1 of 2

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Progress Report for the Scintillator Plate Calorimeter Subsystem*

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Introduction

This report covers the work completed in FY90 by ANL staff and those of Westinghouse STC and BICRON Corporation under subcontract to ANL towards the design of a compensating calorimeter based on the use of scintillator plate as the sensitive medium. It is presented as five task sections dealing with respectively mechanical design; simulation studies; optical system design; electronics development; development of rad hard plastic scintillator and wavelength shifter and a summary. The work carried out by the University of Tennessee under a subcontract from ANL is reported separately. Finally, as principal institution with responsibility for the overall management of this subsystem effort, the summary here reports the conclusions resulting from the work of the collaboration and their impact on our proposed direction of effort in FY91. This proposal, for obvious reasons is given separately.

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SECTION 1A.

MECHANICAL DESIGN OF THE SCINTILLATING PLATE CALORIMETER SUBSYSTEM

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A) Introduction

The calorimeter for an SSC general purpose detector should ideally have good energy resolution, fast time response, fine segmentation, and a high degree of hermeticity. For many SSC detector designs, the calorimeter is located outside a solenoidal magnet and tracking chambers, and weighs thousands of tons. The challenge is to develop a mechanical design that meets the goals stated above, is self-supporting with minimal structural elements (especially in the electromagnetic section), and is of modest cost.

The work for this subsystem is focussed on compensating scintillator plate calorimeters. It is expected that a sampling calorimeter with alternating "plates" of high-Z absorber (lead, tungsten, depleted uranium) and plastic scintillator can be made compensating ($e/h = 1.00$) by the proper choice of thicknesses of the plates. This expectation is based on various experimental tests and on simulation studies. It is not clear that a steel-plastic

scintillator calorimeter could achieve compensation. Thus, steel has not been considered as the absorber in these mechanical designs. Likewise, the cost of pure tungsten as the absorber has removed it from consideration.

Two conceptual designs have been pursued for this subsystem. One is based on lead as the absorber, fiber readout, and separate electromagnetic (EMC) and hadronic (HAC) sections. This allows replacement of scintillator and/or fibers if radiation damage effects become too large. The barrel calorimeter support is taken to be from the "bottom" only. The other design is based on depleted uranium as the absorber, wavelength shifter (WLS) plate readout, nonseparable EMC and HAC sections, and a radial support of the barrel calorimeter from the muon iron.

A number of guidelines were developed for these two designs.

- 1) The calorimeter is separated into towers with three longitudinal sections each - one electromagnetic ($25 X_0$), and two hadronic (HACI, HACII).
- 2) The HACI and HACII sections are approximately projective, whereas the EMC section is rotated 8° from purely radial. This reduces the effect of Cerenkov light in the fibers or WLS plates.
- 3) The total absorber thickness is a minimum of 9λ in the barrel and 11λ in the endcaps.
- 4) The solenoidal magnet is inside the calorimeters permitting a minimum inside diameter of the barrel to be 450 cm.
- 5) The scintillator plates are approximately $11 \times 11 \text{ cm}^2$ at the inside diameter of the barrel. The plates are parallel to the solenoidal axis in the barrel calorimeter and approximately perpendicular to the axis in the endcap calorimeter. These dimensions correspond roughly to $\Delta\eta = 0.05$ and $\Delta\phi = 0.05$.

- 6) A 12" thick iron cylinder outside HACII is present for magnetic flux return and phototube shielding in the barrel calorimeter, and 1.0 m in the endcap calorimeter. It may be used as a structural element.
- 7) Deflections from gravity loads should be minimized (≤ 0.7 cm). In magnetizeable steel, such deflections could lead to sizeable forces on the solenoidal magnet coils. Also, the solenoidal magnet and central tracking detectors may be supported from the calorimeter with tight tolerances. Finally, "cracks" in the calorimeter active volume may occur at the boundary between the barrel and endcap calorimeter sections.
- 8) Structural material inside the EMC should be minimized.
- 9) Scintillator plates, WLS plates, and fibers should not be compressed.
- 10) Calorimeter modules should be of transportable size and weight.
- 11) The materials used in the design must withstand ≥ 10 Mrad over a ten year period.
- 12) Thermal effects should be considered. Temperature changes of 30-40°C may occur during shipping.
- 13) For the conceptual designs, a scintillator thickness of 2.5 mm and depleted uranium thickness of 3.3 mm was assumed to be compensating ($e/h = 1.00 \pm 0.05$). Similarly, 2.5 mm scintillator and 10.0 mm lead in the HAC sections was assumed to be compensating. However, 5.0 mm lead was assumed in the EMC to get improved energy resolution for electromagnetic showers. Simulation calculations proceeding in parallel with the mechanical design are expected to confirm that these thicknesses are approximately correct.

A zeroth order calorimeter design is shown in Figs. 1.1 and 1.2. These were used as starting points for the two conceptual designs.

B) Lead-Based Conceptual Design

Westinghouse Science and Technology Center in Pennsylvania performed most of the work on the conceptual design of a compensating calorimeter with lead absorber. Initial calculations focussed on deformation of the full barrel calorimeter under gravity loading and evaluation of stresses in the assembled barrel. An estimate of stresses within a module during assembly was also made. A study of lead materials (alloys and composite) was performed in parallel. On the combined basis of the stress calculations and materials study, a design concept for a lead calorimeter was developed. Further details on each of these topics follow.

A module shape was first selected based on designs of other calorimeters and on the evaluation of various module shapes at Argonne. The barrel is assumed formed of 64 identical wedge-shaped modules, each module two towers wide. The endcap is assumed to be formed of 16 identical pie-shaped modules, each module up to eight towers wide.

B.1 Barrel Calorimeter Deformation Calculations

A finite element model was used to study deformations in the barrel calorimeter under gravity loading and to study stresses at various points within the barrel. Checks of this 2-dimensional model were performed using classical analytical calculations. The effects of the location of the barrel supports and of the coupling method between the modules were also studied with the model.

Various options for the form of the lead absorber were considered prior to the calculations of stresses and deformations. These options are illustrated in Fig. 1.3. For the barrel calorimeter, the three options were: 1) plates parallel to the axis of the barrel, 2) plates extending

radially from the axis with slots punched for the scintillator tiles, and 3) cast modules with slots. The first option appeared to require reinforcement of the plates to accommodate compressive loading in the modules (see Sec. B.6). The second option would need binding of the plates into a module and machining of the surfaces. Alignment of the slots in the plates would be quite important. These extra steps and problems in the manufacturing of the modules for option 2 were expected to lead to higher costs than casting (option 3). For the second and third options, aligned or staggered scintillator slots were possible (see Fig. 1.4), but there was too little material between aligned slots to provide adequate strength in the EMC while maintaining uniformity of response to electromagnetic showers. As a result of the previous considerations, the cast lead module option with staggered slots was adopted for further study. We are indebted to J. Freeman and G. W. Foster (Fermilab) for their suggestions to consider some of these options. Similar ideas had been evaluated earlier by the UA1 collaboration at CERN, and perhaps other groups.

Analytical calculations were performed of the barrel calorimeter to estimate the magnitude of the deflections, and to provide a verification of the finite element model. These calculations included a) lead in the HACI and HACII sections supported only at the bottom of the barrel, b) lead in the EMC section, c) the 12" steel cylinder containing a fluid with average density corresponding to the HAC lead, and d) a 6 cm thick steel cylinder containing a fluid with average density corresponding to the EMC lead. In all cases, the average density used for both the EMC and HAC calorimeter was that of an 80% lead, 20% plastic scintillator volumetric mixture. The estimated maximum deflections and the maximum tensile stress (at the bottom of the barrel) are summarized below:

	<u>Maximum Deflection</u>	<u>Maximum Stress</u>
HAC Lead	1.0 mm	750 psi
EMC Lead	15 mm	2700 psi
Outer Steel Cylinder + HAC Lead (as a fluid)	42 mm	35000 psi (in steel)
6 cm Steel Cylinder + EMC Lead (as a fluid)	70 mm	35000 psi (in steel)

In addition, estimates of the average compressional stresses at the horizontal midplane of the barrel calorimeter gave 62 psi (confirmed by ANL calculations). It was thought that such stresses might be small enough to employ pure lead in much of the calorimeter without significant creep.

Following the analytic calculations, a 2-dimensional finite element model of the barrel calorimeter was constructed (see Fig. 1.5). Half of the calorimeter was analyzed. A total of 128 elements were included - 32 modules, with each module separated into the EMC, HACI, HACII, and the steel outer cylinder. The calorimeter was assumed to be supported at the bottom and at one other angle. In all cases considered, the steel outer ring elements were taken to be coupled (for example, bolted at the inner and outer radius). The steel elasticity was taken to be isotropic, but the lead elasticity was anisotropic to allow for the slots in the lead to accept the scintillator tiles.

Several cases were considered; four are of primary interest for calculations of deflections. The maximum deflection, maximum stress, and method of connecting or "joining" of the elements between adjacent modules are summarized below. The elements could be coupled or bolted together; linked radially, such as with a dowel pin, but still allowed to move apart forming a gap; or "open", so that they could move apart, or deform and be at a different

radius from the element in the adjacent module. The elements are not allowed to overlap, and the connections between elements within a module are assumed to be coupled or bolted. In all four cases, the barrel supports were taken to be located at 0° , or the bottom of the calorimeter, and at $\pm 28^\circ$.

<u>Case</u>	<u>C₂</u>	<u>C₄</u>	<u>C₅</u>	<u>C₆</u>
Inter-module Connection				
EMC inner radius	Coupled	Open	Open	Open
EMC/HACI interface	Coupled	Linked	Open	Linked
HACI/HACII interface	Coupled	Open	Open	Linked
Maximum Deflection	2.5 mm	12.6 mm	14.0 mm	3.6 mm
Peak Stress		11,000 psi	10,000 psi	32,500 psi

The peak stress includes a correction that increases the calculated maximum stress by a factor to account for the slots in the lead for the scintillator tiles. Local stresses at slot corners, etc. were not included in this global barrel calorimeter model. The stress pattern in the lead for case C5 is shown in Fig. 1.6.

The conclusions drawn from these calculations are 1) the computed deflections are close to the desired limits. In particular, case C6 has a maximum deflection about half the limit suggested in guideline # 7. 2) All peak stresses are above the yield strength of pure lead or lead alloys. The need for lead composites is evident. Note that "room temperature" creep in the lead or lead alloys occurs at stresses above roughly 1000-3000 psi, an order of magnitude below the computed peak stresses in cases C4, C5, and C6.

Finally, 3) the expected increase of peak stress with decrease in maximum deflection is observed.

B.2) Deformation of the Barrel as a Function of the Location of the Supports

The same finite element model was used to evaluate the maximum deflection as a function of the support angles. In these calculations, three supports were assumed - one at 0° or the bottom of the barrel, and the others at $\pm \theta$. Curves showing the computed radial displacement at the inner bore of the barrel as a function of the azimuthal angle are given in Fig. 1.7. These curves correspond to different θ for case C5, and typically show the maximum displacement at the top of the barrel.

Figure 1.8 shows the maximum deflection as a function of the support angle θ for cases C2 and C5. The deflection is significantly reduced with increasing θ . On the other hand, constraints from the location of the muon chambers and muon iron suggest possible limits to θ of about 30° (see Fig. 1.9). Therefore calculations performed for section B.1 above used $\theta = 28^\circ$ as a realistic support angle. The detailed design of the barrel support has not yet been performed, and therefore the size is not known.

B.3 Barrel Calorimeter Module Design

Both analytical and finite element calculations were performed for the design of a barrel module. Composites of lead and either nonmagnetic steel or tungsten have been considered in a "rebar-type" design. These calculations are continuing at present.

Two simple analytical calculations were performed for a module. One assumed the lead in the hadron section of the module was homogeneous and isotropic, with support from the 12" outer steel only. With the module horizontal, a peak tensile stress of 210 lb/in^2 was computed. This estimate was

expected to be subject to significant concentration factors resulting from the slots for the scintillator tiles. A second calculation was performed for a horizontal module supported at the inner and outer radius only. This would occur for example during shipping or handling for installation. The scintillator slots were approximated by considering the module to be plates at the inner and outer radius, with plates connecting them. The connecting plates were assumed to be lead with a thickness equal to the web thickness between towers (≈ 4.8 mm). The maximum stress was computed to be approximately 6000 lb/in^2 , significantly more than could be accommodated by pure lead or a lead alloy. In this case too, additional concentration factors might increase the estimated stress.

Once it was clear that a pure lead or lead alloy hadronic module could not withstand the stresses, a modified "rebar-type" module design was considered. This design has nonmagnetic stainless steel reinforcing plates at the EMC/HACI and at the HACI/HACII interfaces, in addition to the 12" thick outer steel plate; see Fig. 1.10. Initially a tungsten or iron fiber mesh was also included. It was envisioned that the plates and fiber would be assembled first, and then the lead would be cast with slots for the scintillator tiles. The fiber mesh/lead composite would need to be optimized to achieve the required strength with a minimum of fiber mesh and of inhomogeneity in the module. This optimization was begun with a "wire-frame" finite element model of the module as shown in Fig. 1.11. It is a 3-dimensional model with three plates (# 1, 14, 27) and 24 wire elements.

An alternate module design is illustrated in Fig. 1.12 with thin nonmagnetic steel plates separating adjacent towers. The plates may have material removed as "cutouts". Work is proceeding to model the performance of such a module design. Input forces will be taken from the global calorimeter

model described in Section B.1. Stresses in the plates will be evaluated to determine approximate dimensions. The response of the new module design to external forces will then be characterized by finite element calculations. The computed module response will be incorporated back into the full barrel model to reevaluate deflections and stresses. It is planned to verify the calculations by constructing small reinforced lead composite structures and measuring the response to various forces.

B.4 Fiber Routing in the Hadron Calorimeter Barrel Modules

The present conceptual design for the lead absorber and fiber readout calorimeter assumes the fiber is embedded in a groove in the scintillator tile (see Fig. 1.13). The precise path is currently under study. Both ends of the fiber are taken out of the tile and routed to the outside of the barrel calorimeter. The fiber diameter is 0.7 or 1.0 mm, and the minimum radius of curvature is approximately 2 cm.

Three fiber routing schemes were considered: radial, axial, and projective. The radial routing scheme gives the shortest paths to exit from the barrel calorimeter for over 80% of the fibers. However, there are significant problems associated with the proper bundling of the fibers at the outside of the barrel for the projective towers if pure radial routing is used. Axial routing (along the beam direction) will presumably be used for the EMC section of the barrel, and could conceivably also be employed for the HACI and HACII sections. There are also problems in this case with proper bundling of the fibers and with the longer average path length to reach the photodetectors. The average fiber path length for the projective routing is between the average radial and axial path lengths. Note that greater path lengths lead to

larger dead spaces in the calorimeter and higher light attenuation in the fibers.

The projective routing scheme was adopted for the conceptual design as a compromise between longer path length and easier assembly. It is presently envisioned that many scintillators for a single tower would be assembled in a "harness" with the fibers properly arranged and attached together. All the scintillator tiles from the harness would be inserted into the slots in the lead automatically to reduce assembly costs and time. This appears to require the fibers to exit from the scintillator tile tangentially and then to be bent perpendicular to the tile, as shown in Fig. 1.13. The fibers would be arranged in layers, in somewhat the same fashion as wavelength shifter plates (Fig. 1.14). The total HACI and HACII tower readout would consist of 280 fibers from 140 scintillator tiles arranged in five layers for a total thickness of ~ 3.5 mm at the outside of the barrel. For this design, at least 25% of the lead and steel surfaces would be available to be in contact with the material from the adjacent module. This permits loads to be transferred from module to module as assumed in Section B.1.

The fibers would exit from the barrel calorimeter through the 12" outer steel ring at the edges of the modules, and be arranged into two approximately circular bundles. The bundles would correspond to the HACI and HACII sections. The bundle diameters would be about 12.4 mm for 1.0 mm diameter fibers, and each bundle would be attached to a photodetector. The flexibility of the fibers would permit some or all of the photodetectors to be mounted at some distance from the towers. Thus it might be possible to minimize the distance between the muon chambers and the barrel calorimeter, while having access to all the photodetectors.

A scheme was also developed to reduce the number of fibers, and hence the cost, by reading out more than one scintillator tile in series (see Fig. 1.15). Some additional dead space results for more than two tiles in series, but this is compensated by the savings in space from the reduced number of fibers. It is not clear that the series readout scheme will be acceptable, since the time response of the calorimeter will be degraded.

B.5 Endcap Conceptual Design

Some work was begun on the design of the endcap calorimeter. For physics and cost reasons, it was attempted to maintain the projective towers in the HACI and HACII sections. The total absorber thickness was taken to be 11λ , instead of 9λ in the barrel, and the outer steel flux return was assumed to be 1.0 m thick (see Fig. 1.16).

There was a concern that the center of gravity of the endcap might be inside of the 1.0 m steel, requiring the endcap to be cantilevered. An approximate calculation showed that the combined center of gravity for the lead and steel was close to the interface of the HACII/outer steel for the largest angle towers. Hence, the endcap could be supported in a stable fashion from the steel. For safety, the endcap could be installed with additional counterweight outside the steel flux return. The barrel and endcap steel could be bolted together after installation, and the counterweight removed if necessary.

Preparations were made for 3-dimensional finite element calculations of the endcap as shown in Fig. 1.17 and 1.18. The starting endcap concept included pie-shaped modules with purely projective hadron towers. It is anticipated that adjustments to this design will be made, since the scintillator tile size would become too small close to the beam.

B.6 Lead Plates in a ZEUS-Style Module Design

Some analytical calculations were performed assuming lead plates parallel to the barrel axis (as in Fig. 1.3) in a ZEUS-Style design. These calculations complemented the results from the conceptual design for depleted uranium absorber in Sec. C. It was assumed that the lead plates were compressed with aluminum spacers. The scintillator tiles fit between the spacers.

One calculation considered a horizontal module supported only at the inner and outer barrel radius. The bending stress due to gravity at the module center of gravity was computed to be 177 lb/in^2 and the maximum compressive stress at the lead absorber/spacer interface was estimated to be approximately $11,600 \text{ lb/in}^2$, including preload and bending stresses.

A second calculation considered a horizontal module cantilevered from the outer 12" steel. In this case the bending stress at the module outer diameter was 210 lb/in^2 , and the maximum compressive stress at the lead absorber/spacer interface was approximately $16,900 \text{ lb/in}^2$.

In both cases, the computed stresses are far higher than can be achieved with pure lead or lead alloy plates. It is thought that these stresses can be handled with a composite lead plate with steel reinforcement at high stress areas. This would lead to nonhomogeneous absorber plates.

B.7 Cost Estimate for the Lead and Steel in the Barrel Calorimeter

A very rough cost estimate for some of the materials in the barrel calorimeter was performed by an Argonne physicist. Using 3.8 mm slots, 5 mm lead in the EMC and 10 mm lead in the HAC sections of the barrel calorimeter, the total volume of lead is approximately $3.1 \times 10^8 \text{ cm}^3$, or the total weight is ~ 3900 tons. The general barrel shape is shown in Fig. 1.16, but the

dimensions are slightly different. The reinforcing fiber mesh and plates were ignored in this estimate. Likewise, the total volume of the outer 12" steel, assuming it is in the form of a right circular cylinder, is approximately $1.2 \times 10^8 \text{ cm}^3$ and the total weight is ~ 1070 tons. At costs of \$1.75 and \$0.50 per pound of lead and steel, respectively, the total costs of these materials will be \$ 13.7M and \$1.1M. These values are summarized in the following table.

<u>Material</u>	<u>Cost</u>	<u>Total Cost</u>
3900 tons lead	\$1.75/lb.	\$13.7M
1070 tons steel	\$0.50/lb.	<u>\$ 1.1M</u>
		\$14.8M

The total volume of plastic scintillator was estimated to be $0.9 \times 10^8 \text{ cm}^3$ and the area ~ $3.6 \times 10^8 \text{ cm}^2$ for a 2.5 mm thickness. The total length of clear acrylic fiber was estimated to be 6210 km for the separable EMC section, but only 5050 km if the EMC is integral and all fibers are routed projectively. The total length of WLS fiber embedded in the plastic scintillator is roughly 500 km. Costs for machining, shipping and handling, labor for assembly, fibers, scintillator, photodetectors, supports, electronics, inflation, contingency, etc. are not included in the value above.

C) Depleted Uranium - Based Conceptual Design

Most of the calculations for the depleted uranium (DU) absorber, wavelength shifter (WLS) plate readout calorimeter were performed by personnel in the Argonne National Laboratory High Energy Physics Division. Some of the

work was based on previous experience with the design and construction of the depleted uranium barrel calorimeter for the ZEUS detector at HERA.

The initial work concentrated on evaluating various module design alternatives for the barrel calorimeter. The EMC and HAC sections were assumed integral, with the HAC towers projective and the EMC sections tilted at $\sim 8^\circ$ (see Fig. 1.2). The 8° tilt led to an evaluation of different schemes to construct the EMC section and to difficulties with the mechanical design. As a result, "bulkheads" will probably be required on the module ends. A partial solution to the problem of cracks caused by the bulkheads was developed. Finite element calculations of a module and of the full barrel calorimeter were performed to evaluate stresses and deflections. Finally, a radial support scheme for the barrel calorimeter from the muon iron surrounding the barrel was evaluated. Details of these studies follow.

C.1) Conceptual Design for Barrel Calorimeter Modules

The barrel calorimeter with the short magnet coil was assumed to have 128 towers in ϕ and approximately 60 towers in η ($\Delta\phi \approx 0.05$, $\Delta\eta \approx 0.05$). Nonprojective towers that could permit a simple and cheap "flat-washer" module design (see Fig. 1.19) were not considered because of shower localization and trigger problems. Similarly, a "projective-washer" module design as in Fig. 1.20 with one tower in η and 128 towers in ϕ was rejected. Such a module was too heavy (> 80 tons), too large to be easily transportable (~ 10 m diameter), and would contain many small DU plates which would increase the total calorimeter cost. Although the absorber plates could be made perpendicular to a line through the intersection point, a varying amount of absorber would be required before the first scintillator tile. This material would be necessary to avoid a "sawtooth" inner surface to the EMC and to transfer stresses

between modules. However, either solution (sawtooth surface or varying material) was expected to significantly degrade the electromagnetic energy resolution.

Therefore, modules two towers wide in ϕ and many towers along η were chosen for the conceptual design. In this case, the WLS plates are located on the outside surfaces of the modules, giving a one-sided readout of the scintillator tiles. The full barrel calorimeter with the short magnet coil was estimated to weigh ~ 5000 tons. Without longitudinal segmentation of the modules, their weight would be ~ 78 tons each. In order to keep the module weight at less than 30 tons, it was concluded that there should be three longitudinal (η) segments. Note that there are manufacturing advantages to having only two, identical longitudinal barrel segments.

The boundaries to the longitudinal segments could be either projective (Fig. 1.21) or nonprojective (Fig. 1.22). A disadvantage of projective boundaries is the projective crack which would significantly affect the calorimeter response, especially if structural material was required on the module ends. The disadvantage of nonprojective boundaries is related to the readout. As seen in Fig. 1.22, the segment boundaries would intersect a number of towers. Additional WLS plates would be needed to read out the partial EMC or HAC sections at the boundaries, resulting in more dead space in the calorimeter. Such problems would be reduced with fiber readout. However, additional photodetectors and electronics channels would be required for either readout, contributing added cost and trigger complexity.

Projective boundaries to the longitudinal barrel segments were chosen for the conceptual design. To minimize the impact of the projective boundary cracks, the towers are made slightly nonprojective in η . In the present design, the seven hadron towers in η centered on $\eta = 0$ are made to project

perpendicular to the beamline (like the flat-washer solution). The remaining hadron towers project to a point on the beamline approximately ± 39 cm away from the intersection point. Similarly, the segment boundaries project to these points. A straight line from the true intersection point crosses $\sim 1.25 - 2.0$ towers in the barrel calorimeter for essentially all towers with $\eta \neq 0$ in the scheme described above (see Fig. 1.21).

C.2 Calculations of Stresses and Deflections in a Barrel Module

For the analysis of a barrel module, a series of 2-dimensional finite element calculations were performed in addition to analytic computations of deflections. It was initially assumed that the final design would be similar to the ZEUS module design. The DU plates are assumed to be under compression with aluminum spacers between the plates. (For some early calculations, the scintillator tiles were assumed to be compressed between the DU plates.) The compression is provided by the combination of an inner aluminum or steel plate, a center steel tension plate to provide added stability, an intermediate steel plate at the HACI/HACII interface, thin steel skins, and a thick outer steel plate at the outer diameter of the barrel calorimeter. The conceptual module design is shown in Fig. 1.23.

Several classical analytic calculations were performed for the barrel module. For the first, the module was assumed to be vertical, such as during assembly and transportation. In this case, the three steel plates act as cantilevered beams. Maximum deflections for various thicknesses and materials for the inner plate are tabulated below. It is assumed that the entire load from the DU plates is uniformly distributed across the inner plate. In all cases, 1.6 mm thick steel skins were assumed.

<u>Inner Plate Thickness</u>	<u>Steel</u>		<u>Aluminum</u>	
	<u>Without Skins</u>	<u>With Skins</u>	<u>Without Skins</u>	<u>With Skins</u>
12.7 mm	0.4 mm	< 0.1 mm	1.2 mm	< 0.1 mm
19.0 mm	0.1 mm	< 0.1 mm	0.3 mm	< 0.1 mm

For the second analytic calculation, the module was assumed to be horizontal. It was shown that an untensioned steel plate could not support the weight of a module unless it was very thick. When the plate was prestressed at the supporting edges, the deflections become manageable for thin plates. The calculations assumed the plate had the dimensions of the central tension plate, was supported only at the two ends and had the module weight uniformly distributed along the plate. For a 6.35 mm thick steel center plate tensioned to 40,000 psi, the maximum deflection was estimated to be 16 mm. With the addition of two 1.6 mm thick steel skins tensioned to 20,000 psi each, the maximum deflection was very small. However, without adequate precautions the skins could cause pressure on the WLS plates. Thus it was hoped that these skins would not be required except for purposes of optical isolation from the adjacent modules.

A third analytical calculation treated the module as a solid block of material supported from the ends. With mechanical properties of DU, the resulting total deflection was < 0.1 mm. This provides a lower limit to the expected deflection.

Several finite element model calculations of a barrel module were also performed. One model consisted of beam elements with dimensions as shown in Fig. 1.24. The module was vertical and suspended at the top and center of the T-beam. The inner, intermediate, and outer steel plates were connected with non-compressible elements to share the load. The weight of the module was

applied uniformly across the bottom or inner plate. The maximum deflection was calculated to be 0.04 mm and the maximum bending stress was 5800 psi.

This same module model was assumed for a horizontal module. The T-beam was fixed in place at the outer ring, and supported at either the inner plate or both the inner and intermediate plates (Fig. 1.25). The center plate was uniformly loaded with a pressure equal to the weight of the module. The deflections were calculated to be 0.9 and 0.3 mm for the case of two and three supporting plates, respectively, which are quite manageable.

Another simple 2-dimensional finite element model of a barrel calorimeter was also used to compute stresses and deflections. No intermediate plate was assumed, and the inner plate was taken to be aluminum. Thus the deflections were higher than for one of the previous module finite element calculations. The module was assumed to be vertical with the inner plate at the bottom to maximize the stresses. The center plate was taken to be 6.35 mm thick, the outer plate 38.1 mm = 1.5" thick, and the skins each 1.6 mm thick. The model consisted of 53 plate elements and 46 nodes, and it assumed pressure on the inner and outer plates to produce a total tension of 3100 lb. in the center plate. The module weight was assumed to be uniformly distributed across the inner aluminum plate, adding to the pressure from the center plate tensioning. The results are tabulated below. Note that additional concentration factors, in areas such as near the spacers between the DU plates, might increase the estimated stresses.

<u>Case</u>	<u>Inner Plate Maximum Deflection</u>	<u>Inner Plate Maximum Stress</u>
19.0 mm inner plate, with skins	0.28 mm	16,400 psi
12.7 mm inner plate, with skins	0.48 mm	29,600 psi
19.0 mm inner plate, without skins	1.22 mm	39,200 psi
12.7 mm inner plate, without skins	4.14 mm	88,500 psi

The conclusions drawn from these calculations are: 1) the skins are essential to reduce deflections and stresses to acceptable levels when using thin aluminum inner plates. 2) an inner plate thickness ≥ 13 mm aluminum is required. Note that the inner plate is actually located at the EMC/HAC I interface, since most of the module weight is in the HAC sections. The EMC section could then be attached to the rest of the module with significantly less material inside of the first EMC scintillator tile. 3) An inner steel plate of thickness ~ 13 -19 mm may be adequate without tensioned skins.

C.3 Finite Element Analysis of the Barrel Calorimeter

Following the analysis of a single barrel module described in the previous section, a 2-dimensional model of the fully assembled barrel calorimeter with DU absorber was evaluated for stresses and deflections. This model is similar to the one developed for the lead conceptual design (see Section B.1). The barrel consists of a 19 mm thick inner steel ring, a solid stack of compressed DU plates with scintillator tiles forming HACI, a 16 mm thick steel intermediate ring, another stack of DU and scintillator for HACII, and a 12" thick steel outer ring (see Fig. 1.26). The DU absorber/scintillator stacks were assumed to be solid anisotropic bodies. The three steel rings could be used to transfer loads to adjacent modules. A gap was required between DU/scintillator stacks to avoid crushing the WLS plate.

The single module was represented by a total of 4×13 plate elements. The inner and outer rings consisted of 4×2 elements, the intermediate ring of 4×1 elements, and the HACI and HACII of 4×4 elements each. The module was rotated around the beam axis to form the barrel as shown in Fig. 1.27, with each ring connected or bolted together, and with gaps at HACI and HACII as shown in Fig. 1.26.

Several cases corresponding to different supports were evaluated. These included a single support at the bottom of the barrel, a "saddle" or "cradle" extending $\pm 30^\circ$ from the bottom, and saddles at both the top and bottom extending $\pm 22.5^\circ$ and $\pm 28.1^\circ$. The results are tabulated below. Additional concentration factors may apply near the aluminum spacers.

<u>Case</u>	<u>Maximum Displacement</u>	<u>Maximum Stress</u>
Support at Bottom Only	0.76 mm	8700 psi
$\pm 30^\circ$ Saddle at Bottom	0.41 mm	7000 psi
$\pm 22.5^\circ$ Saddles at Top and Bottom	0.08 mm	1100 psi
$\pm 28.1^\circ$ Saddles at Top and Bottom	0.05 mm	900 psi

Deflections with the model with $\pm 22.5^\circ$ saddles on top and bottom are shown in Fig. 1.28. The support case with $\pm 22.5^\circ$ saddle(s) is convenient because the muon iron outside the barrel is expected to be octagonal, which naturally gives rise to a $\pm 22.5^\circ$ angle (see Fig. 1.9). The supports could be in the form of discrete rails extending across the length of the barrel.

Finally, with changes in the mechanical constants for the materials and in the dimensions, this model is also applicable to a cast lead barrel calorimeter. Cross checks with the Westinghouse model in Section B.1 gave reasonable agreement of stresses, for example. Another check of the finite element model was also performed for a steel ring with inside diameter 5.08 m, outside diameter 10.16 m, and thickness 10 cm. The ring was supported at the bottom only, and the load was approximately the weight of the corresponding volume in the barrel calorimeter. Both a classical analytical calculation and the finite element model results yielded a maximum deflection at the top of the ring of 0.28 mm.

C.4 Radial Supports for the Barrel Calorimeter

Calculations for supporting the barrel calorimeter radially to the surrounding muon iron were performed. Assuming 16 supports equally spaced around the barrel (see Fig. 1.29), and 30 supports along the barrel axis, the estimated loads in each support ranged up to ~ 100,000 lb. at the barrel top. If the radial supports were in the form of turnbuckles, and a safety factor of 2.0 is assumed, the turnbuckle diameter would be 7 cm. The difficulty is accessing the turnbuckles for adjustment and the large computed size eliminated this method as a viable scheme for the full support of the barrel calorimeter. However, there may be need for such radial support to complement other support methods.

C.5) The EMC Section of the Barrel Calorimeter

In order to eliminate radially projective cracks (cracks occurring at constant ϕ), the ZEUS barrel calorimeter has the modules rotated slightly as seen in Fig. 1.30. Relatively thick endplates or bulkheads, approximately 6 cm of aluminum and steel, are used to help support the loads on the modules. The inner surface of the EMC is sawtoothed. In contrast, the SSC subsystem conceptual designs have HAC towers that are projective in ϕ , and the EMC sections are rotated ~ 8°. However, the EMC scintillator tiles are not tilted in order to avoid the sawtooth problem. (The 8° rotation was shown to be approximately optimum in ZEUS studies.)

Various options to construct the EMC barrel calorimeter from DU plates were considered. Radial DU plates with punched slots, as in Fig. 1.3, were rejected for several reasons. For compensation, the DU thickness was assumed to be 3.3 mm and the scintillator thickness 2.5 mm. However, allowing for the optical mask, wrapping and cushioning around the scintillator tile, and for

mechanical tolerances, the slot width was estimated to be ~ 4.2 mm. Thus the slot is wider than the DU "plate". As a consequence, staggering the slots does not significantly improve the problem of too little material between slots compared to aligned slots (see Fig. 1.31). Compared to the case with plates parallel to the barrel axis, additional costs result from A) the much larger amount of DU that must be processed into sheets, B) punching of the precision slots, and C) machining the finished module to give smooth sides.

A number of options with plates parallel to the barrel axis were also considered. DU plates with staggered overlapping edges (Fig. 1.32) was rejected as an option because maintaining the correct overlap and keeping plates in position during assembly would be difficult. Costs associated with the larger number of DU plates would also be higher. Another possible option was to compress the scintillator between long DU plates, which violates guideline # 9. Tests of the effects of compressive loading on scintillator are being prepared, but no results have been obtained so far; see Section C.6. The option chosen for the conceptual design was similar to that in ZEUS - long DU plates, parallel to the barrel axis, separated by aluminum spacers. Considerable practical experience with this option exists and the problems are well known and understood.

The $\sim 8^\circ$ tilt to the EMC section introduces a number of problems, primarily related to the compression of the plates and to the width of the WLS plate. In one design under consideration, steel skins and the center plate are used to compress the full module as shown in Fig. 1.33. On the sides of the module, spacers and bolts attach the skins to the plate between the EMC and HADI sections, causing a reduction in the width of the WLS plates from the EMC. The EMC plates are not compressed in a direction normal to their surfaces, rather at $\sim 8^\circ$ to the normal. This causes a force parallel to the

plate surface, in addition to loads from plate weight and from adjacent modules. These loads are opposed by frictional forces and by bulkheads on the module ends and perhaps within the EMC section. In a second design, thin straps that follow the tower boundaries and pass through slots in the DU plates (Fig. 1.34) provide compression in the EMC section. Compression for the HAC section is provided by the center plate and by skins bolted to the plate between the EMC and HACI sections, also reducing the width of the EMC WLS plates. In both designs, the center tension plate extends through the HAC sections only, to minimize structural material in the EMC, and the EMC WLS plates have an 8° bend.

The number of straps required to adequately support the EMC depends on the weight of the EMC and the coefficient of friction (μ) between the DU plates and the aluminum spacers. The coefficient of friction was measured in ZEUS to be $\mu \approx 0.2$, but a value of $\mu = 0.1$ is used in calculations for safety. The present design assumes two steel straps per tower, each tensioned to 12,000 psi. The strap cross sectional area would be 0.5 mm x 25.4 mm. The minimum thickness and number of bulkheads and the minimum thickness of the plate at the front of the EMC have not yet been determined.

C.6 Compression Tests on Scintillator

In some mechanical designs with a stack of absorber plates and scintillator tiles, there are advantages in compressing the stack without spacers between the absorber plates. For example, local stresses in the plates are decreased. The fiducial volume is increased when spacers are eliminated. There is also the possibility in some lead absorber calorimeter designs that local stresses may cause the lead to creep, resulting in compression of the scintillator tiles.

As a result of these considerations, a fixture has been designed and is under construction at Argonne that will allow measurements of the effects of compression on the light output from plastic scintillator. It is planned to have several short stacks of scintillator and absorber. One stack would serve as a control. Another would be used for rapid compression or slow compression studies, and another for compression of irradiated scintillator tiles, etc. The scintillators will be viewed with photomultipliers and the pulse height recorded in Argonne designed ADC's. Calibrations will be performed with cosmic rays and/or a laser. It is expected that the compression tests will begin soon.

C.7) Costs of Depleted Uranium, Steel, and Scintillator for the Barrel Calorimeter

Volumes of DU, steel, WLS plates, and scintillator were computed using similar assumptions as for the lead design. Volumes were $1.2 \times 10^8 \text{ cm}^3$ steel and $1.9 \times 10^8 \text{ cm}^3$ DU. The costs are summarized in the following table.

<u>Material</u>	<u>Cost</u>	<u>Total Cost</u>
4000 tons DU	\$6.00/lb.	\$48.0M
1050 tons steel	\$0.50/lb.	<u>\$ 1.1M</u>
		\$59.1M

The estimated areas for scintillator were $5.7 \times 10^8 \text{ cm}^2$ and for WLS plates $7.1 \times 10^7 \text{ cm}^2$. Costs for machining, shipping and handling, labor for assembly, WLS plates, scintillator, photodetectors, supports, electronics, inflation, contingency, etc. are not included in the value above.

D) Summary

A summary of the conclusions from mechanical design studies of lead and depleted uranium absorber calorimeters follows. Several unanswered questions remain, and some of these will be addressed in future work.

- 1) Pure lead or lead alloys will not work as the absorber for the hadron section of the barrel calorimeter. Stresses are too high for either lead plates or cast lead modules. Lead composites, reinforced with steel, tungsten or some other material will be required. Consequently, the absorber will be inhomogeneous (see Figs. 1.10 and 1.12). It is not yet clear whether composites will be necessary in the EMC.
- 2) For the hadron calorimeter, casting lead in a steel frame with steel reinforcing and with staggered slots appears most economical. The slots can be cast around teflon or plastic forms. It has not yet been established that the slot thicknesses or the slot spacings can be made sufficiently uniform so they do not limit the calorimeter energy resolution. Likewise, the impact of staggered slots on the EMC performance must be studied.
- 3) A calorimeter design with DU absorber and WLS plate readout, similar to ZEUS, seems to work acceptably. However, the DU processing costs and the poor fiducial volume resulting from the WLS plates are primary problems of this design compared to the design with fiber readout and lead absorber.
- 4) A variety of schemes to take advantage of the small size and good flexibility of the fibers exist. The lead absorber design shows reduced cracks between modules with the use of fibers. The photodetector location can be more accessible with fibers than with

WLS plate readout. A scheme for reading multiple scintillator tiles in series has also been developed. However, it has not yet been established whether the routing method in Figs. 1.13 and 1.14 will permit a sufficiently uniform response in the scintillator tiles, or whether the fibers can withstand the radiation doses almost everywhere in the calorimeter.

- 5) Having the EMC modules separate from the HAC modules will probably reduce the size of cracks in the EMC, while also minimizing material inside the first EMC scintillator layer. The EMC modules do not necessarily need to be removable. Fiber readout would be required.
- 6) The hadron section of the barrel calorimeter modules are similar for the two conceptual designs studied. Both designs have evolved toward a module that is two towers wide in ϕ and many towers long in η (Figs. 1.10, 1.12, 1.23). Both contain intermediate steel reinforcing plates and both utilize the outer 12" steel for structural strength as well as magnetic flux return and shielding for the photodetectors.
- 7) The barrel calorimeter will need to be in two or more sections longitudinally for the modules to be easily transportable. For three longitudinal sections, a scheme exists to reduce the effects of cracks and structural material at the ends of the modules. This involves hadron towers that are quasiprojective in η (see Section C.1).
- 8) There are problems for supporting the barrel calorimeter. Pure radial supports (Section C.4) take up too much space and will be difficult to access and adjust within the muon iron. Cradle or

saddle supports from the bottom restrict the muon coverage asymmetrically.

- 9) The endcap towers probably can be projective. The endcap may not need to be cantilevered from the support on the bottom of the attached 1.0 m muon iron and flux return. However, more work is needed to develop a good endcap conceptual design.
- 10) Although very rough cost estimates for some parts of the two calorimeter conceptual designs exist (Sections B.7 and C.7), much more detailed costing is required.

The subsystem collaboration met on 20-22 August 1990 to review progress on the mechanical design, material studies, simulation, etc. Based on the work presented, it was concluded that the lead absorber design should be pursued further. The primary motivations were cost and time response of lead compared to DU as the absorber from simulation calculations. Fiber readout was adopted because of its many advantages compared to WLS plates. However, it was also concluded that there are many similarities in the two conceptual designs. Thus WLS plate readout is considered a "backup option" should a serious problem appear with fiber readout. Similarly, DU or steel may be considered in case the lead absorber design encounters serious problems.

FIGURE CAPTIONS

- Figure 1.1 Starting design for the calorimeter showing projective towers and a "short" magnet coil inside the barrel calorimeter.
- Figure 1.2 Cross sectional view through the barrel calorimeter. The hadronic towers are projective, while the electromagnetic towers are tilted at approximately 8° .
- Figure 1.3 Options considered for the form of the lead absorber. Lower right-plates parallel to the barrel axis. Middle-radial plates with punched slots. Top-cast module with slots.
- Figure 1.4 Staggered (left) or aligned (right) slots for the scintillator tiles in a cast module or a module with radial plates.
- Figure 1.5 Description of the 2-dimensional finite element model for the barrel calorimeter.
- Figure 1.6 Stress pattern for case C5 in the barrel calorimeter lead from a two-dimensional finite element model.
- Figure 1.7 Curves showing computed radial displacement as a function of angle (0° = bottom, 180° = top) in the barrel calorimeter. The curves are labeled with the angles of the supports. All curves correspond to the finite element model C5 described in the text.
- Figure 1.8 Maximum deflection in the hadron barrel calorimeter as a function of the support angle. Results for the finite element models C2 and C5, described in the text, are shown.
- Figure 1.9 Possible support locations considered for the barrel calorimeter.

- Figure 1.10 Conceptual design of a lead hadronic calorimeter barrel module showing the three iron or steel plates and the tungsten or iron fiber mesh reinforcing.
- Figure 1.11 Schematic diagram showing the 3-dimensional "wire-frame" finite element model of a lead hadronic calorimeter barrel module.
- Figure 1.12 Conceptual design of a lead hadronic calorimeter barrel module showing the outer 12" iron plate, a 16 mm steel plate between the HACI and HACII sections and a 38 mm aluminum plate between the EMC and HACI sections. Thin steel plates are present between towers for reinforcing.
- Figure 1.13 Schematic diagram of fiber routing in grooves in a scintillator tile. Two possible paths in the tile are shown. The optimum routing path is under study.
- Figure 1.14 Schematic diagram of fiber routing from a number of scintillator tiles into a readout bundle.
- Figure 1.15 Possible method of fiber readout arrangement for two or more scintillator tiles in series. For the special case of two tiles, some dead space can be saved by having the fiber on the bottom surface of the upper tile.
- Figure 1.16 Dimensions for the barrel and endcap calorimeters with the short magnet coil option. The outer steel flux return is at least 12" thick for the barrel and 1.0 m thick for the endcap. The approximate center of gravity of the endcap calorimeter is indicated.

Figures 1.17-18 Conceptual design of the endcap calorimeter.

- Figure 1.19 Conceptual design of a calorimeter with "flat washer" modules (nonprojective towers).
- Figure 1.20 Conceptual design of a calorimeter with "projective washer" barrel modules. The insert shows the inner surface of the modules. The material will be of varying thickness across the face of the tower in order to transfer loads to adjacent modules and to prevent a sawtooth inner EMC surface.
- Figure 1.21 Conceptual design of quasiprojective hadron towers and quasiprojective cracks at the ends of modules. The true intersection point is along the beamline at the far left. The seven towers centered on $\eta = 0$ have boundaries in planes perpendicular to the beamline. The boundaries of all other towers project to an offset point along the beamline as shown by the dashed lines.
- Figure 1.22 Conceptual design of a barrel calorimeter with nonprojective boundaries between sections. A number of towers are split by the boundary, requiring additional space for WLS plates or fibers and additional readout channels.
- Figure 1.23 A barrel calorimeter module cross sectional view with DU absorber and WLS plate readout. The center steel plate, inner, intermediate and outer steel plates, and the thin skins are shown. The EMC section is tilted at 8° , while the HACI and HACII sections are projective in ϕ .
- Figure 1.24 Finite element model of a DU absorber barrel calorimeter module used to study stresses and deflections in a vertical module. The model consists of beam elements corresponding to a 38 mm outer plate, a 16 mm intermediate plate, a 19 mm inner

plate, and a 6.4 mm center plate, all of steel. The ends of the inner, intermediate, and outer plates are connected with noncompressible elements. The module is supported at the center of the outer (top) plate, and the module weight is uniformly distributed across the inner plate.

- Figure 1.25 Finite element calculation of a horizontal barrel calorimeter module. The same plate dimensions are used as in the previous figure. The module is fixed at the right (outer plate), is tensioned and supported at the inner plate, and is supported at the intermediate plate. The module weight is uniformly distributed across the center plate.
- Figure 1.26 Finite element model of the full barrel calorimeter showing three adjacent modules. Only the HACI and HACII sections are included.
- Figure 1.27 Finite element model of the full barrel calorimeter with DU absorber, and WLS plate readout. The support shown is from the bottom only. Other cases were also evaluated.
- Figure 1.28 Deflection pattern in the barrel calorimeter with DU absorber from a two-dimensional finite element model. The support is from the top and bottom with a $\pm 22.5^\circ$ saddle.
- Figure 1.29 Cross sectional view through the barrel calorimeter showing the locations of the radial supports to the muon iron.
- Figure 1.30 Cross sectional view through the ZEUS barrel calorimeter, illustrating the sawtooth inner surface caused by the slightly rotated modules.

- Figure 1.31 Staggered slots for DU absorber and scintillator tiles with approximately correct relative dimensions. The slots are larger than the 2.5 mm scintillator to allow for the mask, wrapping, clearance and tolerances.
- Figure 1.32 View of flat DU plates with small overlap.
- Figure 1.33 Detailed view of the tilted EMC section and inner HADI section of a barrel calorimeter module. Thin steel skins are used to compress the EMC DU absorber plates, leading to a force tangential to the plates.
- Figure 1.34 Conceptual design of thin steel straps to compress the EMC section of a barrel calorimeter module. The straps follow tower boundaries.

Figure 1.1

Figure 1.2

LEAD CALORIMETER SUBSYSTEM

Figure 1.3

ALIGNED SLOTS

STAGGERED SLOTS

Figure 1.4

BARREL CALORIMETER FINITE ELEMENT COMPUTER ANALYSIS

Finite Element Computer Model

Description of Model

- Why Do It? Usable Classical Analysis Doesn't Exit
- Simple Two Dimensional Model
- 128 Plate Elements
- 448 Nodes
- Symmetrical About Vertical Center Plane
- Flexibility
 - Variable Support Locations
 - Variable Anisotropic Material Properties
 - Variable Loads from EMC
- Verifiable With Classical Analysis

Figure 1.5

1.5A0

ANSYS 4.4
AUG 10 1990
14:23:45
POST1 STRESS
STEP=1
ITER=10
SIGE (HUG)
DMX =0.013986
SMN =52475
SMX =0.618E+07

ZU =1
DIST=4.961
XF =2.255
52475
732983
0.141E+07
0.209E+07
0.277E+07
0.346E+07
0.414E+07
0.482E+07
0.550E+07
0.618E+07

Figure 1.6

LEAD CALORIMETER

INNER BORE RADIAL DISPLACEMENTS - MM

—	0° - 11.2°	0° - 22.5°	0° - 33.8°	0° - 45°
- - -	0° - 67.5°	0° - 28.1°	0° - 28.1°	0° - 61.8°

CASE 5 - UNPINNED MODULES

Figure 1.7

LOCATION FROM BOTTOM POINT - DEGREES
W STC E80 JUNE 1990

LEAD CALORIMETER

MAXIMUM DEFLECTION VS SUPPORT ANGLE

— C2
HOMOGENEOUS
FINGERS&GAPS
----- C5

Figure 1.8

CALORIMETER SUBSYSTEM PROPOSED BARREL SUPPORT BASE

Possible Support for
Locations for
Calorimeter
Subsystem

- A) 28.1° from bottom
- B) 61.9° from bottom

Figure 1.9

LEAD CALORIMETER SUBSYSTEM HAC CAST LEAD CALORIMETER MODULE COMPOSITE / REBAR STRUCTURE

Figure 1.10

CALORIMETER SUBSYSTEM LEAD ABSORBER-SCINTILLATOR-FIBER READOUT

ANSYS 4.4
AUG 6 1990
10:10:44
PLOT NO. 1
PREP7 ELEMENTS
ELEM NUM
XV = 0.56
YV = 0.6
ZV = 1
DIST = 0.897801
XF = 3.335

Figure 1.11

CALORIMETER SUBSYSTEM

LEAD ABSORBER-SCINTILLATOR-FIBER READOUT

HAC CAST LEAD CALORIMETER MODULE

CALORIMETER SUBSYSTEM FIBER READOUT ARRANGEMENT

-47-

(W) STC

Figure 1.13

CALORIMETER SUBSYSTEM

Readout Fiber Arrangement
for General Hadron Tower

(W) Mechanical Engineering

Figure 1.14

CALORIMETER SUBSYSTEM FIBER READOUT ARRANGEMENT

TOP VIEW

-49-

FIBER READOUT IN CENTRAL HAC TOWER WITH 140 TILES
1 FIBER - 2 TILE CONFIGURATION
RELIEF ADDED TO SCINT. AND ABSORBER TILES
SINGLE LAYER OF FIBERS REQUIRED FOR TOTAL TOWER

Figure 1.15

CALORIMETER SUBSYSTEM LEAD ABSORBER-SCINTILLATOR-FIBER READOUT

Figure 1.16

CALORIMETER SUBSYSTEM LEAD ABSORBER-SCINTILLATOR-FIBER READOUT

ANSYS 4.4
AUG 1 1990
11:16:37
PLOT NO. 1
PREP7 ELEMENTS
TYPE NUM
XV -0.6
ZV -1
DIST=4.221
XF -6.6
PRECISE HIDDEN

Figure 1.17

CALORIMETER SUBSYSTEM LEAD ABSORBER-SCINTILLATOR-FIBER READOUT

r_{ff}

Figure 1.18

Figure 1.19

Figure 1.20

Figure 1.21

-56-

Figure 1.12

Figure 1.23

Figure 1.24

10 DEF 10=1

10 DEF 10=1
 10 DEF 10=1
 10 DEF 10=1
 10 DEF 10=1
 10 DEF 10=1

1.5" T-BEAM
 .525" INTERMEDIATE FLARE
 .750" END FLARE
 .206" UPPER SUPPORT PREPARED TO 10 906 10.1

10 DEF 10=1
 10 DEF 10=1
 10 DEF 10=1
 10 DEF 10=1
 10 DEF 10=1

Figure 1.25

2D SSC MODULE CONSTRUCTION FOR FEA MODEL

Figure 1.26

2D SSC RING SUPPORTED AT ONE POINT

CASE 1

2D RING
OPEN MODULE CONFIGURATION
GRAVITY LOADING
LOADS TRANSFERRED ACROSS RING

Figure 1.27

GEOMETRY MESHING PROPSETS FD-CONDS DISPLAY CONTROL POST-PRO :11:55
DISP LC=1

Disp-Res

0.0029556
0.0027586
0.0025615
0.0023645
0.0021674
0.0019704
0.0017734
0.0015763
0.0013793
0.0011822
0.0009852
0.00078816
0.00059112
0.00039408
0.00019704
1E-16

Figure 1.29

Figure 1.30

Figure 1.31

Figure 1.32

Figure 1.33

Figure 1.34

SECTION 1B.

LEAD BASED CALORIMETER MATERIALS STUDY

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As part of the mechanical design studies for the lead based calorimeter, a materials study was initiated to evaluate lead based materials for implementation in the calorimeter structural design. The objectives of the study were: 1) to compare the mechanical properties of candidate materials with the mechanical loading requirements to determine acceptable materials, and 2) to analyze the cost, fabrication and manufacturing issues associated with these materials in order to determine the optimum material for the application. The mechanical requirements for the calorimeter were derived from the ongoing mechanical analysis and were updated periodically as improved designs and analyses were developed. Essentially all the work on both the mechanical design and the materials study for the lead based calorimeter was performed at the Westinghouse Science and Technology Center under subcontract from Argonne National Laboratory. The results of the study are described below. It is concluded that lead based composites are a mechanically feasible and cost effective approach to producing a lead based calorimeter.

The major issue that arises from the use of lead based absorbers in a calorimeter is the low mechanical performance of these materials. Lead is a mechanically soft and weak material. Also, because lead has a melting point of 320°C, it exhibits a time-dependent mechanical response at room

temperature. That is, at room temperature under constant load, lead will slowly deform. The loads that the calorimeter materials must withstand are determined by the materials of construction, since these forces are determined principally by the overall weight of the structure, and by loadings that are imposed to assemble the structure. Viable lead based materials would be those that exhibit elastic stiffness and time dependent strength properties that exceed the loading imposed by the calorimeter structure.

Several lead based materials were considered under the scope of this study. The materials included lead, low alloy content lead alloys, and particulate, fiber, and structurally reinforced lead composites. The following chart describes the materials considered in the study and highlights the generic advantages and disadvantages of each class of materials.

<u>Class</u>	<u>Advantages</u>	<u>Disadvantages</u>
Pure Lead	Cheap, plentiful, readily available, easily worked and fabricated, homogeneous	Mechanically soft, creeps at low temperature
Lead Alloys (low alloy content)	Improved strength and creep resistance compared to pure lead, homogeneous, machinable	Still not high strength
Particulate Reinforced Lead Composites	Improved stiffness and creep resistance, homogeneous, machinable	May be problems joining pieces
Fiber Reinforced Lead Composites	Superior stiffness and creep resistance	Probably requires integrated material/component manufacturing approach, anisotropic, may be problems joining pieces and fabricating

In summary, commercially available lead and its alloys are expected to display inferior but homogeneous mechanical properties, while the composites are expected to exhibit superior but nonhomogeneous and anisotropic mechanical properties. Moreover, composites are also expected to require somewhat more complex fabrication and manufacturing procedures.

The mechanical properties of the candidate materials were collected and compared with the load bearing requirements developed from mechanical analyses. The goal was to identify materials that could support gravity loads without distortion, both within the assembled calorimeter and during construction. Of particular importance are local stresses, which may be design sensitive. In order to efficiently screen materials, some order of magnitude estimates were employed to provide a preliminary comparison of materials and to eliminate materials that would not meet the system requirements. For instance, because creep properties were generally unavailable for the more complex alloys and composites, the creep strength was estimated to be about one half of the material yield strength at room temperature. Also, the load bearing requirement was estimated to be approximately 20,000 psi from several finite element model analyses of the barrel calorimeter. Although this value is actually design sensitive, it is important because it is much greater than the load levels that were expected on the basis of preliminary analyses.

The tensile properties of a wide range of lead alloys were collected and compiled (see Table I); a summary is shown in Fig. 1.35. These tables clearly show that candidate lead alloys exhibit mechanical properties that are below the 20,000 psi requirement. The strongest of these alloys is Pb - 0.065% Ca - 1.3% Sn, which exhibits a yield strength of about half of the acceptable value. Because it may be possible to use such an alloy in a lower stress

region of the calorimeter, for example in the EMC section, creep rupture data were collected for this alloy and several similar ones as shown in Fig. 1.36. This figure indicates that the creep rupture strength of Pb - 0.065% Ca - 1.3% Sn for lifetimes of greater than 11,000 hrs (= 1.25 years) is about 3000 psi. It is therefore concluded that lead alloys can only be considered for use in regions of the calorimeter where the computed stresses do not exceed 2500 psi, and that the alloy to be used should be Pb - 0.065% Ca - 1.3% Sn.

Concepts for using composite materials and techniques were included from the early stages of this study because lead alloys were known to exhibit poor mechanical properties by themselves. These concepts included: 1) cast alloy plates stacked with external supports. In this case, creep was anticipated to be a problem. 2) cast composite plates with stiffened outer plate layers. Both creep and fabrication problems were expected for this case. 3) a bonded structure with cast plates and the hot isostatic process (HIP) for bonding. An integrated structure would result from this concept, and perhaps a composite framework is possible, and 4) a cast structure with a composite framework and slots for installing the scintillator tiles. For these composite concepts, candidate mechanical systems were examined using a computer synthesis of the composite mechanical properties. In some cases, after determining mechanical suitability, laboratory castings were made to evaluate the viability of the composite and the difficulties of fabrication.

Composite systems with the following reinforcements were considered:

- 1) Copper
- 2) Steel
- 3) Molybdenum
- 4) Tungsten

These reinforcing materials are ordered from the material that will provide least strengthening to the maximum strengthening. They are also ordered from

the most easily "wetted" by lead, and thereby most easily processed into a composite, to the least easily wet by lead and least easily processed. The computer syntheses of the mechanical properties of the composites indicated that all of the materials could produce composites that would exhibit the required strength levels. Figure 1.37 compares the synthesized composite properties with the yield strength, ultimate tensile strength and elasticity of other candidate materials. It is also important to notice that, because the reinforcement bears most of the load in these composites, the mechanical properties of the composites will not be significantly time-dependent. Thus, the structural analysis can be based on short-time tensile data rather than on creep strength data.

Based upon the computer simulations, laboratory casting trials were conducted to determine the feasibility of fabricating lead based composites. In particular, the laboratory trials were performed to determine whether lead could be cast around reinforcements and whether the lead composite structures could be subsequently cast to shapes that would contain precision slots into which scintillator tiles could be placed (see Fig. 1.38 and 1.39). Although mechanical tests were not performed on these bars, their durability in handling indicated that they were much stronger than similar sized lead bars. In order to provide precision slots cast into the lead composites, a casting technique using a Teflon insert was developed. Figure 1.40 shows a casting that was made around a Teflon insert, which, because of its high coefficient of thermal expansion and low coefficient of friction, was found to be very easily removed after the casting had cooled to room temperature.

From the computer strength simulations and the laboratory casting trials, lead based composites appear to be a viable materials option for a SSC calorimeter system. Because the data to date are only preliminary, several

issues remain, such as the optimum casting geometry, the wetting of the reinforcement by the lead matrix, and the surface produced by the teflon casting insert. These and other fabrication and manufacturing issues should be assessed and optimized. Nevertheless, it appears that composite lead based structures could be fabricated as EMC or HAC calorimeter modules. In these cases the reinforcement would be judiciously placed to absorb essentially all of the load, such as in Fig. 1.41. More appropriate and detailed concepts are currently under development.

Several suppliers of lead alloys and castings were contacted in order to support the development of cast lead composite structures. Communications with these vendors determined that large castings of the type proposed for the calorimeter modules were feasible and that these vendors (Fig. 1.42) would be available to provide this capability. Preliminary cost estimates were also explored with these vendors, and costs on the order of \$1.50 per pound were quoted for cast structures (Fig. 1.43). Thus, lead based composite concepts appear to be feasible based on mechanical and fabrication criteria, and also appear to be attractive based upon costs.

In order to fully develop these concepts for implementation in a SSC calorimeter system, it is necessary to 1) verify the mechanical performance of the case composite structures, 2) determine the reliability of casting the composite structures, 3) assess the precision of casting scintillator slots using the Teflon-insert technique, and 4) optimize the casting process for fabricating the reinforcement and insert containing structures. The program proposed for the coming year to address these issues is summarized in Fig. 1.44. The program has been structured to develop casting technology and to optimize the structural elements using laboratory methods before developing prototype calorimeter module castings that will be evaluated in a Fermilab

test beam. Figure 1.45 illustrates how the proposed program will lead to a phased development of technologies that are required for a lead based calorimeter for the SSC.

FIGURE CAPTIONS

- Figure 1.35 Table of yield strength, ultimate tensile strength and elasticity for pure lead and selected lead alloys.
- Figure 1.36 Creep properties of several lead alloys as a function of stress.
- Figure 1.37 Table of yield strength, ultimate tensile strength and elasticity for selected lead alloys and composites, and for depleted uranium.
- Figure 1.38 Photograph of a lead casting with thick tungsten rods.
- Figure 1.39 Photograph of a lead casting with thin tungsten rods.
- Figure 1.40 Photograph of a lead casting with thick tungsten rods and a teflon insert.
- Figure 1.41 Conceptual design of a cast lead barrel calorimeter module with steel reinforcing plates.
- Figures 1.42 Listing of potential lead vendors that could produce large
and 1.43 castings for SSC calorimeter modules.
- Figure 1.44 Outline of proposed program for lead composites by Westinghouse Science and Technology Center.
- Figure 1.45 Flow chart showing steps in the development of lead composite SSC calorimeter modules.

MATERIALS EVALUATION

Lead Alloy Tensile Properties

	YS (ksi)	UTS (ksi)	E (msi)
<u>"Pb"</u>			
Cast Pb	1.6	2.1	2.0
Cast Pb + 1% Sb	2.1	3.0	3.0
<u>ALLOYS</u>			
Pb + 4% Sb	3.0	3.0	3.0
Pb + 2.5% Ag	2.7	4.7	3.3
Pb + 63 Sn	3.04	3.31	4.21
Pb + .1% Ca	4.0	6.0	3.0
Pb + .065% Ca + 1.3% Sn	9.5	10.0	3.0

MATERIALS EVALUATION

RT Creep Rupture Properties of Pb Alloys

LEAD BASED CALORIMETER

MECHANICAL PROPERTIES OF LEAD MATERIALS

	YS (ksi)	UTS (ksi)	E (msi)
"Pb"			
Cast Pb	1.6	2.1	2.0
Cast Pb + 1% Sb	2.1	3.0	3.0
ALLOYS			
Pb + 4% Sb	3.0	3.0	3.0
Pb + 2.5% Ag	2.7	4.7	3.3
Pb + 63 Sn	3.04	3.31	4.21
Pb + .1% Ca	4.0	6.0	3.0
COMPOSITES			
Pb - 10% Cu Fiber	6.0	6.2	3.1
Pb - 10% W Fiber	17.5	17.5	5.7
Pb - 50% Cu Fiber	14.0	17.0	7.6
Pb - 50% W Fiber	58	58	18.9
DEPLETED URANIUM	35	80	25

Figure 1.37

Chart 23

LEAD CALORIMETER
SUBSYSTEM

TUNGSTEN STRENGTHEN LEAD
COMPOSITE (LARGE BARS)

Figure 1.38

Chart 24

LEAD CALORIMETER
SUBSYSTEM

TUNGSTEN STRENGTH LEAD
COMPOSITE (FINE FIBERS)

Figure 1.39

Chart 26

LEAD CALORIMETER
SUBSYSTEM

TEFLON
INSERT

STC

INTEGRALLY CAST SLOTTED
LEAD BASED COMPOSITE

Figure 1.40

MATERIALS EVALUATION

Lead Composite Module Concepts

Westinghouse
Science & Technology Center

Viewgraph 14
MAB
August 20, 1990

Figure 1.41

CALORIMETER SUBSYSTEM

ENTHUSIASTIC LEAD VENDOR

TARACORP Industries - Granite City, Illinois

618-451-4517

50 Million Dollar Company

Lead Fabricators

Rolled Plate with Copper Mesh

Capacity to Pour 5 x 60 Ton Pieces

Pete Horton - Purchasing

Elbert Minarcik - Consultant

Harry Schlechde - Plant Manager

Tony Lindsay - General Manager

TYPICAL LEAD PRICES

\$0.35 a Pound Pig Lead

\$0.60 a Pound Plate (Plain)

\$1.25 to \$1.75 a Pound Cast

Includes Mold, Slots No Mesh Material Cost

CALORIMETER SUBSYSTEM

POTENTIAL LEAD VENDORS

Lead Industries Association - New York, NY

Jerome Smith - 212-578-4750

RSR Mill - Dallas, Texas

David Prengamen - 214-631-6070

Asarco (American Smelting) (Integrated Lead Supplier)

Salt Lake City, Utah

Douglas Hayduk - 801-262-2459

Doerun Mill - St. Louis, Missouri

John Pasmore - 314-933-3172

(W) Mechanical Engineering

Figure 1.42

MATERIAL STUDY

Pb Composite Module

Technology Demonstration and Beam Test

Objective:

Implement cast Pb-composite system in demonstration modules. Optimize materials and processing options and verify mechanical and physical performance.

Tasks:

Casting technology development

Mechanical property verification

Processing & structure optimization

Preprototype production & mechanical evaluation

Test module production and beam test

Figure 1.44

Viewgraph 17
MAB
August 20, 1990

MATERIALS EVALUATION

Module Development & Test

Figure 1.45

TABLE I

Summary of Wrought and Cast Lead and Lead Alloys for an SSC Calorimeter

Summary of Wrought and Cast Lead and Lead Alloys for SSC									
0 Name	1 Commercial Designation	2 % Cu	3 % Sb	4 % Ca	5 % Sn	6 % Al	7 UTS (ksi)	8 YS (ksi)	9 % Elong.
1 Common/Commercial Pb	ASTM B29						1.80	-	40
2 (Corroding Pb)	ASTM B29	0.00					2.50	1.30	45
3 Chemical Pb									
4	1% Sb		1.0				3.40	-	16
5	3% Sb		3.0				4.70	-	15
6	4% Sb		4.0				5.70	-	22
7	6% Sb		6.0				4.40	2.80	40
8	8% Sb		8.0				4.05	-	31
9	9% Sb		9.0				7.50	-	17
10				0.010			2.50	-	53
11				0.030			3.50	-	45
12				0.065			4.70	3.00	30
13				0.070			5.40	-	38
14				0.075			6.50	6.50	26
15				0.080			5.50	4.50	35
16				0.100			5.60	-	38
17				0.110		0.03	5.70	-	20
18				0.040	0.50		7.00	6.40	14
19				0.065	0.50		7.00	6.30	15
20				0.085	0.70		9.00	8.50	10
21				0.090	1.00		9.75	9.25	10
22				0.080	1.00		9.00	8.00	20
23				0.065	1.30		10.00	9.50	10
24				0.070	0.70		7.25	-	35
25				0.100	0.30		8.25	-	30
26				0.100	0.30	0.03	6.10	-	18
27				0.100	0.50		6.75	-	30

SJM 020 is the best wrought material for creep
 SJM - St. Joe Mineral
 SJMFA cast materials fully aged.

Summary of Wrought and Cast Lead and Lead Alloys for SSC

2 Name	10 Remarks	11 Source
1 Common/Commercial Pb	Used as sheets.	St. Joe Lead
2 (Corroding Pb)	Used as sheets.	St. Joe Lead
3 Chemical Pb		ASM Handbook
4		
5 Pb + 1% Sb	Cable sheathing	St. Joe Lead
6		
7 Pb + 3% Sb	Rolled sheet.	St. Joe Lead
8		
9 Pb + 4% Sb	Rolled sheet.	St. Joe Lead
10		
11 Pb + 6% Sb	Rolled sheet.	St. Joe Lead
12		
13 Pb + 8% Sb	Battery plates	St. Joe Lead
14		
15 Pb + 9% Sb	Battery plates	St. Joe Lead
16		
17 Pb + 0.01% Ca	High purity strip.	St. Joe Lead
18		
19 Pb + 0.03% Ca	Casting alloy.	St. Joe Lead
20		
21 Pb + 0.005% Ca	Wrought product.	St. Joe Lead
22		
23 Pb + 0.07% Ca	Casting alloy.	St. Joe Lead
24		
25 Pb + 0.075% Ca	Wrought product.	St. Joe Lead
26		
27 Pb + 0.00% Ca	Wrought product?	Mtl's Eng. (1990 Sel.)
28		
29 Pb + 0.1% Ca	Casting Alloy	St. Joe Lead
30		
31 Pb + .11% Ca + .03% Al	Al stab. Ca/cast.	St. Joe Lead
32		
33 Pb + 0.04% Ca + 0.05% Sn	Wrought alloy.	St. Joe Lead
34		
35 Pb + 0.005% Ca + 0.5% Sn	Wrought alloy.	St. Joe Lead
36		
37 Pb + 0.005% Ca + 0.7% Sn	Wrought alloy.	St. Joe Lead
38		
39 Pb + 0.00% Ca + 1% Sn	Wrought alloy.	St. Joe Lead
40		
41 Pb + 0.00% Ca + 1% Sn		Mtl's Eng. (1990 Sel.)
42		
43 Pb + 0.005% Ca + 1.3% Sn	Wrought alloy, best for	St. Joe Lead
44		
45 Pb + 0.07% Ca + 0.7% Sn	Casting alloy.	
46		
47 Pb + 0.1% Ca + 0.3% Sn	Casting alloy.	St. Joe Lead
48		
49 Pb + .1% Ca + .3% Sn + .	Al Stab. Ca/Casting	St. Joe Lead
50		
51 Pb + 0.1% Ca + 0.5% Sn	Casting	St. Joe Lead

SJM 620 is the best wrought material for creep
 SJM - St. Joe Mineral
 SJMFA cast materials fully aged.

Summary of Wrought and Cast Lead and Lead Alloys for SSC

6 Name	1 Commercial Designation	2 % Cu	3 % Sb	4 % Ca	5 % Sn	6 % Al	7 UTS (ksi)	8 YS (ksi)	9 % Elong.
52	63 Pb + .1% Ca + .05% Sn + SJMFA 900+Al		0.100	0.05	0.03		7.30	-	18
54	66 Pb + .1% Ca + 1.0% Sn SJMFA 910		0.100	1.00			7.75	-	28
56	67 Pb + .15% Ca + .2% Sn + SJMFA 1502+Al		0.150	0.20	0.03		0.25	-	20

6 Name	10 Remarks	11 Source
52	63 Pb + .1% Ca + .05% Sn + Al Stab. Ca/Cast.	St. Joe Lead
54	66 Pb + .1% Ca + 1.0% Sn Casting alloy.	St. Joe Lead
56	67 Pb + .15% Ca + .2% Sn + Al stab. Ca/Casting	St. Joe Lead

SJM 020 is the best wrought material for creep
 SJM - St. Joe Mineral
 SJMFA cast materials fully aged.

2. SIMULATION STUDIES

P. K. Job, H. J. Trost, J. Proudfoot, L. E. Price

Three distinct categories of simulation study have been carried out:

a) benchmarking of the CALOR 89 code for two scintillator plate systems; b) a survey of the unit cell space for modest statistics; c) and initial GEANT simulations of the transition region between barrel and endcap calorimeters in the conceptual design.

a) The CALOR simulation in this subsystem is by necessity distributed over several processors. As a result it was necessary to ensure that all codes were generating consistent results by having benchmark runs computed on each installation and a detailed comparison of results made (shower longitudinal and lateral profile, e/h etc.). The systems computed at Argonne are Fe/Scintillator and Pb/Scintillator. The energy deposition computed by each process is given in Table I. Further details of these runs are given in Appendix I.

Initial simulation studies of the unit cell (thickness and relative thickness of absorber and scintillator) have been carried out on the Cray and IBM computers at Argonne by P. K. Job. The objective is to determine the unit cell which optimises individual electron and pion resolutions and simultaneously obtains a configuration in which both electrons and pions have equal response ($e/h = 1$, or "Compensation"). The variation in the relative response of electrons to pions for depleted uranium (DU), lead and iron absorber systems as a function of absorber thickness for 0.25 cm scintillator is shown in Fig. 2.1. These results are in general agreement with the available experimental data and other simulation experiments (The

ZEUS Detector, Status Report, 1989). Uranium and lead absorbers can both yield compensating systems whereas this is not the case for pure iron absorbers. The time dependence of compensation is also an issue at the SSC due to the 16 nsec bunch spacing as it is expected that some component is due to slow neutron capture. Preliminary results on this are shown in Fig. 2.2 and indicate that both depleted uranium and lead absorber systems yield approximate compensation ($e/h \leq 1.05$) in less than 16 nsec. Rapidity dependence in e/h may be expected for sampling with constant absorber thickness. This has been studied for the compensating DU/scintillator unit cell (Fig. 2.3) and we find $e/h \leq 1.05$ for $n < 1.3$. The last in our series of initial studies was to evaluate the effect of varying the scintillator thickness for constant absorber thickness (Fig. 2.4). In this case we simulated this parameter in the vicinity of a Pb/scintillator compensating geometry and observed the expected increase in e/h with reduction in scintillation thickness.

To date these studies have been limited by availability of cpu and it is planned to extend them by approximately a factor of four in order that the limitation is in the computation model. To accommodate part of this we are presently commissioning the CALOR 89 code and geometry for scintillator calorimetry on the Lawrence Livermore Cray. These runs will be distributed amongst collaborators at Oak Ridge, University of Mississippi, University of Tennessee and Argonne. We anticipate a program studying a matrix of four scintillator thicknesses, four absorber thicknesses, three absorbers (lead, iron and depleted uranium) three particle energies and six integration gates to be completed in FY91.

- c) A GEANT based simulation of support structure in the transition region between barrel and endcap calorimeter and the solenoid coil has

been initiated to evaluate the benefit of a design with slightly non-projective longitudinal geometry. This is obtained by requiring towers in this region to project to a point in Z which is offset from the true interaction point. The variation of response in the transition region as a function of this offset is shown in Fig. 2.5, indicating that an offset of approximately 40 cm may be adequate to cover this gap. However, many tests remain to be done in FY91 and beyond (e.g. resolution, ratio of resolution to energy deposited, jet responses).

Table I

Energy Deposition in Scintillator (MeV)(For 10 GeV Incident Energy and 50 nsec Integration Time)

<u>Unit Cell (cm)</u>	<u>Particle Type</u>	<u>Spect</u>	<u>EGS</u>	<u>MORSE</u>	<u>TOTAL</u>	<u>RMS</u>	<u>(σ/E)</u>	<u>$\sigma/\bar{E}$</u>	<u>$\bar{x}/n$</u>
FE-SCIN (1.76/0.25)	π^-	75.4 $\pm$ 2.0	83.2 $\pm$ 2.0	9.4 $\pm$ 1.0	168.0 $\pm$ 5.0	30.4	18.1	57.2	1.24 $\pm$.0
	e^-	---	208.2 $\pm$ 3.0	---	208.2 $\pm$ 3.0	14.7	7.1	22.3	
PB-SCIN (0.56/0.25)	π^-	199.7 $\pm$ 3.0	131.0 $\pm$ 2.0	81.5 $\pm$ 1.0	412.2 $\pm$ 6.0	51.6	12.5	39.6	1.04 $\pm$ 0.0
	e^-	---	431.9 $\pm$ 5.0	---	431.9 $\pm$ 5.0	23.9	5.5	17.5

2 of 2

Relative response of electrons to pions (e/h)
as a function of absorber thickness and composition
for a fixed scintillator thickness of 0.25 cm

Fig. 2.1

e/h as a function of integration gate for
typical Iron, compensating Lead and Uranium
geometries for Scintillator thickness of 0.25 cm

Fig.2.2

e/h as a function of pseudorapidity (η)
for a compensating Uranium geometry
with Scintillator thickness of 0.26 cm

Fig 2.3

e/h as a function of Scintillator thickness for
a fixed Lead absorber thickness of 0.5 cm

Fig 2.4

Minimal response in transition region

Figure 2.5

3. OPTICAL SYSTEM DESIGN

D. G. Underwood, R. T. Hagstrom

Production of radiation hard scintillator plates by BICRON has been somewhat slower than hoped. This has been principally due to manufacturing difficulties in converting their RHI series from fiber to cast plate scintillator of appropriate mechanical and optical properties (as discussed in the section on the scintillator development program).

The first set of plates for testing were received in August. Initial tests included an evaluation of the mechanical variation in milling a groove, and an optical survey of the face of the plate to study surface crazing, performed by Ray Hagstrom. The preliminary conclusion is that although an acceptable quality of cut could be obtained, the plate showed considerable surface crazing, due to problems in casting, and would therefore be unlikely to form the basis of a high precision calorimeter. We are now in the process of resolving this problem with BICRON.

While awaiting scintillator plates, work proceeded at Argonne to study particular aspects of the optical design. A stack compression fixture to be used in evaluating the mechanical properties of this new plastic has been designed and is in the process of being set up. Some critical tests have been carried out on the fabrication and uniformity of scintillator tiles read out by embedded WLS fiber. In particular, a UV reflective foil capable of significantly improving the optical uniformity has been identified and a fixture for controlled bending and annealing of fibers into the grooves designed and fabricated (Fig. 3.1). This will be used in the near future to develop a radiation hard fabrication process. Finally a lead scintillation stack was

placed in a neutral beam dump at Fermilab and exposed to up to 40 MRad. Serious problems due to radiation induced physical damage were observed on plastic materials used in the test, paper and the plastic foam as used by CDF to cushion the scintillator in compression with the lead. (This had disintegrated and stuck to the lead.) Further details of this test are found in Appendix II. Clearly, radiation induced damage is a major issue for the whole optical system, and will be addressed in the upcoming program of work.

FIBER PATH

FIBER BENDING FIXTURE

Figure 3.1

4. Electronics Development

C. Einolf, T. Porter, R. Ravas, and S. Weinstein

Science and Technology Center
Westinghouse Electric Corporation, Pittsburgh, Pennsylvania 15235

J. Dawson, T. Ekenberg, D. Hall, J. Schlereth, A. Stevens, and R. Talaga

High Energy Physics Division
Argonne National Laboratory, Argonne, Illinois 60439

The electronics development tasks included gathering information on radiation hard processes for producing electronic chips, obtaining data on existing fast analog to digital (A/D) converters, evaluating methods of locating the calorimeter electronics remotely, and preparing plans for electronics for a test beam module. As was anticipated, it was found that much of the electronics development for other subsystems was inappropriate for the fast signals with a large dynamic range from a scintillator calorimeter. Nevertheless, in order to prevent duplication of effort, considerable time was spent understanding and coordinating activities with groups working on electronics in other subsystems.

In a survey of radiation hard processes, data were collected on chips produced by UTHC (CMOS - Fig. 4.1), AT&T (Bipolar), Tektronix (Bipolar - Fig. 4.2), and Westinghouse (BICMOS - Fig. 4.3). It was concluded that existing processes would probably be adequate for electronics mounted on the outside of the barrel calorimeter, especially with the revised estimates of radiation levels by D. Groom et al.

In discussions with personnel at Westinghouse ATL in Baltimore, it was suggested that developments for high definition television (HDTV) would probably result in cheap A/D converters coupled with memory lookup that could correct for nonlinearities and potentially perform conversion of pulse height

to energy (see Fig. 4.4). The development timescale for such devices is the next few years. This will probably occur before a final decision on electronic components for an SSC calorimeter would be required.

Considerable effort was devoted to evaluating the possibility of locating the electronics remotely, away from the calorimeter. Advantages would include accessibility, ease of maintenance, removal of electronics from significant radiation doses, reduced problems with cooling, and potential ease of upgrading the electronics. The systems considered involved either using fiber optics for signal transmission between photodetectors on the calorimeter and remote electronics, or bringing fibers from the scintillator tiles to remote photodetectors and electronics. A "fallback" scheme using coaxial cables between the photodetectors and the electronics is also under consideration.

An investigation of the performance and cost of fiber optic links for the transmission of data from the outside surface of the calorimeter was begun. Both analog and digital fiber optic link systems (transmitter, fiber optic cable, receiver) are available. Analog bandwidths above 200 MHz and digital rates up to 2 Gigabits/sec exist for these systems and typical costs per channel are \$300 and above. A very approximate cost estimate is provided in Fig. 4.5 assuming 10,500 towers with EMC, HACI and HACII sections each.

Long, low attenuation fibers are required for the approach of bringing light from the scintillator tiles to remote photodetectors and electronics. For example, if the electronics were to reside on the outside of the outer muon chambers at a radius of ~ 10m from the beamline, then a minimum length of the optical fiber would be 8m. Low loss glass and clear acrylic fiber have been considered for this purpose. The much higher cost of glass fiber (\$3000/km vs. \$200/km for acrylic fiber) and potential problems with bonding the glass fibers to the WLS fibers embedded in the scintillator tiles have focussed work on the acrylic fibers for this application. Note that the total

fiber length required is more than 10,000 km, and thus cost is a substantial issue.

The most promising clear acrylic fiber is manufactured by Mitsubishi. The properties of this fiber are shown in Fig. 4.6. Some of this fiber has been acquired, and it is planned to verify the quoted attenuation. One drawback of acrylic fiber is oxidation yellowing that affects light transmission. The yellowing is thought to be caused by oxygen bonding to the acrylic molecular structure. Radiation damage could exacerbate the problem, though tests at the 1 Mrad level indicate minimal damage (see Fig. 4.6). Future studies on splicing acrylic fibers to WLS fibers, yellowing effects, and radiation damage effects are planned.

Work on instrumentation for a detector testbeam module was begun in May 1990. The tasks for Westinghouse include:

- 1) Complete the design of an analog storage module utilizing the LBL integrated circuit design of S. Kleinfelder et al. Produce a layout of a PC board for the module including shaping, capacitive storage, buffer and multiplexing functions.
- 2) Fabricate, test, and debug a prototype analog storage module and assist in tests of its performance on a testbeam calorimeter module.

The tasks for Argonne include:

- 1) Design a VLSI chip to store analog signals from a scintillator plate calorimeter. The photomultiplier signals are integrated for 16 nsec and stored on capacitors. Integration, storage, and digitization are performed on a single chip upon issue of a second level trigger signal. The architecture stresses simplicity of logic and has the potential for deadtimeless operation. The VLSI chip design has been begun (see Figs. 4.7 - 4.11), and it will be submitted to the MOSIS foundry by the beginning of November 1990. The chip is expected back

in January, 1991 and it will be used in the testbeam measurements. Negotiations with Hughes and UTMC for a radiation hard version of the chip are underway.

- 2) Perform bench tests of the electronics system. Excite the primary fluor of the scintillator with short (~ 300 psec) bursts of U.V. laser light via optical fibers. The laser bursts are in phase with the sampling frequency of the chip. Experiment with signal integration techniques.
- 3) Provide data acquisition hardware and software for bench tests and for the testbeam effort. The hardware will consist of a CAMAC crate and modules, a VME crate and modules, and a computer workstation. The data acquisition will include readout of the ANL VLSI chip, the LBL chip as interfaced by Westinghouse, and standard LeCroy 2262 waveform digitizers from Iowa State.
- 4) Provide multiwire proportional chambers and readout electronics, if necessary, for the testbeam.

Finally, Westinghouse has been approved to perform a scintillator tile/readout fiber manufacturing study. Significant effort will be involved in the construction of the more than 1.7×10^6 tile/fiber assemblies for the calorimeter. The tile physical size and the location of the groove for the fiber will depend on the position of the tile in the calorimeter. The response of each tile/fiber assembly will probably need to be mapped, a suitable mask prepared and installed, and the assembly calibrated before installation. The study tasks include identifying the assembly operations, evaluating approaches to automation of the assembly, and estimating manufacturing time and costs.

FIGURE CAPTIONS

- Figure 4.1 Information from UTMIC on their radiation hard manufacturing process for electronic chips.
- Figure 4.2 Information from Tektronix on their radiation hard manufacturing process for electronic chips.
- Figure 4.3 Information from Westinghouse A.T.L. on their radiation hard manufacturing process for electronic chips.
- Figure 4.4 Possible use of future high definition television (HDTV) analog to digital (A/D) converters for the calorimeter readout.
- Figure 4.5 A very preliminary cost estimate for locating the electronics remotely, or far from the outside surface of the calorimeter.
- Figure 4.6 Properties of Mitsubishi clear acrylic optical fibers.
- Figure 4.7 Schematic layout of the ANL VLSI chip.
- Figure 4.8 Schematic diagram of the input circuit for the ANL VLSI chip. Three amplifiers are used to 1) integrate the photodetector current, 2) store the corresponding voltage in analog memory, and 3) reset the memory cell.
- Figure 4.9 Switch settings for the input amplifiers on the ANL VLSI chip.
- Figure 4.10 Schematic diagram of one of the eight capacitor arrays on the ANL VLSI chip.
- Figure 4.11 Schematic diagram of the output circuit on the ANL VLSI chip, showing digitization of the analog signal on receipt of a level-2 trigger "ACCEPT" signal.

ELECTRONICS ACTIVITY FOR APRIL

UTMC Rad Hard Process

CMOS for Digital Applications

Offer Some Standard Chips

RISC Processor, Clock Rate

Probably Can Achieve >25 MHz Clock Rate on ASIC

Provide Cell Library on Various Work Stations - \$7000

They Make Masks and Make 10 Prototypes - \$35,000 (1000 Gate Device)

50,000 Parts, 20-30\$, Level B

Total Doses - 10^6 Rads - to Meet Mil Spec

Total Dose - 10^7 Rads - Functional

Neutrons - $>10^{14}$ - Neutron/cm²

Viewgraph 4
TFP
APR-30-90

ELECTRONICS ACTIVITY FOR APRIL

Textronix

TKAD20C A/D Converter

8 Bit/250 MSPS

T/H Amp Built-In

5 W Power Dissipation

50 Ohm Input

ECL Output

Bipolar Process

TKAD10C A/D Converter

8 Bit/500 MSPS

T/H Amp Built-In

7.5 W Power Dissipation

50 Ohm Input

ECL Output

Bipolar Process

QuickChip2 Linear Integrated Circuit Arrays

Bipolar (NPN) [ft = 8 GHz]

Bipolar (PNP) [ft = 80 MHz]

JFET (P Channel)

Resistors (Trimable)

Capacitors (MOS Programmable)

U of Penn Has Tested Some Chips to Several Megarads

Viewgraph 11
TFP
APR 30-90

ELECTRONICS ACTIVITY FOR APRIL

Westinghouse A.T.L. (Baltimore)

Rad Hard Bipolar

1 Micron CMOS

Used in Many Defense Applications
Bipolar Suitable for Analog Shaping

Amplifier, Bandwidth Achievable
CMOS A.S.I.C. Probably Can Handle

60 MHz Data Rate

Can Meet Rad Requirement

Viewgraph 3
TFP
APR-30-90

Westinghouse
Science & Technology Center

Figure 4.3

ELECTRONICS ACTIVITY FOR APRIL

Westinghouse ATL Suggestion

Amplifier/Bandpass Shaper
Bipolar With RC Tuning
Hard Enough for Calorimeter Mounting
Single Channel per Package
0.25 W

A/D Converter from HDTV
8 Bit
Bipolar Process
Low Precision
1 W Power Dissipation
Commodity Parts Prices [\$3]
Memory with Instant Cal. Comp. [Proprietary]
CMOS - Rad Hard
Correct for A/D Errors
Correct for Amplifier/Filter Error
Correct for Detector Errors
Slight Additional Gate Count
Eliminates Need for Post Processor Comp.
System Response - Perfect Detector & A/D
0.25 W

Viewgraph 12
TFP
APR-30-90

Westinghouse
Science & Technology Center

ELECTRONICS ACTIVITY FOR APRIL

Remoting of Electronics

Cost

Glass Fiber - \$1 a M
Cost - 30,000 KM - \$30 million
Series Fiber Through Two Tiles - 15 Million
Mitsubishi Plastic - 10 Cents a M - 3 or 1.5 Million \$

Electronics Package on Calorimeter

- Assume 12 Photon Transducers Per Package
No. of Packages = $31,500/12 = 2,625$
Each Package Needs:

1 or 2,600 Megabit/Sec - Digital Data Links
3 Analog Trigger Links
1 Trigger Pulse Links
1 Clock Link

Cost is $3 \times 900\$ + 3 \times 400\$ = 27,000 + 1200 = 3900\$$

Total Cost = $3,900 \times 2625 = 10.2$ Million \$

Viewgraph 9
TFP
APR-30-90

CALORIMETER ELECTRONICS

REMOTE ELECTRONICS

- Acrylic Optical Fibers
- Sizes (total fiber diameter): 250 μm to 1000 μm
- N.A.: .46-.47
- Max. Operating Temp.: 85°C
- Average Attenuation: 150 dB/km
- Radiation Effects (1 MRad):
 - 2917 dB/km immediately after exposure
 - 153 dB/km one month recovery after exposure

Viewgraph 8
CWE
7-AUG-90

Figure 4.6

Layout of Analog Storage Chip

Figure 4.7

Input circuit

Figure 4.8

Switch setting while integrating

Switch setting while charging storage capacitor

Switch setting while resetting integrating capacitor
and recharging self referencing capacitor

Figure 4.9

8 x 16 capacitor storage array with associated shift registers

Figure 4.10

Output circuit

Figure 4.11

BICRON

BICRON CORPORATION

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Telex 980472

PROGRESS REPORT

SCINTILLATOR DEVELOPMENT PROGRAM SCINTILLATING PLATE CALORIMETER SUBSYSTEM

27 August 1990

This reports on the Bicron work initiated at a planning meeting in May.

RADIATION-RESISTANT SCINTILLATORS

In its SBIR fiber development program, Bicron had previously investigated novel plastic materials which might exhibit resistance to yellowing from high dose exposure. The first of a series of materials of this type, designated RH-1, was fabricated into scintillating fiber and tested by Stan Majewski on the electron beam facility at Florida State in December, 1989. He reported its superior resistance to yellowing at the Tallahassee Workshop this spring. RH-1 and its precursor, Type B, are actually part of a larger program in which the material, RH-2, is the goal. The RH-1, being easier to make initially, served as a proof-of-principle step in the project.

SHEET PRODUCTION

Most of the physical effort of the past 3 1/2 months has been in casting RH-1 scintillator plates for supplying 10 cm x 10 cm x 2.5 mm tiles to various collaboration members in accord with the schedule from the April meeting at Bicron. Difficulties were encountered in making the transition from fiber preforms to sheets. The excellent mechanical properties of the fibers were not reproduced in the sheets. The latter were plagued by highly crazed surfaces and general brittleness. The actual polymerization cycle was time consuming, up to triple those for polyvinyltoluene (PVT) and polystyrene(PS) based scintillators. The several small scale process problems with RH-1 material would be eliminated in a mass production system.

The second casting, in July, incorporated changes to deal with the crazing. Clear improvements were achieved, but the problem persisted.

Had yields been good, enough RH-1 sheet was cast to supply over 400 tiles.

In the meantime, parallel fiber work revealed a possible chemical weakness of the RH-1 when it was potted into a lead-fiber calorimeter module. This is being investigated separately. This new mystery and the immediate need for large numbers of mechanically and optically reliable tiles has forced us to change directions.

RH-1 sheet production will be abandoned, at least temporarily, in favor of a Bicron's RH-1 precursor, Type B, which was originally made in PS and was nearly as good as RH-1 in the December fiber tests. The difference should be even less in the small tiles. Sheets will be immediately made with this formula in both PS and PVT. The first lots of 20-30 tiles in several casting variations, will be available by September 30, 1990.

Recent separate tests at Tallahassee showed PVT possibly more rad-hard than PS. The problem with PVT for plate tower calorimetry is its mechanical weakness. Concurrent with the Type B casting, Bicron will investigate methods of strengthening PVT sheet. A specific plan for this has been written.

FLUOR RESEARCH

1. A five-month fluor development contract has been made with Dr. Joel Kauffman at the Philadelphia College of Pharmacy and Science (PCPS). The prime goal of this work is the development of a spectrum shifting fluor for use in the WLS plates or fibers. This is to replace the fluor Y-7, which is also the same as the commercial green fluor K-27. Y-7 has recently been characterized by Dr. V. Hagopian as relatively rad-soft.

The properties of the new fluor should be:

- Rad-hard
- Absorption spectrum: 430 nm - 460 nm
- Emission spectrum: 500 nm - 550 nm
- High quantum efficiency, above 75%
- Fast timing
- Small self-absorption.

2. Bicron will undertake the development of a more efficient and more rad-hard blue scintillator fluor system as an extension of its successful SBIR work on new green scintillators for fiber based tracking.

Recognizing the need for improved blue scintillator tiles (for efficient optical match to green WLS materials), Bicron developed a blue variant of the above green fluors which exhibits higher efficiency than traditional ones and which also should be relatively rad-hard. More of this particular fluor will be made for use in further testing and tile manufacture.

A second blue variant, which should be more rad-hard, is planned.

Schedules for this work are included on the attached Bicron Rad-Hard Scintillator Program dated 18 August 1990.

SHEET PRODUCTION DEVELOPMENT

The sheet line has been totally torn down and refurbishment and rebuilding begun. The main structural frame has been sandblasted and repainted. The rolling drums have been stripped down and crated for transport to a local company capable of performing the critical resurfacing. This represents approximately four man-weeks of labor and \$5K expenditure to date.

BICRON CORPORATION

Charles R. Hurlbut
Manager, Organic Scintillators

SSC SUBSYSTEM
RAD-HARD SCINTILLATOR PROGRAM

The following Scintillator development program will begin on Sept. 4, 1990 with Bicron manpower allocation as so indicated. The goal is to develop and demonstrate stable rad-hard plastic scintillator and WLS materials for sheet and fibers by Spring of 1991 providing time for iterative testing and reports submitted in late 1991. This work will build upon the foundation of knowledge in this field developed in the Bicron SBIR program.

A. CAST TILES FOR IMMEDIATE TESTING AND TOWER PROTOTYPE

All Variants on Type B (precursor to RH- mat'ls.)

Bases: PS, PVT, RH-4, RH-5

Quantities: 20-30 10 cm tiles each.

Shipment by:

Sept. 30, 1990

Recast one or two best physical types

50 tiles minimum

Shipment by:

Nov. 15, 1990

B. POLYMERS

RH-1:

Cease development work other than making a few more plates and fibers for testing purposes.

The manufacture of large amounts of this material was never intended. RH 1 served to prove a point: that our general approach to formulating rad-resistant polymers is likely correct. Furthermore, we have recently discovered a specific weakness in its chemical properties which additionally supports our original plan that the ultimate rad-hard polymers would be the RH-2 or RH-3 materials.

RH-2:

Based on chemical theory, this should be the most rad-hard scintillator base. Because of this, we will make a strong effort to solve a difficult polymerization problem.

Process development

- Cross-linking for sheet production
feasibility trials completed

Sept. 30, 1990

- High pressure polymerization
feasibility trials completed

Oct. 15, 1990

Begin sheet casting trials
Est. complete by

Oct. 1, 1990
Feb. 28, 1991

Begin radiation trials

Jan. 5, 1991

Time commitment: 33% of full time basis
Wayne Moser

RH-3:

- Priority over RH-2
- Monomer synthesis, 1.2 liter initially,
2 weeks full-time, starting with new lab,
Complete date: (5-6 wks. calendar time) Oct. 15, 1990
Wayne Moser and Bill Harder

- Trial ampules
Pure and Type B fluor formula
Molecular weights
First small ampule samples out on Nov. 11, 1990

Begin R&D preform casting trials Nov. 20, 1990

Begin sheet casting trials Dec. 1, 1990
Est. complete by Feb. 28, 1991

Begin radiation testing Jan. 5, 1991

C. FLUORS

Bicron Synthesis Research

Work up lab-scale preps for our continued supply and leading to large scale manufacture.

Bill Harder: 3 man-months = 6 calendar months

- Delta and Epsilon, First Priority
- Beta and Gamma
- V-2 and V-3
Perhaps V-4 and V-5, coordinate with PCPS work
- P-2 and P-3

Characterization

Photophysics:

Dilute and concentrated in toluene

Concentrated in PS

Light output, solutions and plastic scints.

Decay times of plastics

Wayne Moser: complete by Nov. 30, 1990

Fiber preforms of best, starting Dec. 1, 1990
Update selection at that time

Radiation studies starting Jan. 15, 1991

D. FLUOR DEVELOPMENT AT PHILA. COLLEGE OF PHARMACY

Primary Task: Develop efficient, high Stokes-loss, fast waveshifter fluors with following shifting spectra:

<u>Absorption</u>	<u>Emission</u>
430-460 nm	500-550 nm
430-460 nm	580-620 nm
450-500 nm	580-620 nm

Secondary Task: Rad-hard monomer research:

Date complete: Jan. 31, 1991

E. INDUSTRIAL FLUORS STUDY

Photophysics

Approximately six fluors, green and red

Absorbance: dilute and conc. in toluene

Emission:

As function of concentration in toluene

Front and backface spectra

In PS at 100 mg/l.

Wayne Moser: two man-weeks, complete

Nov. 30, 1990

BICRON CORPORATION

C. Hurlbut

13 August 1990

CONCLUSIONS

The first key issue for a calorimeter based on plastic scintillator for an SSC experiment is that of radiation damage. For a calorimeter based on scintillator to be at all viable, it is essential to demonstrate the survivability of plastic scintillator in the expected radiation field at the SSC (of order 1 to 10 MRad over most of the central rapidity region). Initial tests of both blue scintillator plates and assorted fibers show that at the component level, significant progress has been made in this area this year. For example after 1 MRad of irradiation followed by 22 days of annealing, a scintillator plate based on the Bicron RH1 plastic showed no measurable change in either attenuation length or initial light output (within a 1% measurement error). Similarly, a fiber based on the green scintillator 3HF showed only a 10% decrease in attenuation length and an 8% loss in light output after an irradiation of 3 MRad followed by a few days of annealing. These successes coupled with the fact that scintillator manufacturers are bettering their understanding of the damage and recovery process and thereby hope to significantly improve on this performance demands that we continue to aggressively pursue this approach to calorimetry at the SSC. We are therefore so proposing in our FY91 plan and in addition intend to acquire a deeper understanding of the system dependent issues of radiation damage on the performance of the calorimeter.

The choice of absorber is the second key issue for our design of calorimeter as our stated goal is a compensating calorimeter with high precision and uniformity. Our simulation studies have shown that both depleted uranium and lead absorbers of appropriate thicknesses relative to the chosen thickness of the scintillator plate can yield a calorimeter which has equal response to

both hadrons and electrons or photons of the same energy. A calorimeter based on a pure iron absorber does not. In addition, the time dependence of compensation in both lead and depleted uranium systems is very similar in the initial part of the shower and both can yield a response which is almost compensating in less than the 16 nsec between bunches at the SSC ($e/h < 1.05$). Therefore, even trigger signals for these calorimeters measure an essentially compensating response. Energy release from delayed de-excitation of neutron capture reactions is observed only in the uranium system and may be the physics reason to prefer lead. This gives approximately 3-10% of the total signal stretching out over 200-500 nsec. Although we have not yet quantified the experimental effect of this energy, such pileup is very undesirable (and yet more so at the higher potential luminosities). Mechanical solutions for both choices of absorber have been evaluated using both analytical and simulation techniques. Both absorbers are feasible with the caveats that both allow azimuthal load transfer in the body of the calorimeter and that in the case of lead it is embedded in a composite structure. This structure is estimated to comprise at worst < 10% of the lead volume and potentially can be distributed where it will have least affect on the performance of the calorimeter (this is part of the work being proposed for FY91). Moreover, the fabrication process of lead casting and the cost of the raw material greatly favours lead over depleted uranium. It is therefore our assessment that the appropriate choice for the absorber is lead and lead/composite and that the fabrication process to be used should be casting. Our proposal of work for FY91 assumes this conclusion and is directed at demonstrating this conclusion with physical devices.

Two options for the optical system used to couple scintillation light from the plate to the photon transducer were conceptually evaluated. Wavelength shifter plate is a very well known and well understood approach and for it. One the serious limitation for waveshifter plate is in the necessity to allow azimuthal load transfer between modules and therefore the need to modify the plate cross section at these radii (with resulting serious implications for both lateral and depth uniformity). A second serious limitation is the dead fiducial volume associated with the waveshifter plate and its associated air gaps and tolerances to preclude its being crushed. This loss can amount to as much as 7% of the surface area and although energy measurement in this region can be obtained by a suitable tilting of the front section, high quality electron measurements in this region would probably be impossible. The third serious limitation of this approach is Cerenkov light in the waveshifter plate itself. Although this can again be largely removed by tilting the front section of the calorimeter, this design, by using single sided readout to reduce dead space, has no intrinsic capability of identifying such light and thereby of vetoing the associated spurious signals. On the other hand, readout via embedded wavelength shifting fibers can potentially remove all of these limitations and in addition could be used in a design to allow refurbishment of those parts of the calorimeter exposed to the greatest radiation damage. However, it has a very large potential for intrinsic non-uniformity. The Fermilab group lead by G. W. Foster and J. Freeman have completed some early tests using this optical approach and have had considerable success. It is our assessment that this approach is the one with greatest potential for achieving our stated goal of maximum hermeticity and fiducial volume and we therefore propose it, as the favoured choice, as the one to be allocated our resources in FY91. It is nonetheless true that should we demonstrate that scintillator itself is radiation hard, then should we fail

to accomplish the necessary performance with a fiber-based readout then waveshifter plate can also be accommodated within this mechanical design (albeit with reduced performance of the calorimeter relative to our goals).

As a result of conclusions we opened discussions with the fiber tile component of the scintillating-fiber group with regard to a combined proposal in FY91. These discussions concluded with an agreement to submit a combined proposal in FY91 to specifically develop a calorimeter based on scintillator tile with embedded wavelength shifter fiber readout. Our main point of contention is that they anticipate that an iron based calorimeter with tuned absorber inserts can yield adequate compensation whereas we anticipate that a lead/composite structure (in which the composite is also iron) can be designed to be mechanically stable and to yield adequate compensation. All other areas of development are common to both absorber choices. Whether this calorimeter is eventually described as iron with some lead to achieve compensation or lead with some iron to yield mechanical stability is one of the key issues to be resolved by this collaboration in FY91.

APPENDIX I

Report on Benchmarking CALOR at ANL

John P. K. Jim Proudfoot and Larry Price

The Benchmarking of CALOR 59 for two scintillator plate systems has been carried out at Argonne. The salient features of the three systems chosen for benchmarking are given in table I. Out of this Iron and Lead systems were analysed at ANL.

All calculations were done for 10 GeV pions and electrons. The energy cut used for hadrons in HETC is 1.0 MeV. The energy cut used for electrons in EGS is 1.5 MeV and for photons 0.1 MeV. The ESTEPE parameter in EGS is not used. Neutrons below 20 MeV were transported by MORSE. The low energy photons from EGS were not transported by MORSE because of their negligible effect on the energy deposition (less than 0.2%). The light curves were calculated for Birks Constant 0.0131 and were used in SPECT and MORSE.

The electron response plot, longitudinal shower distribution and two dimensional shower distribution were calculated using EGS on a CRAY-XMP. The CALOR suite of codes were run on an IBM 3084. The eventwise energy deposition in the scintillator plates from each of the three codes of CALOR (HETC, EGS and MORSE) and their averages were calculated and stored in separate files. From these files the response plot for pions were calculated by a user written program.

Table II gives the summary results. The response plots for pions and electrons, their resolutions and the e/h ratio for both the configurations are given. These values are to be verified independently by the other groups.

TABLE I
SALIENT FEATURES OF BENCHMARK CONFIGURATIONS

	DEU-SCIN	Pb-SCIN	Fe-SCIN
Absorber medium	Depl Uranium	Lead	Iron
Absorber Thickness	0.33 cm	0.56 cm	1.76 cm
Radiation Length	0.33 cm	0.56 cm	1.76 cm
Nuclear Int. length	10.5 cm	16.76 cm	17.09 cm
Density	18.95 gm/cm ³	11.35 gm/cm ³	7.87 gm/cm ³
Number Density	4.794×10^{22}	3.299×10^{22}	8.486×10^{22}
Active medium	Scintillator	Scintillator	Scintillator
Scintillator Thickness	0.25 cm	0.25 cm	0.25 cm
Density	1.04 gm/cm ³	1.04 gm/cm ³	1.04 gm/cm ³
Number Density			
Carbon	4.81×10^{22}	4.81×10^{22}	4.81×10^{22}
Hydrogen	4.92×10^{22}	4.92×10^{22}	4.92×10^{22}
Birks Constant	0.0131	0.0131	0.0131
Global Dimensions	100"100 cm ²	100"100 cm ²	100"100 cm ²
Depth	$8 \lambda_{int}$	$8 \lambda_{int}$	$8 \lambda_{int}$

Table I

Energy Deposition in Scintillator (MeV)

(For 10 GeV Incident Energy and 50 nsec Integration Time)

Unit Cell (cm)	Particle Type	Spect	ECS	MORSE	TOTAL	RMS	(σ/E)	$\sigma/\sqrt{E}$	q/n
FE-SCIN (1.76/0.25)	π^-	75.4 ± 2.0	83.2 ± 2.0	9.4 ± 1.0	168.0 ± 5.0	30.4	18.1	57.2	$1.24 \pm .03$
	e^-	---	208.2 ± 3.0	---	208.2 ± 3.0	14.7	7.1	22.3	
PB-SCIN (0.56/0.25)	π^-	199.7 ± 3.0	131.0 ± 2.0	81.5 ± 1.0	412.2 ± 6.0	51.6	12.5	39.6	1.04 ± 0.02
	e^-	---	431.9 ± 5.0	---	431.9 ± 5.0	23.9	5.5	17.5

10 GEV ELECTRONS Pb-SCIN CONFIGURATION

10 GEV PIONS PB-SCIN CONFIGURATION

10 GEV PIONS Pb-ScIN CONFIGURATION

10 GEV ELECTRONS FE-SCIN CONFIGURATION

10 GEV ELECTRONS FE SCIN CONFIGURATION

10 GEV PIONS FE-SCIN CONFIGURATION

APPENDIX I

Report on Benchmarking CALOR at ANL

Job P. K. J. J. P. and Larry P.

The Benchmarking of CALOR 50 for two scintillator plate systems has been carried out at Argonne. The salient features of the three systems chosen for benchmarking are given in table I. Out of this Iron and Lead systems were analysed at ANL.

All calculations were done for 10 GeV pions and electrons. The energy cut used for hadrons in HETC is 1.0 MeV. The energy cut used for electrons in EGS is 1.5 MeV and for photons 0.1 MeV. The ESTEPE parameter in EGS is not used. Neutrons below 20 MeV were transported by MORSE. The low energy photons from EGS were not transported by MORSE because of their negligible effect on the energy deposition (less than 0.2%). The light curves were calculated for Birks Constant 0.0131 and were used in SPECT and MORSE.

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	DEUT-SCIN	Pb-SCIN	Fe-SCIN
Absorber material	Depl Uranium	Lead	Iron
Absorber Thickness	0.33 cm	0.36 cm	1.76 cm
Radiation Length	0.33 cm	0.36 cm	1.76 cm
Nuclear Int. length	10.5 cm	16.76 cm	17.09 cm
Density	18.95 gm./cm ³	11.35 gm/cm ³	7.87 gm./cm ³
Number Density	4.794×10^{22}	3.299×10^{22}	8.486×10^{22}
Active medium	Scintillator	Scintillator	Scintillator
Scintillator Thickness	0.25 cm	0.25 cm	0.25 cm
Density	1.04 gm/cm ³	1.04 gm/cm ³	1.04 gm/cm ³
Number Density			
Carbon	4.81×10^{22}	4.81×10^{22}	4.81×10^{22}
Hydrogen	4.92×10^{22}	4.92×10^{22}	4.92×10^{22}
Birks Constant	0.0131	0.0131	0.0131
Global Dimensions	100*100 cm ²	100*100 cm ²	100*100 cm ²
Depth	8 λ_{int}	8 λ_{int}	8 λ_{int}

Table I

Energy Deposition in Scintillator (MeV)(For 10 GeV Incident Energy and 50 nsec Integration Time)

<u>Unit Cell (cm)</u>	<u>Particle Type</u>	<u>Spect</u>	<u>EGS</u>	<u>MORSE</u>	<u>TOTAL</u>	<u>RMS</u>	<u>(σ/E)</u>	<u>$\sigma/\sqrt{E}$</u>	<u>E/μ</u>
FE-SCIN (1.76/0.25)	π^-	75.4 ± 2.0	83.2 ± 2.0	9.4 ± 1.0	168.0 ± 5.0	30.4	18.1	57.2	1.24 ± 0.03
	e^-	---	208.2 ± 3.0	---	208.2 ± 3.0	14.7	7.1	22.3	
PB-SCIN (0.56/0.25)	π^-	199.7 ± 3.0	131.0 ± 2.0	81.5 ± 1.0	412.2 ± 6.0	51.6	12.5	59.6	1.04 ± 0.03
	e^-	---	431.9 ± 5.0	---	431.9 ± 5.0	23.9	5.5	17.5

10 GEV ELECTRONS Pb-SCIN CONFIGURATION

10 GEV ELECTRONS PB-SCIN CONFIGURATION

10 GEV PIONS PB-SCIN CONFIGURATION

10 GEV PIONS PB SCIN CONFIGURATION

10 GEV ELECTRONS FE-SCIN CONFIGURATION

10 GEV ELECTRONS FE SCIN CONFIGURATION

10 GEV PIONS FE-SCIN CONFIGURATION

10 GEV PIONS FE-SCIN CONFIGURATION

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ANL-HEP-TR-90-77

SDC-90-00073

24 August 1990

A First Simulation Study of the Barrel-Endcap Transition Region in a Calorimeter of the Scintillator Tile Design*

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ABSTRACT

We have made a first study of the calorimetric response to 10 GeV/c charged pions in the transition region between barrel and endcap for the scintillator-tile design pursued at Argonne National Laboratory using the simulation program ANLSIM. For (very nearly) projective tower orientations in the barrel, the crack appears deep within a narrow angular range, causing a loss of the response in that region up to 40 %. Pointing the towers onto the beam axis 35 cm or more away from the nominal interaction point leads to a shortened depth of the barrel-endcap crack as seen by particles incident from the interaction region, cutting the maximum loss down by almost one half. The worsening of the resolution follows the same trend. Introduction of a solenoidal coil in front of the calorimeter causes an overall degradation of the response by an amount nearly comparable to the effect of the crack. Electrons of the same incident momentum are more strongly affected by the coil than pions but see only a much narrower region of degradation by the crack.

* Work supported by the U.S. Department of Energy, Division of High Energy Physics, Contract W-31-109-ENG-38

1. Introduction

Calorimeter designs for SSC detectors are often subject to a variety of mutually contradictory semi-hard requirements and boundary conditions. The underlying demands arise from the physics issues expected to be addressable by SSC experiments. These include hermeticity and homogeneity of the response over most of the solid angle and requirements on position and energy resolutions for electromagnetic and hadronic showers. In particular at the size scale to be considered at the SSC, the technical feasibility tends to create contradictions between those requirements. For instance, good spatial resolution is best achieved with a projective-tower readout geometry. This leads either to projective gaps ruining the hermeticity and local homogeneity of the response or to large cracks between large modules or to large amounts of nonsensitive materials in the region of the shower development.

In this note we present a simulation study of the barrel-endcap transition region for a calorimeter design as pursued at Argonne National Laboratory for a scintillator-tile sampling calorimeter.^[1] In the following, we describe the tools and procedures used (section 2) and the results of the simulation runs and conclusions (section 3).

2. Tools and Procedures

The starting point for the present study is a design by N.Hill^[1] shown in Fig.1. We have coded this geometry as shown in Fig.2 for use in the simulation program ANLSIM,^[2] which is based on GEANT.^[3] In the azimuthal direction, the setup is simplified for the simulation as being cylindrical everywhere. The tower geometry is coded and handled independently of the GEANT data structures. The simulation program is kept flexible with respect to the design by basing it on a number of parameters measuring various dimensions that can be set at run-time. Thus a design change can be accommodated without additional coding

and recompilation, within some limits. The relevant parameters are listed in Table 1. In this setup, the coil produces a homogeneous axial magnetic field of 2 T strength (dialed by input at run time) in the volume it encloses. There is no flux return modeled, so the calorimeter resides completely in a field free region. The essential features of this design for the present study are detailed in Appendix 1 which may serve as a guide to set the input variables for the program as well.

A set of options are investigated below making use of the selections offered in the program setup:

1. the standard design as given by N.Hill,⁽¹⁾ with 7 towers at the center oriented straight at a right angle to the beam axis, i.e. 3.5 on each side of $z = 0$ m, four more towers maintaining the radial thickness of the barrel and pointing, like all further barrel towers, to $z = 3.5 \cdot \text{towerwidth}$, and endcaps "fitting" into the conical end faces of the barrel with axially oriented towers of constant cross section; this is a nearly projective geometry in the barrel, avoiding the gaps between the barrel and the endcaps to point directly to the interaction point;
2. the strictly projective design, different from the standard simply by having no straight central towers;
3. further nonprojective designs like the standard one with the offset of 3.5 tower widths replaced by 1.5, 2, 2.5, 3, 5.5, 7.5 and 20 tower widths.

The variation the offset for projecting the towers determines the projectivity of the crack between the barrel and the endcap. In all cases, the endcap is moved in to just touch the aluminium support cones (1 inch thick) of the barrel. This leads to a minimal air gap. No material inside the volume enclosed by the calorimeter is simulated in the round through varying tower offsets; the magnetic field in that volume is taken present nevertheless. The calorimeter response is calibrated in the simulation for electromagnetic and hadronic energy depositions separately to recombine to an e/π ratio of close to 1.0 and to reproduce the absolute energy

scale, both to within about three percent.

For each setup, program runs are made sending negatively charged pions of momentum $10 \text{ GeV}/c$ into the calorimeter at 14 values of pseudorapidity, $\eta = 1.20, 1.30, 1.34 - 1.58$ in steps of 0.04, at 1.80 and intermediate points at $1.40 - 1.52$, and randomly chosen azimuth ϕ . The center of the gap between the barrel and the endcap is located around $\eta = 1.44$. The pion induced showers are simulated in ANLSIM using full analog simulation with relatively high cuts on the kinetic energies; they are set to 100 MeV to limit the execution times. This will misestimate the absolute resolution somewhat and also slightly reduce the shower size. It will nevertheless give a reasonable relative comparison of the design variants under consideration.

3. Results on Calorimeter Response

The total deposited energy before any clustering is performed is taken as the response of the calorimeter for the present purposes. The distributions of this energy normally contain about one thousand entries for each preset value of the pseudorapidity η . The results for three of the offsets investigated are collected in Table 2.

The calorimeter shows a flat response (Fig.3) of about 10 GeV with a deep dip of observable width in the gap between the barrel and the endcap developing as the tower orientation offset goes towards zero. (The error bars for the means in this figure show the r.m.s. value of the distribution and not the error of the mean, for the r.m.s. values, the error bars have no physical meaning at all.) At the "standard" design offset of 35 cm , the dip is a little more than 20 % for $10 \text{ GeV}/c \pi^-$ incident, up from 40 % for the projective design, and has begun to level off in dependence on that offset (Fig.4). Adding more material in the gap will widen and deepen the dip in the response curve particularly for (nearly) projective designs. Choosing a point away from the deep-dip region as given by

the present study will then provide some safety margin against getting into the large uncertainties connected with the strong response variations.

We then include a simple model of the solenoidal coil in front of the calorimeter as shown in Fig.2 using the standard 35 cm tower projection offset and study the resulting response to pions (Fig.5). We find an overall degradation of more than 10 % within the solid angle coverage of the coil with only half of that effect in the crack-related dip. Clearly, the coil as modeled provides a scattering center in front of the crack that spreads the energy deposition beyond the coil into the sensitive regions of the calorimeter. The range in pseudorapidity affected by the coil end is about $\eta = 1.42 - 1.52$ and the resolution is degraded by less than 30 %. This is certainly a somewhat too optimistic picture of the reality since there may be more material in the coil end itself (we use a massive aluminium ring of thickness 15 cm along the beam axis and 30 cm radially) and will be more material for support of tracking systems and supplies for everything inside the volume enclosed by the calorimeter. For comparison, the simulation efforts for the SDC Expression of Interest^[4] assume the range of degradation to be $\eta = 1.25 - 1.5$ and the increase of the resolution up to 70 %.

An additional check on the performance for the standard geometrical choice is to look at the response and acceptance for electrons. We performed runs for the standard design without and with coil in place for electrons of 10 GeV/c momentum. For the set and density of points in pseudorapidity used, the crack produces a very deep but also narrow ($\Delta\eta \approx 0.01$ wide) dip in the response. The coil takes much more energy away from the electrons than from pions as has to be expected (Fig.6) and also worsens the response in the dip significantly. This means the design under consideration essentially will have a narrow ring almost blind to electrons of moderate energies. This is probably acceptable unless the gap has to be widened for hardware support installations a lot.

To conclude, we have obtained support from full simulations of pion showers for a preference of using a quite moderately nonprojective tower geometry in the

absorber-scintillator tile calorimeter as considered for SDC. The tower orientation determines the orientation of the gaps in the calorimeter coverage, and it is these gaps that have to be well covered by active detectors in a view from the interaction point. The impact of having a solenoidal coil in front of the barrel calorimeter the ends of which reach into the barrel-endcap region is in size comparable to the effect of the crack itself. In the final detector, the crack will contain more material than only the support cones for the barrel calorimeter. For that total amount of passive material, the 1 inch thickness of the support cones is a very crude and possibly thin approximation. In continuing this study, we will look at the impact on particle and jet reconstruction in some detail, and we will also attempt to improve the geometry to reflect more realistically the dead material needed by the detectors and the simulation technique to study higher particle energies.

APPENDIX 1

The following is a detailed description of the structure of the geometry setup used in ANLSIM:

1. The central towers in the barrel are oriented strictly at a right angle with respect to the beam axis, thus they are not projective in the (r, z) plane (where r denotes the radius in the plane transverse to the beam axis). The number of these towers, counted from $z = 0$ to one side only, is given in the variable BARTOF. In the range of these towers the total transverse thickness of the barrel calorimeter is set by the variable BARDRC. The side length of the central towers at their front face is taken to be BARTOW.
2. At the front faces, a conical shell of aluminium of thickness BARCON is attached to support the barrel.
3. By projecting the outside boundary of the central towers onto the beam axis, a secondary origin is defined. From this origin outward, i.e. away from the main coordinate origin, a pseudorapidity variable is used to define the polar boundaries of the remaining barrel towers. A constant stepping in pseudorapidity produces a constant *projected* size of the towers at the inner surface of the barrel (see appendix 2). The same side length BARTOW is imposed here for the projected size that is used for the central towers also. Thus, a strictly projective tower geometry in the barrel can be produced by having zero central towers as defined above; this is in fact allowed by the simulation program. In turn, an extremely nonprojective geometry can be defined by making the central towers extend over most of the barrel range. This range or half length at the inside surface is defined as the half length of the coil COILZE plus an extension BAREXT over this point, truncated to the largest number of complete towers that can be contained in this bound.
4. Across the first BARTOF towers in the - relative to the secondary origin - projective region, the central transverse thickness of the calorimeter is

maintained. Beyond those, the outer transverse radius decreases linearly with the axial coordinate z to produce an outer side length `BARDRE` of the "last" ring of barrel towers. (That length is measured on a ray from the secondary origin along the side face of the towers.)

5. The endcaps are constructed as thick cylinders (length/depth `ENDDZC`, radial extent `ENDDRT` starting at an inner radius `ENDRIN`), with a few (`ENDDRI`) rings within the radial extent reduced in depth on the inside and a larger number (`ENDNST`) of rings added on the outside to form an approximation to a conical shape. The inside rings follow a cone with its apex at the primary origin. The outer rings are aligned to have their edges at a constant distance from the outermost ring of barrel towers, i.e. they follow a cone parallel to the cone with an apex slightly further out than the secondary origin and an angle given by the end face of the barrel. The placement of the whole endcaps along the beam axis is governed by the half length `COILZE` of the coil and the gap width `ENDGAP` between the coil and the front face of the endcap. The towers are oriented axially, i.e. not projective; this feature is fixed.
6. The outer rings of the endcaps are divided into a short and a long remnant piece each such that the short rings just overlap by a given amount `ENDRGO`. The idea is to allow to form pseudotowers on the endcap side of the gap between the barrel and the endcap that approximately continue the tower structure of the barrel by one more layer. This could be useful for pattern recognition across that gap. In the present study, this feature has not been used and the short pieces are effectively joint with the longer remnants into one piece.
7. The azimuthal subdivision throughout all of the calorimeter parts is chosen to give a width at the inner face of the calorimeter as close to the desired tower side length (`BARTOW` and `ENDTOW` resp.) as possible under the restriction of having an integral number of towers around the azimuthal

circumference. (This will give an inaccurate model of the performance of pattern recognition in the endcap region; for the current purpose, this does not matter.)

8. The whole calorimeter is subdivided into one longitudinal electromagnetic section of transverse/axial thickness BARDEM and ENDDM resp., and one hadronic section.
9. Each tower (electromagnetic and hadronic separately) is assigned artificially a coordinate in the pseudorapidity-azimuth plane (η, ϕ) as follows:
 - (a) The ϕ coordinate is taken at the azimuthal center of the tower in all cases.
 - (b) The η coordinate for the electromagnetic towers is taken at the halfway point into the tower on their center lines.
 - (c) The η coordinate for the hadronic towers in the barrel and in the main body of the endcap is taken 1.5 times the depth of the electromagnetic section (not the length of the tower in front), i.e. BARDEM and ENDDM resp., into the hadronic section at right angles, not measured along the center lines of the towers.
 - (d) In the rings of the endcaps, the assigned η coordinates are picked on cones connecting to the plane used in the main body, with a cone angle taken wide enough to conserve the spatial radial order of rings of towers in the pseudorapidity order.
10. The detector geometry can be extended (via input flags at run time) to include a beam pipe, a coil, a model of an all-scintillating-fiber tracker, and a muon system. The coil parameters are used in the setup of the calorimeter as is evident above; they are available and modifiable even if no actual placement of the coil into the geometry setup to be known by ANLSIM/GEANT is requested.

The routines needed to define and use the setup are kept in a separate file, replacing the default ones of ANLSIM at linking time.

APPENDIX 2

The equivalence of constant tower size in the pseudorapidity coordinate η and in projected size (side length $2 \cdot \Delta w$) at the inside of a cylinder of inner radius R_0 can be seen as follows:

Let the ray from the interaction point into the center of a tower have the polar angle Θ with respect to the beam axis. Then the half width Δw of the tower is related to a deviation of the polar angle

$$\Delta w = \frac{R_0}{\sin(\Theta)} \tan(\Delta\Theta) .$$

In order to study the angular dependence of the "cumulated half widths" function w , let us use in the limit of small angular deviations the approximation of the tangent function by its argument,

$$\tan(\Delta\Theta) \rightarrow \Delta\Theta .$$

This substitution leaves the limit $\Delta\Theta \rightarrow 0$ of Δw invariant, being

$$\frac{dw}{d\Theta} = \frac{R_0}{\sin(\Theta)} ,$$

as the difference $\tan(\Delta\Theta) - \Delta\Theta$ is continuously differentiable in a whole neighborhood of zero and it and its first derivative vanish at zero (the former quadratically as its Taylor series exists and converges in that region). By integration from $\Theta = \pi/2$ to any polar angle we find⁽⁴⁾ for the function w the representation

$$w(\Theta) = R_0 \ln\left(\tan\left(\frac{\Theta}{2}\right)\right) = -R_0 \eta .$$

Thus, the request arising from the physics of jets to define towers with constant width on the (pseudo-) rapidity scale and that one arising from pattern recognition to define towers of constant width across the lateral extension of showers

actually coincide in a cylindrical calorimeter aligned on the beam axis. This coincidence is lost in the endcaps where Δw has a different dependence on Θ .

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TABLE CAPTIONS

1. Design parameters used in the geometry-setup for ANLSIM (lengths in cm; defaults in parentheses)
2. Pseudorapidity, polar angle, momentum components, mean response and r.m.s. of the response for a) the standard design, b) the projective design, c) the highly nonprojective design with 2 m offset

FIGURE CAPTIONS

1. Side view of the calorimeter design addressed in this study
2. Side view of the mechanical calorimeter geometry as seen by the ANLSIM program - standard design with optional coil
3. Mean response and resolution for 10 GeV/c π^- of the calorimeter of ref.1 for different offsets of the tower orientation; the errors on the mean shown are the resolutions, and the error bars shown for the resolution have no physical meaning
4. Minimum response to 10 GeV/c π^- in dependence on the tower projection offset; the additional star for 35 cm offset shows the effect of the solenoidal coil.
5. Mean response and resolution for 10 GeV/c π^- of the calorimeter of ref.1 without and with coil in place
6. Mean response and resolution for 10 GeV/c e^- of the calorimeter of ref.1 without and with coil in place

Table 1

PIPEIN	inner radius of Beryllium beam pipe (4.9)
PIPEDR	thickness of beryllium beam pipe (0.1)
COILIN	inner radius of inner coil shell (185.0)
COILMI	inner radius of central coil shell (198.5)
COILUT	outer (!) radius of outer coil shell (215.0)
COILZH	axial half length of coil (450.0)
COILEN	axial length of massive coil end pieces (10.0)
COILD1	radial thickness of inner coil shell (3.0)
COILD2	radial thickness of central coil shell (3.0)
COILD3	radial thickness of outer coil shell (3.0)
BAREXT	axial extension on each side of the front face of the barrel calorimeter (5.0)
BARGAP	radial space between outside radius of coil and the barrel calorimeter (10.0)
BARDRC	total radial thickness of barrel at $z=0$ (234.9)
BARTOF	number of towers from center out that have constant width in z (3.5)
BARTOH	number of additional towers beyond the constant width ones for which the radial thickness of the barrel remains constant (4.0)
BARDRE	total depth of barrel along side to end cap (243.8)
BARDEM	thickness of electromagnetic barrel section ($19.3=7.592*2.54$)
BARTOW	projected azimuthal front width of towers (10.0)
BARCON	thickness of aluminium support cone at end faces (2.5)
ENDGAP	space between coil end and front face of end cap (25.0)
ENDRIN	inner radius at front face of end cap (50.0)
ENDDRT	radial thickness of end cap at front face (180.0)
ENDDRI	radial number of inner towers shorter than full axial thickness of end cap (3.0)
ENDDZI	length of innermost hadronic endcap towers (12.8)
ENDDZC	axial thickness of end cap ($278.2=375*0.292*2.54$)
ENDDEM	thickness of electromagnetic end cap section ($19.3=7.592*2.54$)
ENDRGO	axial overlap of rings ($2.3=3*0.292*2.54$)
ENDTOW	side length of end cap tower (10.0)
ENDNST	number of steps for outside rings of end caps (11)

Table 2a

eta	theta	pz	pT	number	$\langle E(\text{obs}) \rangle$	r.m.s.
	[degrees]	[GeV/c]		of events	[GeV]	[GeV]
0.00	90.00	0.000	10.000	1000	10.16	1.25
1.20	33.50	8.337	5.523	1000	10.17	1.20
1.30	30.50	8.617	5.074	1000	10.10	1.30
1.34	29.35	8.717	4.901	1000	10.14	1.21
1.38	28.24	8.810	4.732	1000	10.04	1.26
1.40	27.71	8.854	4.649	1000	10.12	1.32
1.41	27.44	8.875	4.608	1000	10.05	1.28
1.42	27.18	8.896	4.567	1000	10.07	1.24
1.43	26.92	8.917	4.527	1000	9.91	1.39
1.44	26.66	8.937	4.487	1000	9.41	1.39
1.45	26.40	8.957	4.447	1000	7.72	1.97
1.46	26.15	8.977	4.407	1000	9.44	1.57
1.47	25.90	8.996	4.368	1000	9.79	1.31
1.48	25.65	9.015	4.328	1000	9.92	1.30
1.49	25.40	9.033	4.290	1000	10.00	1.32
1.50	25.16	9.051	4.251	1000	10.04	1.26
1.52	24.67	9.087	4.175	1000	10.14	1.26
1.54	24.20	9.121	4.099	1000	10.13	1.25
1.58	23.28	9.186	3.952	1000	10.14	1.32
1.80	18.77	9.468	3.218	1000	10.18	1.26

Table 2b

eta	theta	pz	pT	number	<E(obs.)>	r.m.s.
	[degrees]	[GeV/c]		of events	[GeV]	[GeV]
0.00	90.00	0.000	10.000	1000	10.16	1.16
1.20	33.50	8.337	5.523	1000	10.09	1.40
1.30	30.50	8.617	5.074	1000	10.09	1.41
1.34	29.35	8.717	4.901	1000	10.13	1.35
1.38	28.24	8.810	4.732	1000	10.15	1.39
1.40	27.71	8.854	4.649	1000	9.94	1.32
1.41	27.44	8.875	4.608	1000	9.85	1.37
1.42	27.18	8.896	4.567	1000	6.95	2.08
1.43	26.92	8.917	4.527	1000	6.06	3.27
1.44	26.66	8.937	4.487	1000	9.26	1.60
1.45	26.40	8.957	4.447	1000	9.73	1.51
1.46	26.15	8.977	4.407	1000	10.04	1.31
1.47	25.90	8.996	4.368	1000	10.02	1.29
1.48	25.65	9.015	4.328	1000	10.00	1.33
1.49	25.40	9.033	4.290	1000	10.13	1.34
1.50	25.16	9.051	4.251	1000	10.14	1.39
1.52	24.67	9.087	4.175	1000	10.15	1.22
1.54	24.20	9.121	4.099	1000	10.20	1.28
1.58	23.28	9.186	3.952	1000	10.11	1.29
1.80	18.77	9.468	3.218	1000	10.15	1.31

Table 2c

eta	theta	pz	pT	number	<E(obs.)>	f.m.s.
	[degrees]	[GeV/c]	of events		[GeV]	[GeV]
0.00	90.00	0.000	10.000	1000	10.21	1.26
1.20	33.50	8.337	5.523	1000	10.15	1.31
1.30	30.50	8.617	5.074	1000	10.22	1.32
1.34	29.35	8.717	4.901	1000	10.10	1.28
1.38	28.24	8.810	4.732	1000	9.91	1.37
1.40	27.71	8.854	4.649	1000	9.78	1.33
1.41	27.44	8.875	4.608	1000	9.70	1.42
1.42	27.18	8.896	4.567	1000	9.55	1.57
1.43	26.92	8.917	4.527	1000	9.72	1.43
1.44	26.66	8.937	4.487	1000	9.96	1.39
1.45	26.40	8.957	4.447	1000	10.06	1.29
1.46	26.15	8.977	4.407	1000	9.99	1.34
1.47	25.90	8.996	4.368	1000	10.08	1.36
1.48	25.65	9.015	4.328	1000	10.12	1.21
1.49	25.40	9.033	4.290	1000	10.11	1.25
1.50	25.16	9.051	4.251	1000	10.09	1.29
1.52	24.67	9.087	4.175	1000	10.18	1.26
1.54	24.20	9.121	4.099	1000	10.18	1.21
1.58	23.28	9.186	3.952	1000	10.06	1.25
1.80	18.77	9.468	3.218	1000	10.20	1.22

Fig. 2

$\langle E_m \rangle$ - Strictly projective barrel

$\langle E_m \rangle$ - Projection effect 15 cm no coil

$\langle E_m \rangle$ - Projection effect 20 cm no coil

Fig. 3 (1 of 6)

Fig. 3 (2 of 6)

$\langle E_{\text{cal}} \rangle$ - Projection offset 55 cm no coil

$\langle E_{\text{cal}} \rangle$ - Projection offset 75 cm no coil

$\langle E_{\text{cal}} \rangle$ - Projection offset 200 cm no coil

Fig. 3 (3 of 6)

Fig. 3 (4 of 6)

Fig. 3 (5 of 6)

Calorimeter response over

$\sigma_{em}/\langle E_{em} \rangle$ at 1 GeV - projection offset 55 cm, no coil

$\sigma_{em}/\langle E_{em} \rangle$ at 1 GeV - projection offset 75 cm, no coil

$\sigma_{em}/\langle E_{em} \rangle$ at 1 GeV - projection offset 200 cm, no coil

Fig.3 (6 of 6)

Minimal response in transition region

Fig. 4

Calorimeter response over

Fig. 5

Calorimeter response over

Fig. 6

APPENDIX III

REPORT ON RADIATION EXPOSURE OF LEAD-SCINTILLATOR STACK

D. Underwood

16 August 1990

A stack of lead and scintillator was placed in a neutral beam obtained from targeting 800 GeV protons. Small pieces of film containing radiochromic dye were placed adjacent to the layers of scintillator for the purpose of measuring the radiation dose to the scintillator. Our motivation was to calibrate the radiation dose obtainable in this manner for future tests of scintillator for SSC experiments. We also observed several other radiation effects which should be considered for an SSC calorimeter.

The lead-scintillator stack was constructed in a simplified manner due to limitations of space and materials. It consisted of CDF scintillator (5 mm) at 1/2 and 6 radiation lengths of lead, old scintillator from a prototype (5 mm) at 3 and 4.5 rad. len., Y7 waveshifter plate (3 mm) at 6 rad. len., and 1/2 rad. len. of lead behind. Dye film was placed at .5, 1.5, 3, 4.5, and 6 r.l.

The stack was placed at the face of the neutral beam dump of the polarized beam at Fermilab. The neutral beam is from very forward production and consists mainly of photons and neutrons. The collimator acceptance in the sweeping magnet is approximately ± 0.7 mr angle both horizontally and vertically. Approximately $1.5 \text{ E} 12$ primary beam was targeted per minute (on a 1 r.l. target) from July 26 to August 13 (18 days with about 30% down time). Approximately $2.5 \text{ E} 16$ protons were targeted. The order of magnitude neutral

beam we expected (gammas and neutrons) was one order of magnitude less than the number of primary protons.

The radiation exposure was determined by measuring the optical density of the radiochromic dye films with a spectrophotometer at two wavelengths. Calibration curves provided by Far Western Technology and traceable to NIST only covered .3 MRad to 2. MRad for 600 nm and .5 to 5. MRad for 510 nm. Curves for up to 100 MRad are published in a survey article on dosimetry.¹ The curve turns over at 50 MRad.

The dose was higher than expected and in a non-linear part of the response curve of the film. At .5 r.l. we found 8. MRad in the center and 1 to 2 MRad at the edges due to the beam profile. At 6 r.l. we found 40 MRad on the scintillator and 20 MRad on the waveshifter behind it. It is not known whether this difference is measurement variation or if the dose immediately behind the lead really is higher than behind 5 mm scintillator.

One possible problem with calibration of dose was possible exposure of the film to UV light from the scintillator excited by the particles in the electromagnetic shower. Possible light shields such as the garbage bag disintegrate. In fact, measurements between layers of lead with no scintillator were in reasonable agreement with measurements at the scintillator.

When the stack was removed from the beam, the induced radiation level in the lead at 6.5 rl was about 700 mR/hour on contact. The upstream side was about 200 mR/hour. The radiation was mainly gamma rays and had a half life of about 3 days. We believe that the isotopes responsible for the radiation can be determined. We are in the process of arranging for measurement of the gamma spectrum. Knowing the radiation history and the time constant, we could find the amount of induced radiation per primary proton, and using the

radiochromic dye to measure exposure, we could find induced radiation vs. radiation exposure. The induced activity is probably due to the neutron beam, but the hadron to photon ratio may be typical for hadronic reactions.

The steady state activity for constant rate exposure is the dose rate * ratio factor * decay time constant. Crudely, if we take 40 MR in 18 days and a time constant of 2.5 days, and .8 Rad activity, the ratio factor is $1.6 \text{ E-}7$. When the stack was disassembled after 2.3 days, the scintillator was found to have very little induced radiation (less than .005 of the lead).

When the stack was disassembled, there was radiation induced physical damage to plastic materials and paper. A thin dark plastic garbage bag disintegrated into small flakes. The paper on the CDF scintillator (the same paper used in the calorimeter) at 6 rl which was in contact with the lead turned to powder in the area of the beam, but the paper in contact with the scintillator was not as badly damaged. There was less obvious damage at 0.5 rl. Some white plastic foam used to cushion the older scintillator in compression with the lead disintegrated and stuck to the lead. The glue in stick-on paper labels used to attach the dye films became very hard and brittle. The CDF scintillator at 6 rl was yellow-brown but the others were transparent. The protective paper on the Y7 waveshifter surface had not been removed and became a white powder which was stuck to the surface.

This experience may aid in the future to make comparative measurements of the optical properties of damaged and undamaged stacks with the configuration of calorimeters. It would also be interesting to relate the dose to the photon and neutron flux if these could be determined adequately.

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