27
1-21-81
24 to 27
ORNL

OAK
RIDGE
NATIONAL
LABORATORY

UNION
CARBIDE

OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL/TM-7123

MASTER

**A Monte Carlo Simulation
of an Actual Segmented
Calorimeter: A Study of
Calorimeter Performance
at High Energies**

T. A. Gabriel
B. L. Bishop
M. S. Goodman
A. L. Sessoms
B. Eisenstein
S. C. Wright
R. D. Kephart

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A03; Microfiche A01

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.

Contract No. W-7405-eng-26

Engineering Physics Division

A Monte Carlo Simulation of an Actual Segmented Calorimeter:
A Study of Calorimeter Performance at High Energies*

T. A. Gabriel
B. L. Bishop¹
M. S. Goodman²
A. L. Sessoms^{2,3,7}
B. Eisensteig⁴
S. C. Wright⁵
R. D. Kephart⁶

* Work performed at ORNL supported by the U.S. Department of Energy, Office of High Energy and Nuclear Physics; work at Harvard University, University of Illinois and Fermi National Accelerator Laboratory supported in part by the U.S. Department of Energy; work at Enrico Fermi Institute, University of Chicago, supported in part by the U.S. National Science Foundation.

¹ Computer Sciences Division

² Harvard University, High Energy Physics Laboratory

³ Alfred P. Sloan Foundation Fellow

⁴ University of Illinois, Urbana

⁵ Enrico Fermi Institute, Univ. of Chicago

⁶ Fermi National Accelerator Laboratory

⁷ Present address: U.S. Department of State

Date Published - January 1981

NOTICE This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
FOR THE
U. S. DEPARTMENT OF ENERGY

DISCLAIMER

This book 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.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
I. INTRODUCTION	1
II. DESCRIPTION OF THE CALCULATIONS AND EXPERIMENTAL DEVICE	2
A. Calculational Procedure	2
B. The Device Geometry	5
C. Beam Simulation and Analysis of Monte Carlo Histories	8
III. RESULTS AND CONCLUSIONS	9
A. Energy Resolution	9
B. Hadron Shower Structure and Angular Resolution . .	12
C. Conclusions	18
REFERENCES	20

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

ABSTRACT

The calculated responses including energy resolution, angular resolution, and spatial energy deposition of a segmented iron and liquid-argon calorimeter to incident pions in the energy range of 10- to 250-GeV are presented. Experimental data for this calorimeter have been obtained in the 10- to 40-GeV energy range and these results compare favorably with the calculated data. The energy and angular resolutions including experimental and calculated data can be summarized by the following expressions:

$$\sigma(E)/E = (5.07 + 33.4/\sqrt{E})\%,$$

and

$$\sigma_{\theta}(E) = 15.7 + 458./E \text{ (mrad)},$$

respectively, where E is in GeV.

I. INTRODUCTION

Experimental studies in high energy physics have become dependent on large, complex, and expensive instruments. For the evaluation of design concepts and of overall performance of such devices, expense and caution preclude full scale construction. More economical in time and money is to base the design on tests with smaller, similar models, and then to extrapolate the results to full size equipment and higher incident energies via Monte Carlo techniques. This is a doubtful procedure unless there is evidence that the calculations mimic the real data. This question is addressed in this paper for a calorimeter.

Presented here are the results of extensive comparisons between the data obtained from an actual large liquid argon-iron device¹ and Monte Carlo calculations.² These comparisons include energy resolution, the longitudinal and lateral spatial distributions of the hadronic shower, and studies of the angular resolution. In contrast to some previous Monte Carlo results on hadronic cascades, an attempt has been made to simulate the experimental conditions and to subject the calculated data to actual experimental analysis.

The tested segmented liquid argon-iron calorimeter, the simulation of which is described in this paper, was designed to measure the energy and direction of hadronic showers with good resolution. The important design characteristics included small sampling steps, low noise amplifiers, uniformity of response, high average density (4.17 g/cm^3), low cost per unit mass, and ease of calibration and monitoring. The small sampling steps allowed detailed measurements of hadronic shower structure to be made. The device was tested in the M-5 beam line at Fermilab over a

range of incident pion energies of 10-38 GeV.

The Monte Carlo code system, CALOR² employed for this study has been utilized extensively in previous calculations dealing with a large number of general detector systems: for example, Fe-plastic, Fe-liquid Argon, U-liquid Argon, etc. This code system has been successful in describing general hadronic shower features which are in good agreement with previous experimental data. In addition to calculations performed for the energy range of the experimental data considered here, additional simulations for incident energies up to 250 GeV have also been performed.

II. DESCRIPTION OF THE CALCULATIONS AND EXPERIMENTAL DEVICE

A. Calculational Procedure

The calculational procedures used here are similar to those described in Ref. 2 (see Ref. 2 for additional references and a more detailed discussion). A flow diagram of the codes is given in Fig. 1. Only those changes that have been implemented for these calculations are described here in detail. The three-dimensional, multi-media, high-energy nucleon-meson transport code (HETC) has been used, with modifications, to obtain a detailed description of the nucleon-meson cascade produced in the device considered in this paper. This Monte Carlo code takes into account the slowing down of charged particles via the continuous slowing-down approximation; the decay of charged pions and muons; inelastic nucleon-nucleus and charged-pion-nucleus (excluding hydrogen) collisions through the use of the intermediate energy intranuclear-cascade-evaporation (MECC) model ($E_{\pi} \lesssim 3$ GeV); and inelastic nucleon-hydrogen and charged-pion-hydrogen collisions via the isobar model ($E_{\pi} \lesssim 3$) and phenomenological fits to experimental data ($E_{\pi} \gtrsim 3$ GeV). Also accounted

Fig. 1. Generalized flow chart of CALOR.

for are elastic neutron-nucleus collisions ($E < 100$ MeV); and elastic nucleon- and charged-pion collisions with hydrogen. In past applications, high energy ($E \gtrsim 3$ GeV) inelastic charged-pion-nucleus and nucleon-nucleus collision data have been obtained by the use of a scaling model that takes data generated at $\gtrsim 3$ GeV by MECC and scales it to all higher energies. Since then, the high energy intranuclear-cascade code (HECC)³ has become available and can now be used to generate this inelastic collision data. This model (HECC), in addition to containing the effects of a diffuse nuclear surface, the Fermi motion of the bound nucleons within the nucleus, the exclusion principle applied to the zero-temperature Fermi gas model, and a local potential for nucleons as did MECC, also takes into account a localized reduction⁴ in the density of the nucleus during the development of the particle cascade. The high energy nucleon-nucleon and pion-nucleon production of pions within the nucleus is taken into account via phenomenological fits to experimental data mentioned earlier. These fits include the increase in particle multiplicity with increasing incident energy. A complete incorporation of this model (HECC) into HETC will not be completed until a much later date. Until then, data generated by HECC for selected nuclides at energies of 5-, 10-, 20-, 40-, 80-, and 160-GeV for incident neutrons, protons, and charged pions have been placed in a data base for use by HETC. The scaling model is used to fill in all intermediate energies above ~ 3 GeV.

In previous calculations similar to the one presented here, neutrons are transported if their energy is above 10 MeV. For neutrons below 10 MeV it was assumed that they deposited their energy at their point of origin or their energy was prorated between different areas on a gram-

thickness basis. To obtain a better smearing of this usually small amount of energy and to prevent isolated localized energy pulses, the cutoff energy in HETC for this study was set at 2 MeV. Neutrons produced below this cutoff deposited all of their energy at that point.

The source distribution for the electromagnetic cascade calculation, which consists of photons from neutral pion decay, electrons and positrons from muon decay, and de-excitation gamma rays from inelastic nuclear collisions, is provided by HETC. The transport of the de-excitation gamma rays has been added as a new feature for the same reasons as stated above for low-energy neutrons. Since the discrete decay energies of the de-excitation gammas are not provided by HETC, but only the total energy is known, individual gamma energies were obtained by uniformly sampling from the available energy until it was completely depleted. The transport of the electrons, positrons, and gammas from the above sources was carried out as described previously.²

B. The Device Geometry

The liquid argon-iron calorimeter consisted of a solid steel high voltage plate, 60 cm x 60 cm x 3 mm, a 4 mm liquid argon gap, and a plane of 30 signal electrodes made up of steel strips 60 cm x 2 cm of 3 mm thickness, followed by another 4 mm liquid argon gap — repeated throughout the device with horizontal (Y) and vertical (X) strips alternating with each other (see Fig. 2). The interleaved X and Y strips, ganged longitudinally in groups of 5 (5X and 5Y), formed a readout "segment" or plane (see Table 1). There were 12 of these. Table 1 gives the general specifications of the calorimeter. References 1 and 5 give details of construction, associated electronics, and the cryogenic system.

ORNL-DWG 79-19481

Fig. 2. Schematic diagram of the calorimeter geometry.

Table 1
Liquid Argon Calorimeter

Active dimensions	60 x 60 x 175 cm
Sampling Step	3.0 mm iron (2.36 g/cm^2) 4.0 mm liquid argon (0.56 g/cm^2)
Electronic readout step:	
transverse (section)	2.0 cm
longitudinal (plane)	14.0 cm x and y steps interleaved
Target thickness	705 g/cm^2
Target weight	2.7 tons
Channels of electronics	696
Average quantities	
density	4.17 g/cm^3
radiation length	3.52 cm
interaction length	19.0 cm
Quantities per readout step:	
radiation lengths	3.52
interaction lengths	0.74
Total length	12 x and 12 y interleaved readout steps
radiation lengths	42.2
interaction lengths	8.6

The calorimeter simulated in the Monte Carlo calculations had the same structure as this experimental device.

C. Beam Simulation and Analysis of Monte Carlo Histories

The experimental beam consisted of a mixture of pions, muons, and electrons. Muons were tagged with scintillation counters behind a 3 m shielding wall at the rear of the calorimeter. To remove the contaminating electrons from the hadron sample, the interaction was required to take place after the first 4 radiation lengths of the calorimeter, i.e., in the second segment. Similarly, in the Monte Carlo calculations, the primary particles were required to interact in the second segment.

In contrast to the distribution of the experimental interaction sites, the distribution of the primary interaction locations in the calculation have been forced to be uniform in the second segment. In addition, the interaction distributions in X and Y are uniform over a 2 cm area, the overlap of a single X and Y strip.

Smearing the energy deposited on each strip with a Gaussian of 0 mean and 3 MeV standard deviation simulated the electronic noise of the apparatus in the calculations. The noise in the experimental data, not inherent in the calorimeter circuitry, derives from such sources as magnet power supplies and radiofrequency noise in the building. An energy threshold cut (~ 5 MeV) decreased the effects of this background in both the experimental and calculated data,⁶ and an ADC truncation performed on the Monte Carlo "data" simulated the effect of a hardware ADC.

Monte Carlo histories were generated at 10- and 30-GeV for comparison with the experimental results, and additional events were

generated extending the incident pion energy to 50-, 125-, and 250-GeV to study the projected calorimeter performance. These simulated events were written on magnetic data tape in a format similar to that used for the real device. In addition, a separate file was written containing the "Monte Carlo answers," that is, the true interaction site of the primary particle, etc. The simulated events were subjected to the same analysis programs as the real data. Comparisons were made of the generated and reconstructed event attributes using the "Monte Carlo answers."

Typical CALOR computer running times for event generation with this geometry on an IBM 360/91 varies from 1 hour at 10 GeV for 500 incident hadrons to 1 hour at 125 GeV for 150 incident hadrons. Maximum memory requirements for the shower simulations was 1000K bytes.

III. RESULTS AND CONCLUSIONS

A. Energy Resolution

The energy resolution of the Monte Carlo events up to 250 GeV as well as the experimentally measured resolutions¹ are shown in Fig. 3. Also included in the figure are the data of Fabjan, Willis et al.⁷ The agreement between the calculated and experimental data is good in the 10-38 GeV energy region. The combined experimental data from 1-38 GeV have been fitted to the function

$$\frac{\sigma(E)}{E} = \left(\frac{28.0}{\sqrt{E}} + 8.5 \right) \% \quad (1)$$

where E is in GeV. The Monte Carlo and experimental data up to 38 GeV may be described by

$$\frac{\sigma(E)}{E} = (30.7(\pm 2.6)/\sqrt{E} + 6.6(\pm 1.3))\%, \quad (2)$$

Fig. 3. Comparison of calculated and experimental energy resolution.

which is in agreement with Eq. (1). Including all of the data from 1 to 250 GeV yields a fit of

$$\frac{\sigma(E)}{E} = (33.4(\pm 1.9)/\sqrt{E} + 5.07(\pm 0.75))\% \quad (3)$$

with a $\chi^2/df \sim 1$. Neither the experimental resolutions or the combined Monte Carlo and experimental resolutions are well described by a simple $1/\sqrt{E}$ law.

The constant parameter in Eqs. (1-3) possibly represents the fluctuations due to binding and leakage energy losses. Since the fitted constant appears to be decreasing as additional data are added at higher energies, either the effect of binding^{*} or leakage must be decreasing at these energies. In Table II are given the Monte Carlo predicted fractions of energy distribution in the shower. The leakage energy fraction is approximately constant over the energy range considered, however, the binding energy fraction slowly decreases as a function of energy. This decrease is due to the fact that a larger fraction of the energy is going into the electromagnetic channel and less into the hadronic channel. Less fractional energy into the hadronic channel will lead to less fractional total nuclear binding energy loss. Neglecting leakage, if the fraction of the electromagnetic contribution to the hadronic cascade continues to rise beyond 250 GeV, it is possible that at higher energies, the constant term will decrease to approximately zero and the resolution will become proportional to just $1/\sqrt{E}$. Studies at higher energies may help to resolve this issue.

^{*} Binding energy loss is defined as the energy lost due to nonelastic nuclear collisions.

Table II
Monte Carlo Predicted Energy Fractions

Incident Energy	Hadronic Energy (GeV)%	Electromagnetic Energy (GeV)%	Leakage (All Sides)	Binding ^a Energy Losses (GeV)
10 GeV	3.29 32.9% ^b	4.5 41.5%	1.24 12.4%	1.32 13.2%
30 GeV	8.19 27.3%	14.8 49.3%	3.81 12.7%	3.20 10.7%
50 GeV	12.8 25.6%	25.7 51.4%	6.02 12.0%	5.48 11.0%
125 GeV	28.6 22.9%	68.1 54.4%	16.2 13.0%	12.1 9.7%
250 GeV	48.4 19.4%	145. 58.0%	33.4 13.3%	23.3 9.3%

^aIncludes $e^\pm$ from $\mu^\pm$ decay and ν 's.

^b% of incident energy.

B. Hadron Shower Structure and Angular Resolution

The longitudinal energy depositions for 10, 20, 30, 50, 125 GeV incident pions are given in Fig. 4. Lines corresponding to 10 and 30 GeV experimental results are also shown. In this energy range, where the data and Monte Carlo results overlap, the agreement between them is good. At 125 GeV the shower is calculated to be contained by the size of the calorimeter tested. This lends support to the suggestions that the size of the shower grows as the logarithm of the energy at high, as well as low energies.

The calculated integral longitudinal energy deposition is presented in Fig. 5. For low energies, the cascade is easily contained in the

ORNL-DWG 79-19479R2

Fig. 4. Longitudinal energy deposition profile.

Fig. 5. Integral energy deposition vs sampling depth for hadronic showers.

first few interaction lengths downstream of the primary interaction vertex. For higher energies, the containment of the cascade also occurs rapidly. At 125 GeV the shower appears contained ($\sim 90\%$) after about 5 interaction lengths from the vertex.

The projected lateral shower distribution to the X-Z plane can be described by

$$I(X) = \sum_{j=1}^{12} Q(X, z_j) \quad (4)$$

where $Q(X, z_j)$ is the collected charge at position X in the z_j th segment. The lateral spread of the hadron induced cascade for 10 GeV pions is shown in Fig. 6 for the Monte Carlo histories and for the experimental data. Experimental results indicate that the full width of this distribution is 3.6 cm at 10 GeV and it increases slowly to 4.0 cm at 38 GeV. The Monte Carlo result is 4.2 cm at 10 GeV. This result is reflected in a larger calculated angular resolution at 10 GeV.

The projected shower angles were calculated using an energy weighted average over all the sections of the calorimeter downstream of the detected primary collision vertex. In order to assure consistent comparison of the angular resolutions, RMS widths were used. The calculated and experimental angular resolutions are shown in Fig. 7. These are raw resolutions; no attempt has been made to reduce them by 'road searches' or other statistical techniques. A fit to all these data gives

$$\sigma_{\theta}(E) = 15.7(\pm 1.5) + 458(\pm 27.5)/E \text{ (MRAD)} \quad (5)$$

in excellent agreement with the fit of the experimental data¹ from 10-38 GeV of

ORNL-DWG 80-18160

Fig. 6. Transverse shower distribution as a function of x for 10 GeV hadrons. a) Monte Carlo, b) Experimental Data.

Fig. 7. Comparison of angular resolution.

$$\sigma_{\theta}(E) = 16 + 433/E \quad (\text{MRAD}). \quad (6)$$

The χ^2 in all cases is ~ 1 per degree of freedom.

C. Conclusions

A computer program, CALOR, has been used to simulate data taken at Fermilab with a large segmented Fe-liquid argon hadron calorimeter. Monte Carlo histories were analyzed in the same manner as actual beam data. The data were taken in the energy range 10-38 GeV. CALOR was used to extend the energy range studied to 250 GeV. In all cases the CALOR results were consistent with the experimental data within errors. The two data sets were combined to calculate the angular resolution of this instrument from 10-250 GeV. Lower energy data were added to derive the energy resolution in the range 1-250 GeV. The general behavior of the instrument and of hadron showers was studied over this energy range. The energy resolution in the range 1-250 GeV was found to be described by

$$\frac{\sigma(E)}{E} = (33.4/\sqrt{E} + 5.07)\%$$

and is consistent with the results of the lower energy experimental data alone.

The angular resolution in the range 10-250 GeV was found to be described by

$$\sigma_{\theta}(E) = 15.7 + 458/E \quad (\text{MRAD})$$

and is in agreement with a fit to the experimental data alone (10-38 GeV). The fractional leakage from all sides of the calorimeter is calculated to be about 13%, almost independent of energy from 10-250 GeV. However, the total nuclear binding energy and hadronic energy is decreasing, while there is a corresponding increase in the electromagnetic form.

The results of this study suggest areas where further work would be useful. More information on the lateral development of hadronic showers, both from Monte Carlo studies and experiments is needed for the design of larger devices. Further work on the energy resolution at higher energies is important for high energy neutrino experiments and colliding beam experiments at the next generation of accelerators. Measurement of the fraction of energy deposited in electromagnetic and hadronic form in a hadron shower is needed to determine the asymptotic form of the energy resolution.

REFERENCES

1. A. L. Sessoms, M. S. Goodman, L. Holcomb, E. S. Sadowski, A. Strominger, B. Eisenstein, L. E. Holloway, W. T. Wroblecka, S. C. Wright and R. D. Kephart, Nucl. Instr. Methods 161, 371 (1979).
2. T. A. Gabriel, J. D. Amburgey, and B. L. Bishop, "CALOR: A Monte Carlo Program Package for the Design and Analysis of Calorimeter Systems," ORNL/TM-5619, Oak Ridge National Laboratory (1977).
3. H. W. Bertini et al., Phys. Rev. C17, 1382 (1978).
4. This localized reduction in density is necessary at higher energies (> 3 GeV) as the number of nucleons removed from the nucleus becomes large. The sequencing of the interaction events correctly in time is also included.
5. A. Strominger et al., IEEE Trans. Nucl. Sci., NS-25 (1978) p. 354.
6. This value was derived from studying the width of the noise broadened ADC pedestal in the experimental data.
7. C. W. Fabjan et al., Nucl. Instr. and Methods 141, 61 (1977).

Internal Distribution

1-2.	L. S. Abbott	17.	G. W. Westley
3.	R. G. Alsmiller, Jr.	18.	G. E. Whitesides
4.	D. E. Bartine	19.	C. Zeigler
5-6.	B. L. Bishop	20.	A. Zucker
7.	G. F. Flanagan	21.	P. Greebler (Consultant)
8-9.	T. A. Gabriel	22.	H. J. C. Kouts
(Consultant)
10.	H. Goldstein
(Consultant)	23.	W. B. Loewenstein
(Consultant)
11.	F. C. Maienschein	24.	R. Wilson (Consultant)
12.	J. B. Mankin	25-26.	Central Research Library
13.	B. F. Maskewitz	27.	ORNL Y-12 Technical Library
Document Reference Section
14.	R. W. Peelle	28-29.	Laboratory Records Dept.
15.	R. T. Santoro	30.	ORNL Patent Office
16.	C. R. Weisbin	31.	Laboratory Records - RC

External Distribution

- 32. Office of Assistant Manager for Energy Research and Development, DOE-ORO, Oak Ridge, TN 37830
- 33. M. Binkley, Fermilab, Batavia, IL 60510
- 34. R. Eisenstein, University of Illinois, Urbana, IL 61801
- 35. Dr. R. Fricken, Ofc. of High Energy & Nuclear Physics, U.S. Dept. of Energy, Washington, DC 20545
- 36-37. M. S. Goodman, Harvard University, Dept. of Physics, Cambridge, MA 02139
- 38. R. D. Kephart, Fermilab, Batavia, IL 60510
- 39. A. L. Sessoms, Harvard University, Dept. of Physics, Cambridge, MA 02139
- 40. Dr. W. A. Wallenmeyer, Ofc. of High Energy & Nuclear Physics, Division of High Energy Physics, U.S. Dept. of Energy, Washington, DC 20545
- 41. S. C. Wright, Enrico Fermi Institute, Univ. of Chicago, Chicago, IL 60637
- 42-68. Technical Information Center (TIC)
- 69-116. Given High-Energy Accelerator Shielding distribution