 g cm^{-2} converter should have converted between 30% and 40% of the incident neutrons, so that the overall neutron detection efficiency for maximum energy neutrons probably lay between 1% and 10%. (The neutron spectrum from the A.G.S. had been determined separately from a small-angle elastic scattering experiment and was known to be peaked near the A.G.S. proton energy.) The calorimeter used in this experiment is seen in a photograph in Figure 5.

A second calorimeter has been made for the neutron cross section and small-angle elastic scattering angular distribution experiment at the Lawrence Radiation Laboratory Bevatron. The calorimeter for this experiment employs 14 scintillators each spaced by 30 g cm^{-2} of iron, with an overall length of 70 cm and an area of 60 x 85 cm^2. The neutron converter and particle position detector are 25 x 50 cm^2, allowing at least 17 cm for lateral development of cascades from the converter.

In the A.G.S. experiment the neutron positions were determined by 7.0 and 12.1 cm diameter counters behind the converter and coaxial with the smaller neutron beam. In the Bevatron experiment optical time-of-flight of light in plastic scintillators will be used to locate particle positions to about ±2 cm in a plane normal to the neutron beam, a resolution comparable to the diameter of the collimated neutron beam.

Earlier experiments on np forward elastic scattering[5] have used iron plate spark chambers with interspersed scintillators to locate neutron vertices, however the scintillator was not used to define neutron energies as in a calorimeter.

Obviously such spark chamber-scintillator combinations could be used to both locate the position and (qualitatively) the direction of the interacting neutron, and to measure its energy. This is being done in a cosmic ray experiment currently being performed by our group in an experiment to determine total cross sections in the 100 - 1000 GeV energy range.[6] Here a 10-gap spark chamber with 20 g cm^{-2} of iron between gaps has scintillators located at the 40, 120, and 200 g cm^{-2} levels. Below this are a further 900 g cm^{-2} of iron (about 75 tons, 2.5 x 2.5 m^2) interspersed with 7 more layers of scintillator.

IV. Other Applications

As accelerator energies climb toward 10^{11} eV and beyond it is plausible for experimentalists at these facilities to borrow from the technology which has been developed for cosmic ray research at comparable energies. Thus the ionization calorimeter provides an energy-sensitive detector for hadrons which, combined with position definition, can find application in research with accelerators.

The examples of neutron total cross section measurements and small-angle neutron elastic scattering are accelerator experiments where simple calorimeters are already employed.

Experiments to study energetic K_2^o (above 10 GeV) might also use calorimeters. Thus a $K^o p$ scattering or total cross section experiment might employ a high-momentum K^+ beam incident on material to produce a monochromatic K^o beam by charge exchange. The K_2^o could then be detected with the ionization calorimeter as in the neutron experiments.

Neutrons produced by diffraction dissociation of nucleons could be detected in this manner. For example a proton beam of 70 - 200 GeV incident on a target could produce a final state $\pi^+ n$; the π^+ could be analyzed by a Cherenkov counter-magnet-spark chamber system while the neutron energy (roughly) and direction (more precisely) could be ascertained by a spark chamber-calorimeter system.

A calorimeter could be used to trigger a magnet-spark chamber system on rare final states. For example a calorimeter behind a magnet-spark chamber analysis system and to the side of a beam path could detect elastic or inelastic final states of large transverse momentum. The spark chamber analysis would subsequently reveal the details of the final state.

The ultimate development of the ionization calorimeter may be represented by a homogeneous crystal device being tested by Hofstadter.[7] Although expensive, it should have significantly better energy resolution than the sampling type of calorimeter discussed above. In principle the addition of image intensifiers to Hofstadter's large crystals could give us a combined calorimeter and triggered luminescent chamber combining all of the desired features of spatial and energy resolution.

It is a pleasure to acknowledge the contributions and discussions of ideas presented herein with M. J. Longo, M. N. Kreisler, P. V. Ramana Murthy, D. E. Lyon, and A. Subramanian.

References

1. V. S. Murzin, "Progress in Elementary Particle and Cosmic Ray Physics" (North-Holland Publishing Company, Amsterdam, The Netherlands, 1967), Vol. IX, p. 245.
2. R. W. Huggett (private communication).
3. D. E. Lyon and A. Subramanian "Design of Ionization Spectrometers Using Iron and Scintillators, for the Detection of Hadrons in the 100 - 1000 BeV Range" (1967) (unpublished).
4. M. N. Kreisler, L. W. Jones, M. J. Longo, and J. R. O'Fallon, Phys. Rev. Letters 20, 468 (1968).
5. M. N. Kreisler, F. Martin, M. L. Perl, M. J. Longo, S. T. Powell, Phys. Rev. Letters 16, 1217 (1966).
6. L. W. Jones "A Cosmic Ray Program for the Study of Strong Interaction Physics in the Range of 100 - 1000 GeV" Proceedings of the Tenth International Conference on Cosmic Rays, Calgary, Canada, June, 1967 (Calgary, The University of Calgary, 1968). Part A, pp. 480-505.
7. R. Hofstadter "Total Absorption Nuclear Cascade Detectors for High Energy Physics" HEPL 556 (submitted to Nuclear Instruments and Methods).

FIGURE CAPTIONS

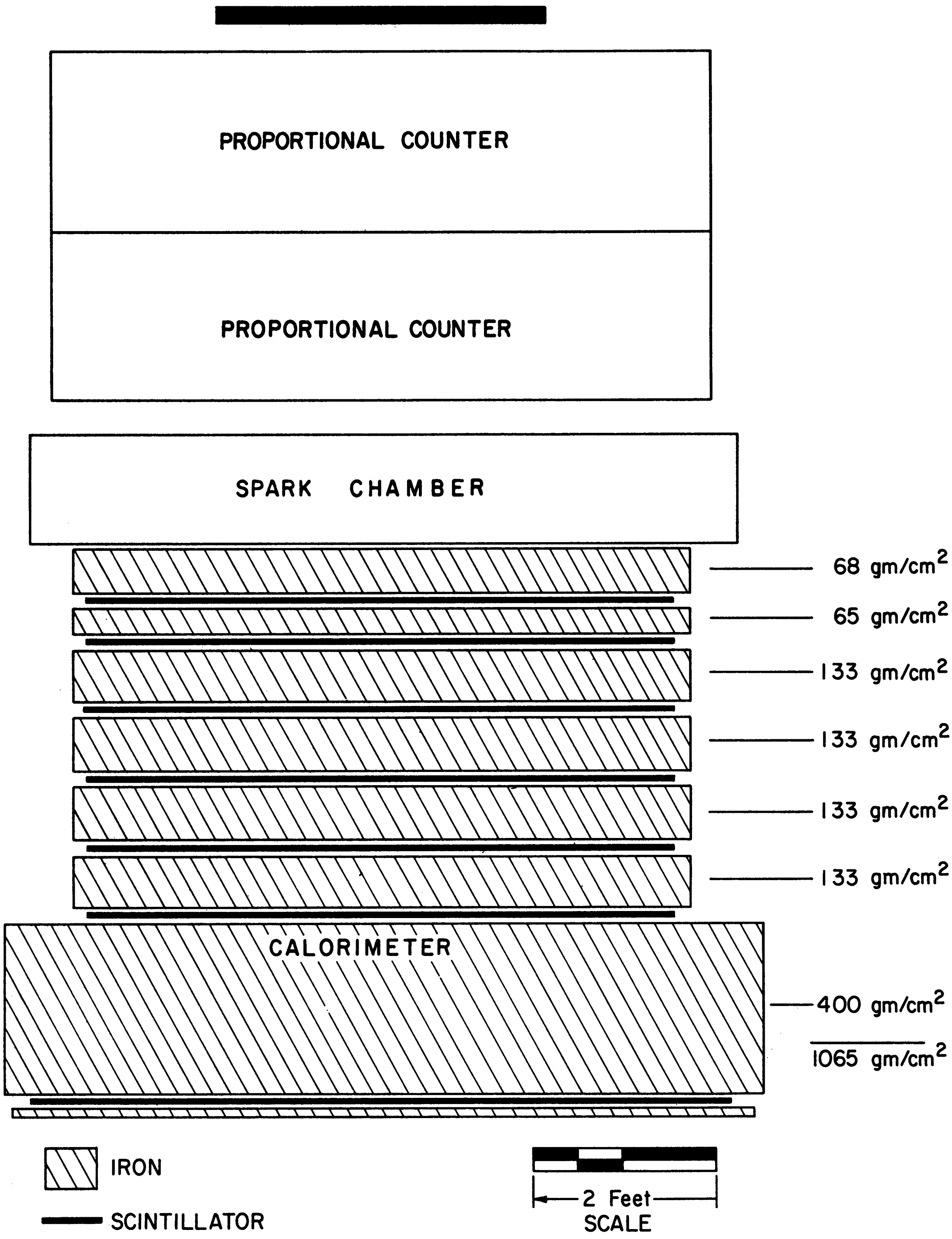
Figure 1. A schematic drawing of the ionization calorimeter used in a cosmic ray search for quarks.

Figure 2. Individual event shower development in the ionization calorimeter showing the wide variation in the energy deposition profiles. The X's are the recorded ionizations at specific depths and the smooth curves are drawn only to guide the eye.

Figure 3. Average shower development for some selected energy bins.

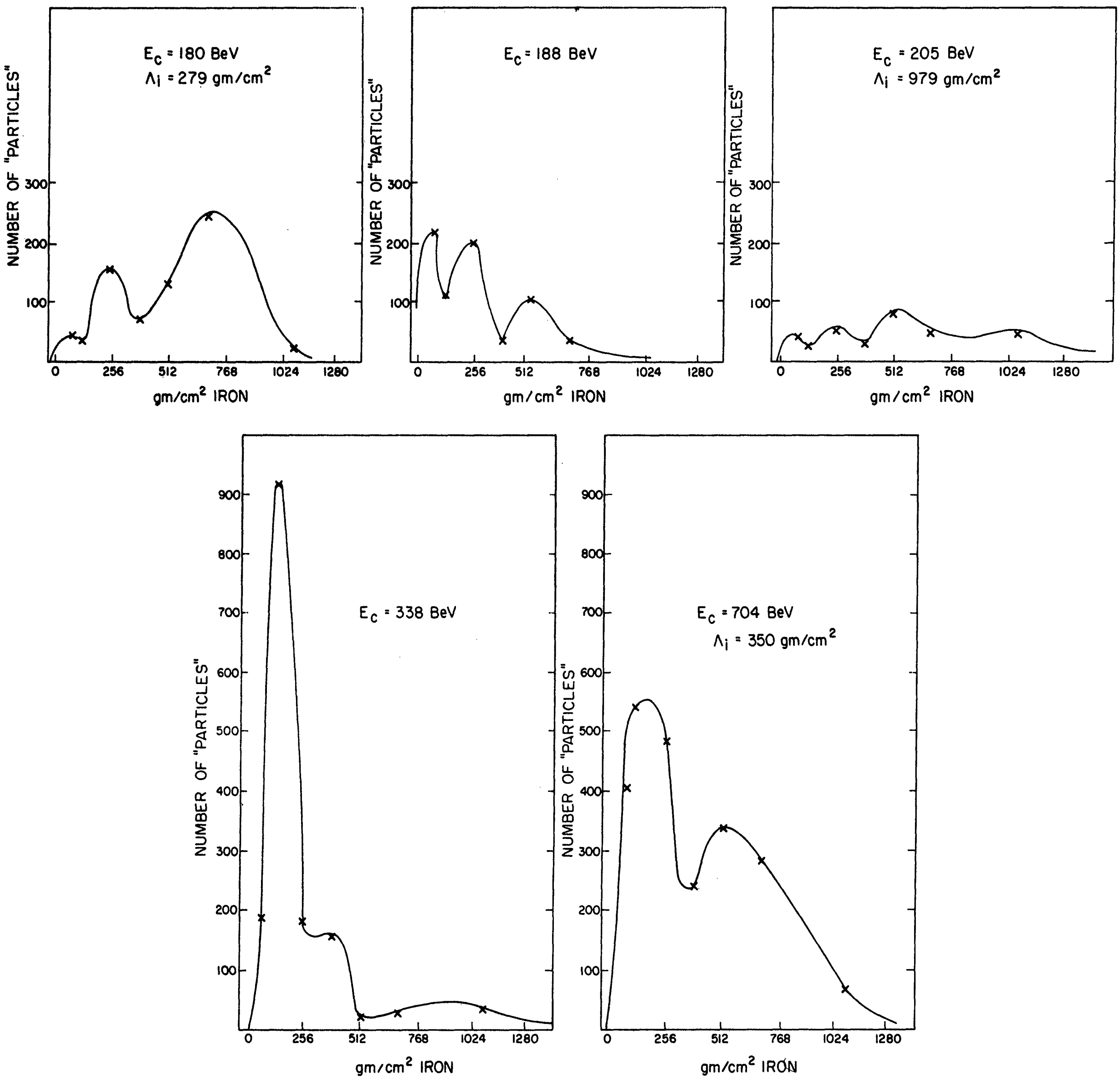
Figure 4. Schematic representation of the ionization calorimeter and other experimental apparatus in the A.G.S. experiment on np total cross sections.

Figure 5. A photograph of the calorimeter shown schematically in Figure 4.



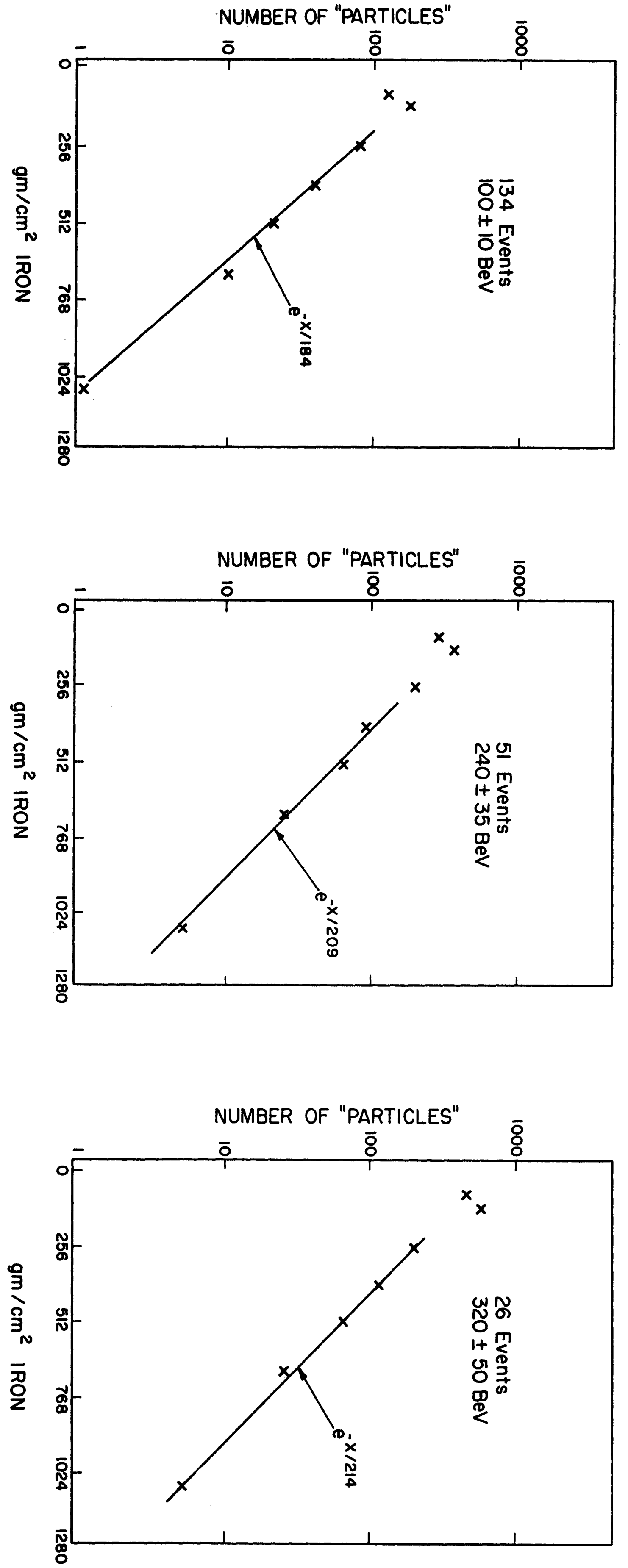
PROPORTIONAL COUNTER
PROPORTIONAL COUNTER
SPARK CHAMBER
68 gm/cm2
65 gm/cm2
133 gm/cm2
133 gm/cm2
133 gm/cm2
133 gm/cm2
CALORIMETER
400 gm/cm2
1065 gm/cm2
IRON
SCINTILLATOR
2 Feet
SCALE

Figure 1



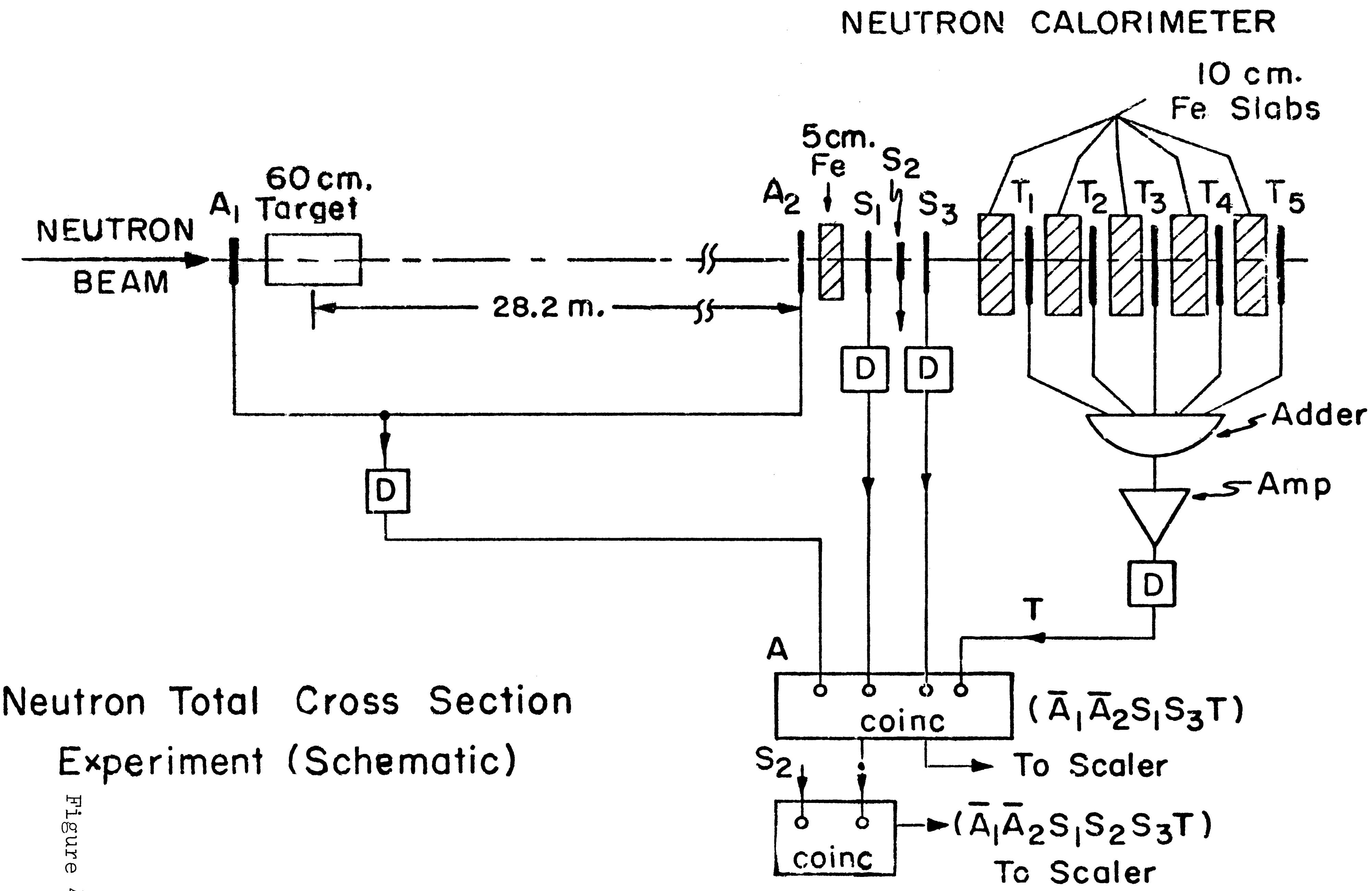
E_c = 180 BeV
Λ_i = 279 gm/cm^2
E_c = 188 BeV
E_c = 205 BeV
Λ_i = 979 gm/cm^2
E_c = 338 BeV
E_c = 704 BeV
Λ_i = 350 gm/cm^2
NUMBER OF "PARTICLES"
gm/cm^2 IRON

Figure 2



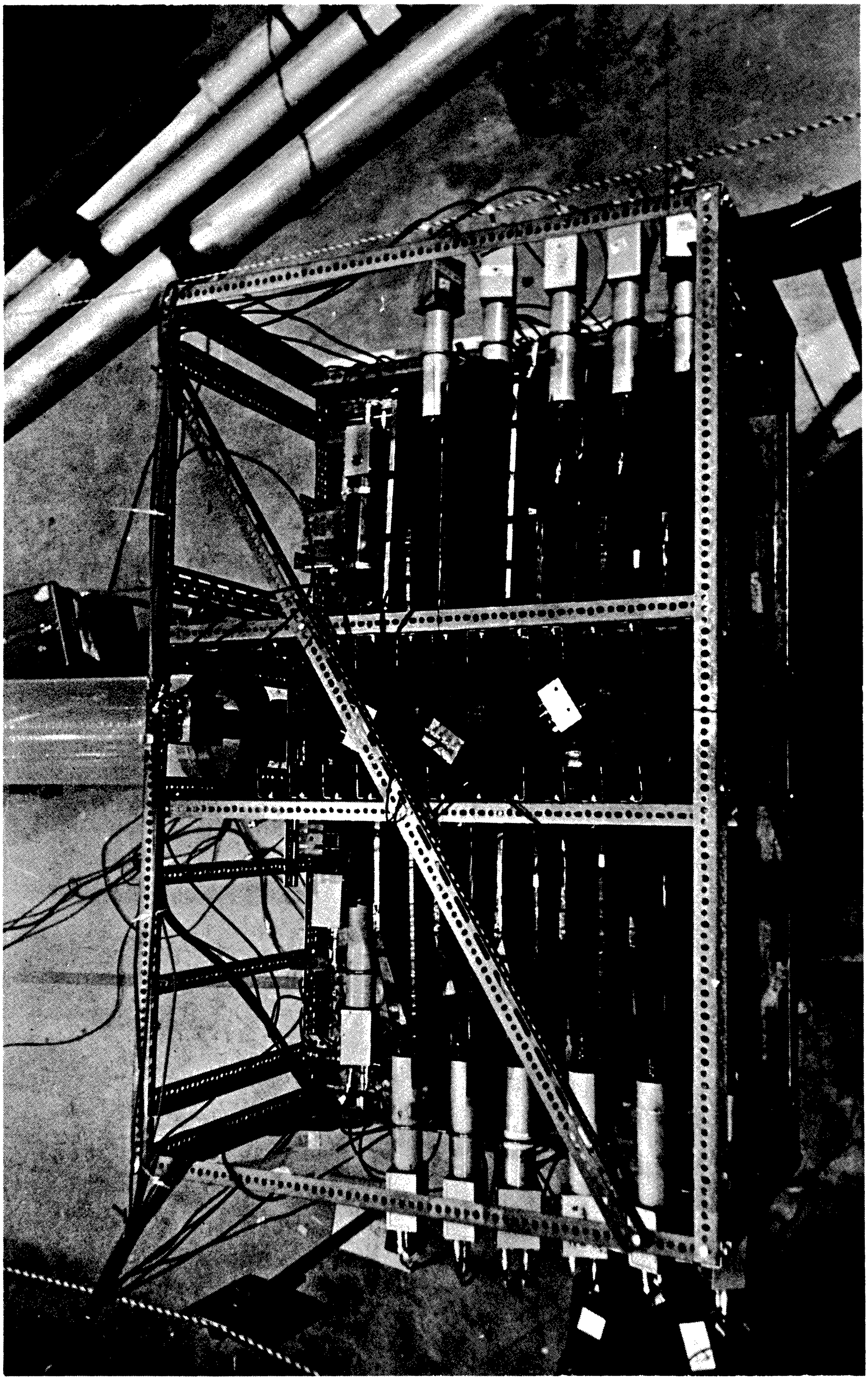
NUMBER OF "PARTICLES"
gm/cm^2 IRON
134 Events
100 ± 10 BeV
$e^{-X/184}$
51 Events
240 ± 35 BeV
$e^{-X/209}$
26 Events
320 ± 50 BeV
$e^{-X/214}$

Figure 3



Neutron Total Cross Section Experiment (Schematic)

Figure 4.



Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) The University of Michigan Department of Physics Ann Arbor, Michigan	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

THE USE OF IONIZATION CALORIMETERS IN HIGH ENERGY NEUTRON EXPERIMENTS AT PARTICLE ACCELERATORS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Report No. 32

5. AUTHOR(S) (Last name, first name, initial)

Jones, Lawrence W.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
July 1968	17	7

8a. CONTRACT OR GRANT NO. Nonr-1224(23) b. PROJECT NO. NR-022-274 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 03106-32-T 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) Technical Report No. 32

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES Submitted to the Versailles International Symposium on Nuclear Electronics	12. SPONSORING MILITARY ACTIVITY Department of the Navy Office of Naval Research Washington, D.C.

13. ABSTRACT

DD FORM 1 JAN 64 1473

Unclassified

Security Classification

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2*a*. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2*b*. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7*a*. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7*b*. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8*a*. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8*b*, 8*c*, & 8*d*. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9*a*. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9*b*. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

Unclassified

Security Classification