BNL--35492

DE85 004645

CALORIMETRY FOR THE SSC

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Presented at the Summer Study on the Design and Utilization of the Superconducting Super Collider

Snowmass, Colorado
June 23 - July 13, 1984

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Calorimetry for the SSC*

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Introduction

The use of calorimetric measurements of particular jet energies, angles and types is expected to be of paramount importance in SSC experiments. The signatures of interesting new physics are imagined to include identification and measurement of jets, electrons, photons and missing energy up to nearly the full beam energies. At high energy, calorimetric measurements are superior to other known methods for a variety of reasons. Up to the limits imposed by calibration systematic error, the relative energy resolution decreases like $1/\sqrt{E}$, whereas magnetic measurement resolution increases like E. The depth required for containment of energy increases only as ln(E) so that calorimeters offer relatively compact detectors. Radiation hardness, a requirement for the full SSC luminosities, is possible to achieve with suitable choices of media. The time resolution required to extract interesting events in the very large collision rates (mean Δt = 10nsec), although insufficient for full time separation, is probably achievable at the level required to extract most physics. It is also true that signals from calorimeters lend themselves to forming fast triggers which can extract useful candidate events for further analysis. Since calorimeters are by nature massive, they complement detection of muons by presenting absorber material required in any case for muon identification. Finally, since measurement of jets will be crucial at the SSC, the similarity in response of calorimeters to charged and neutral hadrons or electromagnetic particles is essential.

The demands upon an ideal SSC calorimeter are many and varied; optimization of parameters for particular physics purposes will depend upon the particular requirements of an experiment. The identification of non-interacting particle production (neutrinos, photinos etc) demands excellent control of energy resolution, and position accuracy as well as careful attention to minimizing dead zones of coverage. Maximizing energy resolution requires the largest possible sampling frequency for energy deposits, as well as sufficient longitudinal depth to avoid degradation due to leakage fluctuations. Use of calorimeters for particle identification (electron/hadron, γ/π^0, W → jets /QCD jets etc.) will place particular premium on segmentation, both transverse and longitudinal. Similar requirements on transverse segmentation result when one desires to isolate particular particles in the vicinity of many other particles (e.g. identification of leptons in the midst of quark jet fragmentation). Study of rare events at the highest accessible luminosity will place particular stress on the speed of signal collection and shaping in order to avoid confusing overlap from unwanted background collisions. Finally the cost optimizations will stongly influence calorimeter choices; beyond the obvious dependence on raw material costs, there is strong benefit from maximizing the mean density and in minimizing the space required for signal collection and processing.

The investigations of calorimetry at the SSC were aided by talks on special topics by M. Abolins, U. Amaldi, C. Baltay, B. Cox, H. Frisch, P. Grannis, C. Heusch, J. Huston, J. Kirkby, S. Linn, T. Steinberger and G. Yodh. We have benefited from several excellent reviews on aspects of EM and hadronic cascades and the performance of calorimetry.[1-5].

The activities related to calorimetry at Snowmass took place in three main areas. These were:

1. The performance criteria for SSC calorimetry, including the requirements on hermeticity, shower contaiment, segmentation and time resolution. The use of calorimetric means of particle identification was studied and is summarized in the report of Fernandez et. al.[6];

2. The study of triggering methods using calorimeter energy, angle and timing information. This work is presented elsewhere in these proceedings.[7];

3. A review of a wide variety of calorimeter materials for absorber and sampling, as well as several means of obtaining the readout of the energy deposits.

The participation of many physicsts in these studies should be explicity noted. Their efforts, both at Snowmass and in the months following, have helped elucidate many of the desired properties of calorimetry at the SSC and have pointed the way toward essential studies and tests in the next few years. These individuals, with the breakdown of the various working groups and the organization of this summary are indicated below.

I. Performance Criteria for SSC Calorimetry

A. Hermeticity – S. Linn, F. Paige, B. Pope, L. Price, S. Protopopescu.
B. Shower Containment and Albedo – C. Newman-Holmes, G. Yodh.
C. Criteria for Segmentation – T. Ferbel, J. Huston, T. Kondo, R. Partridge.
D. Pile-up and Time Resolution – M. Glaubman, H. Gordon, J. Kirkby, P. Wanderer, D.P. Weygand.

II. Calorimetric Triggers – M. Abolins, L. Price, R. Wagner.

*This research supported by the U.S. Department of Energy under Contract DE-AC02-76CH00016 and by the National Science Foundation.

III. Potential Calorimetric Media

A. Uranium Absorbers and Compensation - C. Baltay, V. Cook, T. Ferbel, H. Gordon, P. Grannis, C. Heusch, H. Iwasaki, T. Kondo, I. Leedom, P. Slattery, T. Yamanaka, Y. Watanabe.
B. Warm Liquid Ionization Calorimeters - A. Lu, C. Heusch.
C. Gas Calorimeters - A. Lu.
D. Silicon Sampling - T. Kondo, Y. Watanabe, S. Kim.
E. New Heavy Glasses - B. Cox.
F. Barium Fluoride

I. Performance Criteria for SSC Calorimetry

A. Hermeticity

The recent experience of CERN $Sp\bar{p}S$ experiments shows the power of signalling the presence of neutrinos or other non-interacting particles in high p_T events. This is made possible if the E_T of hadrons, electrons, muons and photons are well measured over the largest possible solid angle. The vector transverse momentum in an event can be then used to infer the existence of non-interacting particles above some threshold in E_T, set by the scale of the E_T resolution errors.

Several effects combine to produce apparent missing p_T from imperfections in the detector. They include the finite energy resolution of the calorimetry, mismeasurement of shower angles, loss of particles within the holes imposed by the SSC beam pipes, loss of particles into cracks between adjacent segments of calorimetry and losses into uncovered regions due to the constraints of real life (supports, cable pathways etc.). Some of these are clearly detector dependant and must be studied with specific designs in mind. In this regard it is interesting to examine the effects of incomplete calorimetry coverage for CDF[8] and DØ[9] at the 2 TeV Fermilab Collider. Both of these detector simulations find that particular care must be paid to minimizing the cracks and dead zones in coverage in order to capitalize on good energy and angle resolution.

The natural scale for assessing instrumental effects is that set by the unavoidable losses by neutrinos. These come primarily from the semi-leptonic decays of c,b, and t quarks produced in hard constituent collisions. The effect of neutrinos has been evaluated for $\sqrt{s}$ = 40 TeV pp collisions using ISAJET[10-11] two-jet events containing the canonical mixture of heavy quark production. The differential cross section $d\sigma/dMPT$, where MPT is the missing p_T, is shown in Fig. 1 for these neutrino contributions above. The MPT distribution is seen to be strongly non-Gaussian for this source, with contributions at the level of 100 pb/GeV around MPT = 100 GeV/c. Figure 1 also shows the differential cross section due to losses within circular beam holes whose angular sizes are $\eta \geq 6$ ($\theta \leq 0.3°$), $\eta \geq 5.5$ ($\theta \leq 0.5°$), and $\eta \geq 5$ ($\theta \leq 0.8°$). These cross sections do not include effects of cracks, energy or angle resolution; they are computed using light quark jet events appropriately weighted over all p_T. The use of ISAJET in simulating the effect of small angle beam holes[11] is suspect, since that program does not include initial state gluon radiation. In particular, disagreement was found between ISAJET and analytic approximate calculations in details such as the dependence of MPT distributions upon jet p_T. Our comparisons in this workshop do indicate that the ISAJET simulations are at least qualitatively correct. Further work is needed to extend the analytic calculations to address the question of the full differential cross section vs. MPT. Taking the ISAJET results shown in Fig. 1, we find that the beam hole effects become less than those from neutrino production at a value of MPT ranging from 20 GeV/c for η(Hole) = 6.0 to about 40 GeV/c for η(Hole) = 5.0.

The effect of energy and angle resolution on the MPT distributions has been investigated for $\sqrt{s}$ = 40 TeV collisions. Figure 2 shows these results, again compared with the effect of neutrino emission. In this study, the energy resolution was assumed to be $\sigma = .35\sqrt{E}$ for hadrons and $\sigma = .15\sqrt{E}$ for EM particles. The energy resolution function was Gaussian. In addition, the impact point of each shower was assumed to have a measurement error of $\sigma_x = \sigma_y$ = 2cm (on a cylindrical approximation to a detector with effective radius = 100 cm, capped along the beams at 200 cm). Such resolutions lead to the expectation of missing p_T resolutions of the form $\sigma(MPT) = C\sqrt{\Sigma E_T}$ with C in the vicinity of 0.3. We see from Fig. 2 that these angle and energy resolutions have only modest effect on that due to a 0.5° beam hole (η = 5.4).

The effect of cracks in calorimeter coverage has been studied. For this calculation, dead regions were introduced into the calorimeter in the form of azimuthal wedges in a cylindrical calorimeter (r_{inner} = 100 cm) which extends between $30° \leq \theta \leq 150°$. These wedges have boundaries which project to the beam axes; they are assumed to be filled with material of the same density as the active regions of calorimetry. ISAJET events are propagated through a shower generating Monte Carlo (see Ref. 9) in which the mean longitudinal and transverse shower profiles are reproduced, as well as reasonable representations of fluctuations in energy deposit. The calorimeter density was chosen to approximate uranium and liquid argon ($\rho = \rho_{Fe}$) with X_0 = 1 cm and λ_0 = 20 cm. That energy which is deposited in the cracks was ignored and the remaining energy in live regions used to form the differential cross section. The results are shown in Fig. 3 for two values of crack size — 1.3% of the total area of the central calorimeter, and 4.0%. Again, the effect of neutrino production is shown in Fig. 3 for comparison. We see that there are some non-Gaussian tails in the cross section due to the cracks. Below MPT = 40 GeV, the effect of these cracks dominates the neutrino effect, even for 1% of dead area. The effect of these cracks at (1.3% dead area) is about the same as that due to a 0.5° beam hole, out to MPT = 30 GeV/c.

It is clear that, of the several controllable effects on missing p_T resolution the presence of cracks and dead spots is potentially most damaging. The cracks investigated in this workshop, even at the level of 1.3% of the area over the range $30° \leq \theta \leq 150°$, give rise to MPT broadening at levels comparable to reasonable beam pipe holes. They also yield non-Gaussian tails to the distribution. It is also found in real simulations of present experiments[8-9] that dead areas introduced for mechanical support and access will give larger MPT contributions unless rigorously controlled. Such calculations[9] indicate that particular attention must be paid to avoiding gaps in coverage for the EM portions of the calorimetry.

The conclusions of this workshop are then that various instrumental effects (cracks, beam holes and energy/angle smearing, in that order) are likely to dominate SSC missing p_T resolutions below about 40

GeV/c. At larger MPT, carefully constructed calorimeters should be sensitive primarily to real effects such as neutrino, photino, etc. production.

B. Shower containment and Albedo

The longitudinal depth required for containment of a fixed fraction of energy in a calorimeter increases logarithmically with incident energy. The longitudinal transition curves for hadrons are usually parametrized using t_{max} (the depth for shower maximum) and A (the effective attenuation length following shower maximum). Both t_{max} and A increase logarithmically with energy, so that the depth required to contain fraction f of a shower takes the form $t(f) = A + B \ln(E)$.

Measurements of A from accelerator data[12] and a cosmic ray experiment[13] give a combined result in the range $20 \leq E \leq 6000$ GeV of $A = 0.16 + 0.294 \ln(E)$ (in λ_0). The depth of shower maximum for energies between 3 and 200 GeV is taken from calculations[14] to be $t_{max} = -0.23 + 0.58 \ln(E)$ (in λ_0). The resulting depth for 95% containment is $t(95\%) = 0.41 + 1.75 \ln(E)$ (in λ_0) which yields 95% containment at 8.5 λ_0 and 12.5 λ_0 at 100 and 1000 GeV, respectively. It is worth noting that the parametrization from the CERN CDHS experiment gives $t(99\%) = 3.5 + 0.9 \ln(E)$, fitted to data between 15 and 140 GeV. This latter expression gives an extrapolated depth for E=1000 GeV of 9.7 λ_0 —considerably lower than the containment depth quoted above.

It is embarassing that such a fundamental parameter as the depth of calorimeter required to contain hadronic showers is known with such imprecision in the TeV regime. Clearly the costs of detectors which employ 15 λ_0 deep calorimeters will be quite a bit larger than those with 10 λ_0 of calorimetry. The issue is important, both for protection of muon detectors from punchthrough, and also for good energy resolution since fluctuations in the leakage fraction can be quite large. The existing accelerator[12] data shows approximately 30% degradation of resolution in going from 99% to 95% containment. Better high energy measurements of shower containment are called for. A contribution to these Proceedings by C. Newman-Holmes[15] tried to assess the importance of energy resolution and containment using the CDF Monte Carlo. It was assumed that μ's and ν's escape, there were no beam holes and some assumed angular resolution. To optimize the missing E_T resolution it was found that the energy resolution was not very important and the calorimeter only had to be 10λ_0 thick in order that the angular fluctuations were about equal to those from leakage.

The loss of energy from the entrance face of a calorimeter (albedo) can be of importance in affecting energy resolution. Albedo arises due to backscattered secondaries as well as long-range components emitted isotropically in nuclear fragmentations. Cosmic ray measurements[16] of the backscattered charged particle component give the number (into $\Delta\Omega = 2\pi$) per shower of $N = 2.4 + 1.13 \ln(E/100\ \text{GeV})$ for showers between 150 and 2000 GeV. Assuming each particle carries an average of 0.5 GeV, this component of albedo represents 1.2% of the full shower energy at 100 GeV and 0.25% at 1000 GeV. The albedo losses due to photons are comparable to those for charged particles[16]; neutron losses are probably greater.

Accelerator test data[17] at 5 GeV using iron and uranium liquid argon calorimeters have seen an apparent loss of about 3% of the incident energy when the position of first interaction is within 1.7 λ_0 of the front face of the calorimeter. If interpreted as albedo, this qualitatively confirms the cosmic ray results.

These estimates of the albedo do not appear to impair seriously the energy resolutions achievable by calorimetry at high energies, although they are uncertain enough to warrant further study. At low energy[17] there is rather direct evidence that resolution is made worse when the first hadronic interaction occurs early in the calorimeter - unless special correction factors are introduced. In addition to worsening resolution in the calorimeter, the albedo has the effect of sending unwanted particles backwards into the detectors closer to the interaction. Since each high energy shower sends several charged particles backward (5 at E = 1000 GeV), this effect can be quite damaging.

C. Criteria for Segmentation

The degree of segmentation of calorimeters is of crucial importance in determining the structure of events and in identifying the character of particles in the events. There are two basic approaches to setting the desired segmentation: the first is to set the granularity of EM and hadronic sections of the calorimeter at the transverse size of the individual showers themselves; the second is to use the structure of certain physics signatures to set the appropriate scale. Clearly the first approach sets the smallest sensible size.

There is considerable data on the transverse sizes of showers in different media. We first examine the EM cascades where data, analytic understanding and Monte Carlos are relatively more reliable than for hadronic showers. Since the mean angles involved in the Bremsstrahlung and pair production processes leading to longitudinal shower development are smaller than the mean angles of multiple Coulomb scattering of the bulk of the electrons, it is the latter which set the transverse size scale through the characteristic Moliere radius:

$$r_m = \frac{21\ \text{MeV}}{\varepsilon_c} X_0$$

where ε_c is the critical energy (at which the ionization loss is equal to radiation losses) and X_0 is the radiation length. Although the Moliere radius sets the scale for the bulk of the energy deposit, the extreme tails of the transverse distribution are believed to be due to the spreading of low energy photons at the minimum attenuation coefficients. At depths beyond the maximum in the longitudinal development curve, this essentially geometric effect contributes to the growth of these wings.

The question of how the transverse profiles of EM showers behave in sampling calorimeters — where both ε_c and X_0 differ between absorber and sampler — received some attention in the workshop. Naively, one may expect considerable broadening of showers when a large fraction of the medium is low Z sampling material, allowing the angular divergencies of the electron and photon populations to open up the spatial distribution. Experiment and calculation show this effect to be of minor importance. Test calorimeters with variable insertions of air or plastic were studied by Yuda.[18] The rms widths shown in Fig 4 show some geometric effect of introducting sizeable air gaps, but very little when acrylic spacers intervene between lead plates.

A quantitative study reported in this Proceedings[19] studied a lead-liquid argon sampling (3.5 mm Pb and 5 mm Ar) calorimeter using the EGS Monte Carlo and found a radius of about 4 cm for 95% transverse containment of a full shower. If the geometric spreading effect in argon were dominant we would expect the radial size to be 2.4 times that for pure lead. The results of Ref. 19 are instead consistent with those obtained using a Moliere radius computed using the weighted average radiation length and critical energy for lead. Thus the transverse sizes of showers in this calorimeter are about 20% larger than in pure lead.

The 95% containment radius for full EM showers is about $2r_M$ as indicated above for typical SSC calorimeter media e.g. (2 mm U/2 mm Ar) gives 95% containment at r=2 cm. Thus, transverse segmentation at the level of 2 x 2 cm seems a reasonable match to the shower sizes. It should be pointed out however that the central core of the shower is quite small indeed; [at a depth of $5/X_0$ in] a 100 GeV shower, the full width of the projected shower is only about 2 mm.[19] Fig. 5 shows this effect. Such small cores may argue for rather fine segmentation at the depth of the shower maxima.

The ability to measure the centroid of a shower has been studied in various experimental tests and in some simulations. There are some discrepancies among these data; some evidence[20] exists for position resolutions which scale like $E^{-0.5}$, while other data[21-22] argues for a weaker energy dependence. A Monte Carlo result[23] using EGS finds position resolutions of a few mm using 5 x 5 cm segmentations with 5-10 GeV electrons.

The longitudinal segmentation in EM Calorimeters can be exploited to give useful discriminating power between electrons (or photons) and hadrons.[24-25-26] It is possible, using the combination of lateral and longitudinal segmentation, to reject hadrons with factors exceeding 10^3 for 100 GeV incident energies. The minimum number of longitudinal samples required for this is three; it is important that these samples be chosen such that one is relatively small and centered on the shower maximum.[25]

The transverse size of hadronic showers is established primarily by the mean transverse momentum in hadronic interactions, as well as by multiple Coulomb scattering. Because of large mean free path of hadrons in materials, the relatively large inelasticity in each collision and relatively few generations in a full cascade, hadron showers are characterized by larger transverse spread and greater fluctuation than are EM showers. The average transverse profile for 200 GeV in an π^- iron-scintillator calorimeter is shown in Fig. 6; although there is a relatively dense core of energy near the shower axis (±3cm) the wings of the distribution extend past 15 cm from the axis.

Despite the complexities of the hadronic multiplication process, there is a reasonable rule of thumb[27] that the lateral profiles of full showers can be expressed as a function of the single variable R_0 = transverse thickness in g/cm (where the appropriate weighted average of material densities is taken) The radius within which 95% of the energy is contained in about 1 absorption length (λ_0) in the particular mix of materials employed. Fig 7 shows such a curve comparing data for π's and p's in the energy range 10 - 200 GeV.[27-28] This scaling behavior may not persist at the highest SSC energies where the fraction of energy in the cascade carried by π^0's is known to increase, leading to narrowing of the transverse profiles. For example cosmic-ray results[29] with an iron-scintillator calorimeter show a decrease in the 98% containment from 40 cm at E = 40 GeV to 25 cm at E = 20 TeV.

The average width of hadronic showers also shows an approximately linear increase with depth into a calorimeter, as shown in Fig. 8. These data[30] also indicate the independence of shower sizes with material when expressed in terms of thicknesses (g/cm^2).

For the sort of dense calorimeters discussed for SSC (e.g. uranium-liquid argon) the radius for 95% containment is thus expected to be about 10 cm; as noted above, the central core of the showers are smaller by a good bit (e.g. 50% containment within a few cm radius). The conclusion at this workshop was that calorimeter transverse segmentation of 5 x 5cm^2 was sufficiently fine to match the average shower sizes to be encountered. In terms of confinement radii, this size is in fact smaller than the 2 x 2 cm^2 EM segmentation recommended above. The larger fluctuation for hadronic showers may justify this; in any case making hadronic segments more than 6 times the area of EM segments leads to diminishing economic return.

The size indicated for hadronic segmentation is also well matched to determining the shower centroid with maximum precision. Studies of centroid measurement in iron-scintillator calorimeters[31] show that little improvement is made if the sampling element widths decrease below about 10 cm (Fig. 9). Since the density of uranium calorimeters should be nearly twice the iron devices, it appears that nearly optimal resolution should be reached with 5 cm wide hadronic segments. The measurements shown in Fig. 9 show an exponentially increasing behavior of centroid error $\sigma = \sigma_0 \exp(d/d_0)$, where d_0=60 gm/cm^2. Fig. 10 shows the energy dependence of position error which falls approximately like $E^{-0.5}$.

The second method for establishing guidelines for calorimeter segmentation is based upon the capability to isolate physical phenomena of particular interest. Two studies were undertaken at this workshop. The first examined how a finely segmented calorimeter could distinguish $W \rightarrow q\bar{q}$ decays from single parton jets at large p_T.[6] In this study using p_T = 500 GeV/c W's or jets, the discrimination was seen to improve as segmentation became finer down to about $\Delta\eta = \Delta\phi = 0.03$ (e.g. about 5 cm x 5 cm at r = 1.5 m). The size indicated in this work pertains primarily to the hadronic segmentation since the jets described are dominated by multihadron fragmentation. The second study examined the ability to isolate electrons from top quark decay.[32] Electrons were considered isolated if no charged particles struck the 3 x 3 matrix of cells surrounding the electron and if less than 5% of the electron energy was deposited by neutral particles. Top quark jets of p_T = 500 GeV/c showed over 80% electron isolation probability with segmentation of $\Delta\eta = \Delta\phi = 0.02$. This result implies EM cells of about 3 x 3 cm^2 at r = 1.5 m.

It is interesting that these two physics studies yield segmentation of calorimetry at about the same level as was dictated by the intrinsic shower sizes themselves. There appears then to be a natural scale to the transverse segmentation desirable in calorimetry for SSC detectors. This size (about 2 x 2 cm^2 for EM calorimetry and 5 x 5 cm^2 for hadronic) is achievable by present techniques; the cost of such granularity is however likely to be large. For a calorimeter covering ± 6 units of rapidity, in a cylindrical geometry of effective radius of 1m, it implies about 2 x 10^5 EM towers and 3 x 10^4 hadronic towers. Allowing for 3 compartments within the EM section and 3 within the hadronic gives a total channel count of about 7 x 10^5. At current costs per channel of electronics of at least \$50, the cost for instrumenting such a calorimeter will be in excess of \$35 M.

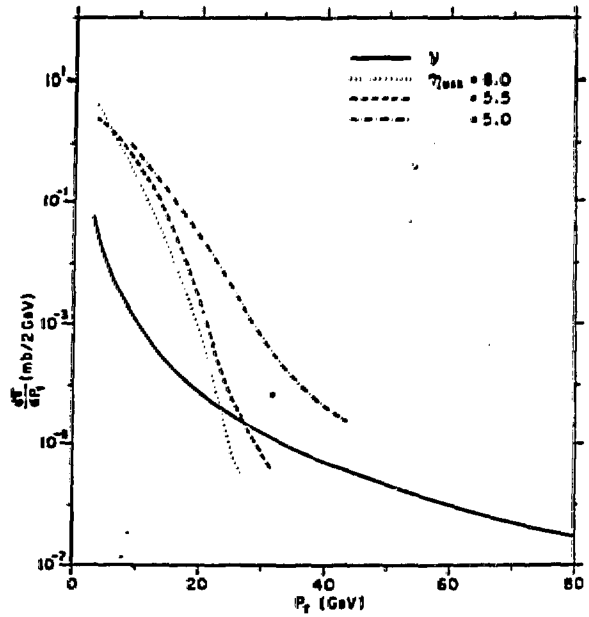

Fig. 1. Contributions to the differential cross-section dσ/dMPT (MPT = missing p_T) due to neutrino production from heavy quark decays (solid) and due to incomplete coverage within beam holes of several sizes. The top quark mass is assumed to 45 GeV/c^2.

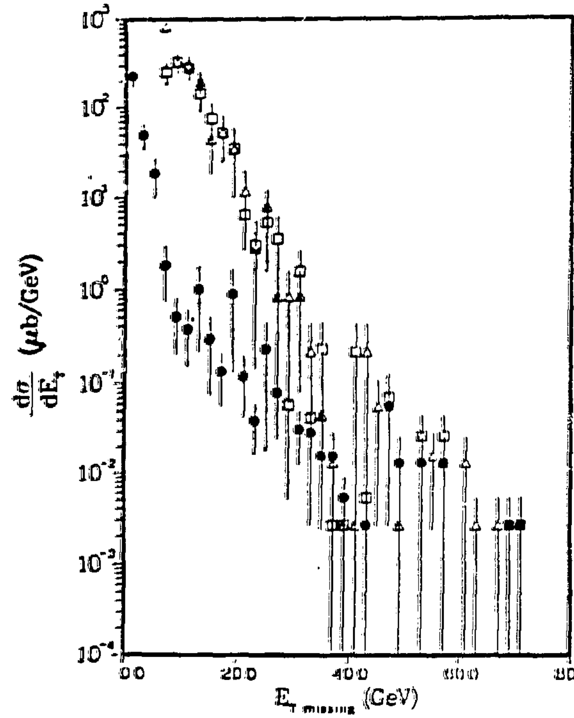

Fig. 2. Differential cross-section vs. missing p_T. The squares show the effect due to a 0.5° beam hole. The triangles show the combination of effects due to 0.5° beam hole, σ (hadronic) = 0.35 $\sqrt{E}$, σ(EM) = 0.15 $\sqrt{E}$ and σ_x, σ_y = 2 cm. The closed circles show the cross-section due to neutrino losses

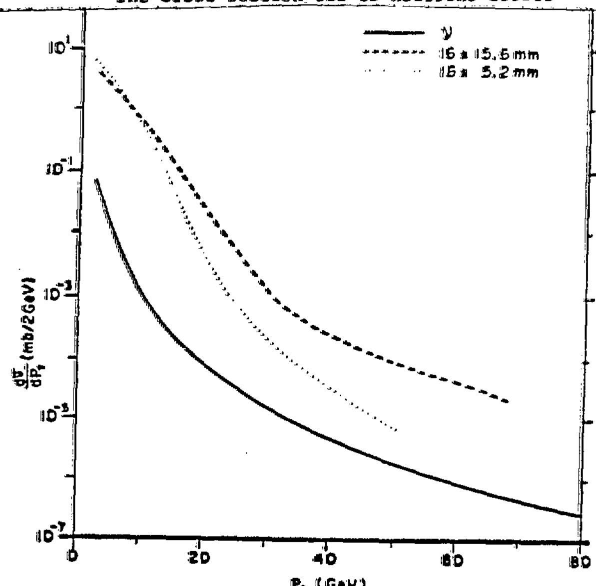

Fig. 3. Differential cross-section vs. missing p_T for the case of azimuthally directed cracks in the calorimetry between θ = 30° and θ = 150°. The cracks represent 1.3% (dotted) and 4.0% (dashed) of the area for the two cases shown. The cross-section due to neutrino losses is also shown (solid). A beam hole of θ ≤ 0.3° (η_{max} = 6.0) is used.

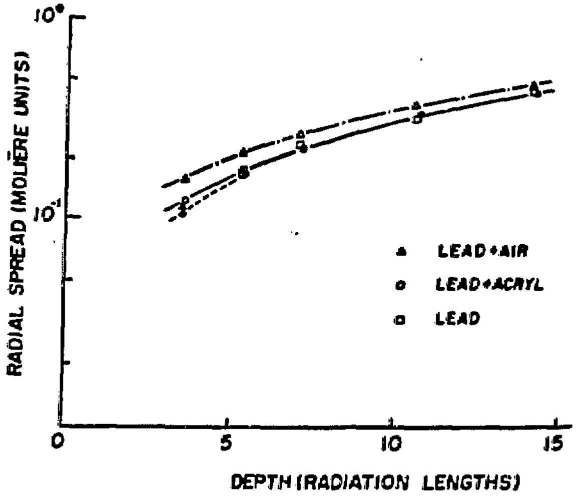

Fig. 4. Mean radial spread of EM showers in Moliere units vs. depth. Circles are for no spaces in the lead-x-ray film calorimeter; squares have interleaved acrylic; triangles have air gap spacers. Data from Ref. 18.

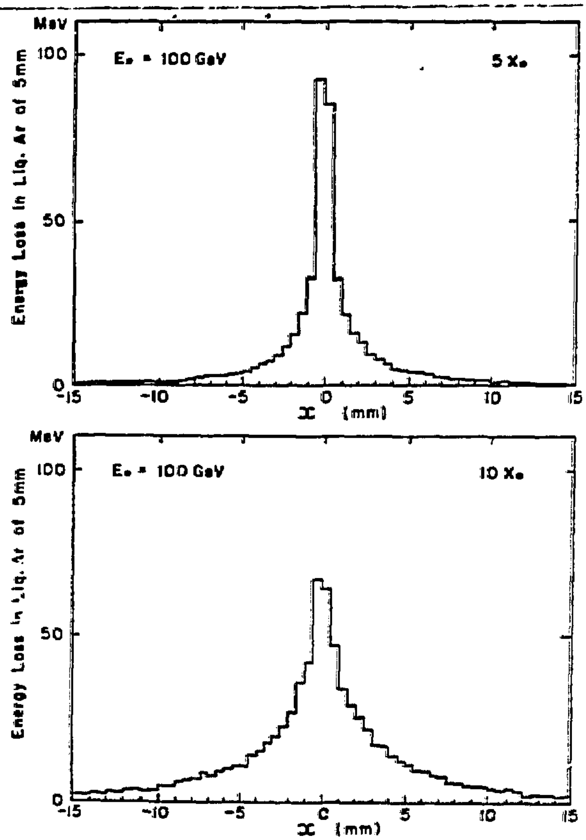

Fig. 5. Radial profiles for 100 GeV electrons in a Monte Carlo simulation of a lead-liquid argon calorimeter. Data from Ref. 19.

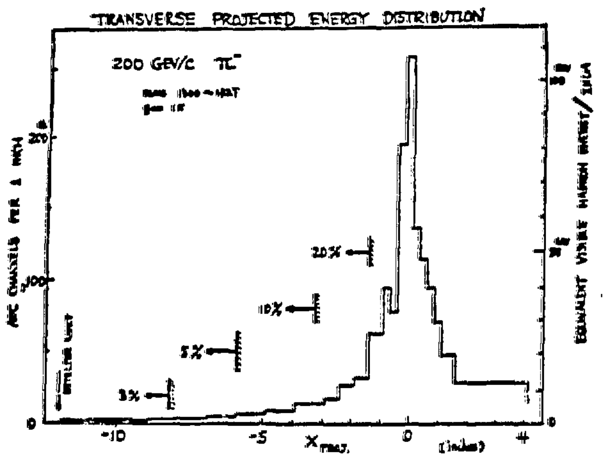

Fig. 6. Projected transverse profile for 200 GeV/c^2 π^- in an iron-scintillator calorimeter. Data from Ref. 28.

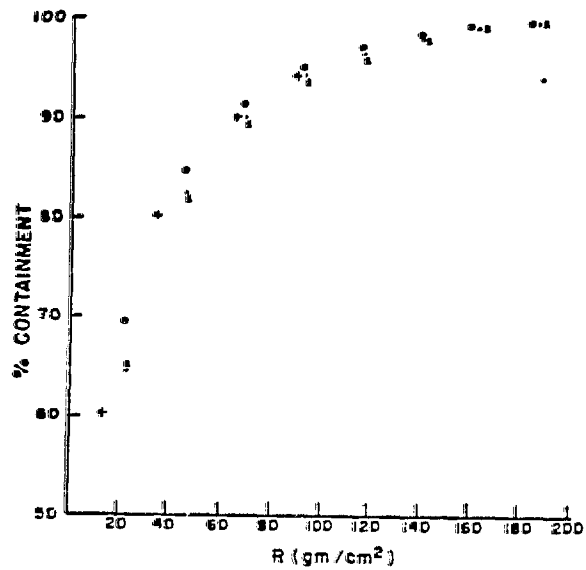

Fig. 7. Fractional containment of hadronic showers vs. radius of calorimetry in g/cm^2. Dots - 10 GeV p, x - 23 GeV p, ◦ - 50 GeV p, + - 200 GeV π^-.

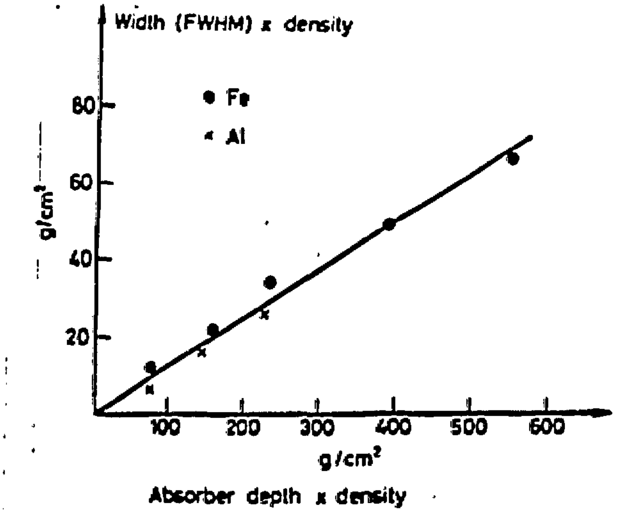

Fig. 8. Width of hadronic showers (g/cm^2) vs. depth. Data from Ref. 30.

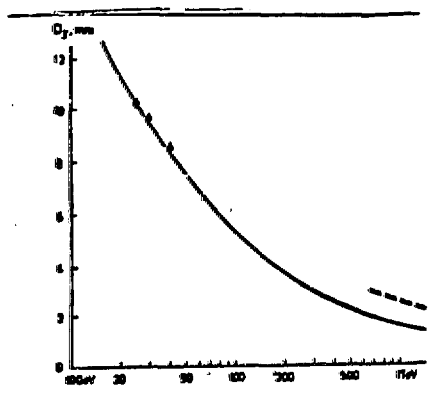

Fig. 10. Projected transverse position resolution vs. energy for hadron showers. The line and data points refer to sampling strip width of 5 cm.

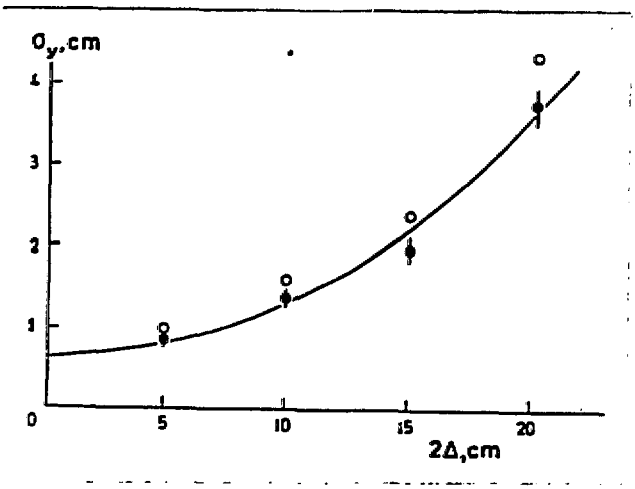

Fig. 9. Projected transverse position resolution vs. sampling strip width for 25 GeV (O) and 40 GeV (O) hadrons. Data from Ref. 31.

D. Time Resolution

In order to utilize the high luminosity of the SSC for rare processes such as heavy Higgs or quark production it is crucial to determine whether the calorimeter will function at sufficiently high rate. This subject has been widely discussed recently, eg. Snowmass '82[33], the DPF Berkeley meeting[34], the PSSC[35], and the $\bar{p}p$ conference.[36] The conclusions are that all known calorimeters have collection times of order 100 nsec. Therefore, not only the events within the same bunch crossing will pile up but also those from crossings before and after. However the calorimeter cell occupancy rate, as we shall outline below, is rather low. Therefore, in designing the SSC: 1) $\bar{n}$, the mean number of interactions/crossing, should be as small as possible approaching 1; 2) a time history of each channel in ≈ 10 nsec intervals is desirable to sort out events from different crossings; and 3) R&D on faster calorimeters should be vigorously pursued.

The occupancy rate for the most popular choice for a calorimeter, liquid argon, can be estimated. With the addition of 1% methane the electron drift time for a 2 mm gap would be ≈ 150 ns. For σ_T = 160 mb and dN(charged particles)/dy = 6.5 this gives $10^{33} \times 3 \times 10^{-7} \times 160 \times 10^{-27} \times 6.5 = 312$ charged particles per unit of rapidity in 300 ns! Assuming a segmentation of $\Delta\phi = 0.03$ and $\Delta\eta = 0.03$ and that each particle affects 3x3 towers, this implies that ≈ 1/2 of the towers have some remnant of a soft shower — a gentle glow. Even though the drift time is slow the time resolution in liquid argon calorimeters is good enough to distinguish signals in a particular bucket if each tower has a time measurement. This reduces the occupancy to ≲ 5%.

There have been studies of a few specific physics topics with the presence of up to 10 minimum bias events.[34] For example very high p_T jets clearly stand out over the background when demanding a minimum p_T in every cell of the calorimeter of a few GeV. For isolated electrons in heavy W's or Z's the signal has been shown to be rather unaffected by the pileup of minimum bias events. Even for SUSY particles where the signature is an imbalance of p_T with no charged leptons, the addition of additional events is not very severe since they all balance p_T.

However as Lederman pointed out in 1982[33], there may be some rare processes which pile up infrequently to simulate an even rarer signal. For example consider the production of heavy quarks:

pp → Q $\bar{Q}$
$\bar{Q}$ → $\nu\bar{q}''$, → $q\bar{q}'$.
Q → νq, → $\ell\nu$

The signature would be a high p_T lepton, a large missing energy and the constraint of the Q mass for both decays. The same signature could be simulated by

a) pp → W + jet
  W → ℓν
  + pp → jet + jet

or b) pp → jet + jet
  + pp → jet + jet
  jet → ℓν.

A detailed Monte Carlo simulation of these two possibilities was made using ISAJET.[10] For example for possibility b), two jet events were generated in 10 equal p_T bins from 0 to 1 TeV/c. The tracks were projected to a model calorimeter with segmentation $\Delta\eta = 0.1$, $\Delta\phi = 0.1$ covering $|y| < 5$. The energy in each cell of the calorimeter was recorded. Similarly a large number of two jet events were generated selecting only those with a charged lepton $p_T > 40$ GeV/c. The particles from these events were also put into cells in the calorimeter. Each of these events carries a weight related to the cross section in the p_T bin in which they were generated. Then the two sets of events were summed: the contents of all calorimeter cells were added. Finally an analysis was performed on both heavy quark events generated by ISAJET and these events that were summed. The signal and background were subjected to the same cuts. These cuts were chosen on the basis of minimizing losses of the signal but maximizing the loss of normal single event backgrounds. The cuts are listed in Table 1 for mass of heavy quarks of 200 and 500 GeV. Table 1 also lists the cross section for the events that survive the cuts. For the background this was derived from the following:

$$P_1 = \rho\sigma_1$$
$$P_2 = \rho\sigma_2$$
$$P_{12} = P_1 \cdot P_2$$
$$N_{12} = NP_1 \cdot P_2 = N\rho^2\sigma_1\sigma_2$$
$$\sigma_{12}L = N_{12}$$
$$\sigma_{12} = \rho\sigma_1\sigma_2$$

Table I.

Analysis of Heavy Quark Signal and Background

A) Cuts used in analysis

		M_Q = 200 GeV	M_Q = 500 GeV
Σ p_T	>	100	200 GeV
p_T(lepton)	>	40	80 GeV
Sum of E_T in 3x3 cell cluster around high p_T lepton	<	5	5 GeV
Transverse momentum of lepton relative to jet* direction	>	20	20 GeV
Transverse mass of jet* and lepton	>	20	100 GeV
Scalar component of p_T^ν transverse to lepton 3-momentum	>	50	100 GeV

B) Results of the cuts

a) signal (Heavy quark)	3.1×10^{-7}mb	1.2×10^{-8}mb
b) signal W + jet jet + jet	1.8×10^{-7}mb	7.0×10^{-7}mb
c) jet + jet jet + jet	9.9×10^{-5}mb	1.8×10^{-5}mb

*the jet is the highest p_T jet in the same hemisphere as the highest p_T lepton.

where $P_{1(2)}$ is the probability of background 1(2) occuring during a beam crossing ρ is the integrated luminosity per beam crossing (3.3×10^{-2} mb^{-1} in this example) $\sigma_{1(2)}$ is the cross section for background 1(2), N is the total number of beam crossings and L = Nρ is the integrated luminosity. It is clear that the type a) background is close to the signal while type b) background exceeds the signal. Unfortunately this study did not optimize the analysis procedure and perhaps it would be easy to suppress the background due to this type of pileup. Clearly more of this type of work is required.

All calorimeters need accurate calibration and monitoring however this is covered in a contribution by P. Slattery.[37]

II. Calorimetric Triggers

With 1.6×10^8 interactions per second there is quite a challenge to the trigger system to reduce this rate to ≈ 1 Hz. This group has a separate contribution to the Proceedings.[7] A first level trigger reduces the rate by ≈ 1000. This is accomplished by demanding $p_T > 75$ GeV in a region of the calorimeter covering $\Delta\eta = 0.25$ and $\Delta\phi = 15°$ or demanding two such regions having $p_T > 25$ GeV or demanding that missing energy > 25 GeV. An implementation of such a trigger with no dead time is given. Finally the additional requirements for various specific physics signatures is discussed. The calorimetric thresholds for each signature is calculated to reduce the rate to 0.2 Hz. The conclusion is that triggers can be devised that allow the study of the 1 TeV mass region.

III. Potential Calorimetric Media

A. Uranium Absorber

A considerable amount of discussion was held on the use of uranium as an absorber. The first use of uranium was in liquid argon calorimeter.[17] This measurement showed both an improvement in the energy resolution using uranium compared to iron and also a more nearly equal response for hadronic showers compared to electromagnetic showers, EM/HAD ≈ 1. Both of these benefits were understood and interpreted as the effect of fission induced in the uranium nuclei by the nuclear cascade giving additional energy in the sampling medium in the form of some mixture of neutrons and gamma rays. Such a fission product is understood to then partially compensate for the energy lost in a non-uranium absorber in the excitation of the nuclei. A confirmation of these effects was later observed by the AFS collaboration using a uranium scintillator calorimeter.[38] However, J. Brau and T. Gabriel[39] have recently suggested that the observed EM/HAD ≈ 1 is primarily due to the transition effect. The transition effect is the observed difference between what an electromagnetic shower deposits in a sampling calorimeter (with many transitions between a high density absorber and low density sampling medium) and what would be expected to be deposited on the basis of considering the fraction of the dE/dx loss in the sampling medium. The Brau and Gabriel suggestion is based on Monte Carlo calculations using EGS3 and HETC. They claim that the transition effect in a high Z material suppresses the electron response thereby giving equality with hadrons. In fact $\mu/e \approx 2$, the experimental measurement of the transition effect, in the original U/LA test[40] where "μ" is the signal observed for a minimum ionizing particle passing through the calorimeter converted to the energy lost by that muon in dE/dx in both the absorber and sampling medium. Brau and Gabriel predict that a lead calorimeter may also give EM/HAD ≈ 1. However both in a 3.5λ lead scintillator measurement[41] and a 5.4λ tungsten scintillator measurement[42] this ratio was ≈1.4 – 1.5. Brau and Gabriel also pointed out that a scintillator-uranium calorimeter may have better performance than a liquid argon uranium one due to increased saturation effects in argon compared to scintillator.

A recent study for LHC has indicated the great importance of this ratio being close to 1.[7] It is obvious that more real data is needed. Currently DØ and SLD have U/LA tests underway and SLD is planning a Pb/LA test for 1985.

B. Warm Liquid Ionization Calorimeters

Compared to liquid argon sampling, the possibility of using room temperature liquids such as tetramethylsilane (TMS)[43] or neopentane[44] offers certain advantages.[45] The need for insulated cryogenic vessels is removed, and the signal collection could be faster. Unfortunately the liquid must be extremely pure, the liquids are flammable, sometimes toxic, and the effective signal obtained is 1/10 – 1/5 compared to liquid argon. At present only J. Engler[43] has obtained results using a 10 liter TMS system with cosmic rays. Work is also going on at LBL (M. Strovink), CERN (D. Schinzel), and Aachen. This technique needs to be proven on a large scale but merits attention for the SSC.

C. Gas Calorimeters

Unofficially it was reported that the LEP-3 group at CERN has obtained EM/HAD ≈ 1 with an appropriate gas mixture and absorber. Unfortunately the energy resolution is about a factor of 2 worse for gas sampling compared to liquid argon. However at the SSC energies the simplification of gas sampling with faster time collection, simpler electronics and mechanical construction could prove very useful. Unfortunately radiation damage still prevents this approach close to the beams. Also it may be pointed out that the density of such a calorimeter is usually 30-40% below alternatives and there is a non-trivial problem to monitor the gain in a large system.

D. Si Sampling

A contribution was prepared for these Proceedings on the use of silicon detectors as the sampling medium for calorimetry.[46] The advantages of using silicon as the sampling medium are the gain stability (since the detector has unit gain as in liquid argon), fast response, compactness, operation at roomtemperature, insensitivity to magnetic field, and ease of fine segmentation. Unfortunately the cost is currently high and radiation damage, particularly to the electronics which needs to be close, could be severe. Also there is currently a fair amount of dead space on the perimeter of a silicon detector which could lead to dead spaces in the calorimeter. Ideally such calorimeters would be best near the beams but there the radiation level is highest. Also the sampling fraction is intrinsically very low since the active thickness is typically ≈ 300 μm. This leads to greater sampling fluctuations which increases the energy resolution compared to using a thicker sampling medium with the same thickness for absorber plates.

E. Heavy glass

New heavy glasses were discussed which have density ≈ 8. They have been developed by A.R. Spowart in small quantities. The compositions are proprietary until agreements are worked out with glass manufacturers. Samples have been checked with sources and seem to be as radiation hard as SCG1-C doped with cerium. At SSC energies there would be enough light output to use photodiodes for all readouts. This topic requires more work.

F. BaF_2 used with PWC

An interesting fast calorimeter was proposed by D. Anderson and S. Majewski.[47] It has not been fully developed but work has been done at CERN and now at BNL (C. Woody et al.). Currently radiation hardness is being measured. The gain calibration and stability could be a problem since there are so many independent photocathode surfaces and proportional chambers. Also there is a need to heat the chambers above room temperature to allow the TMAE to have enough vapor pressure. Perhaps its high cost will be the only major drawback.

Conclusions and Recommendations

As anticipated, the studies done in this workshop have confirmed that calorimetry will be a dominant part of many detectors for the SSC. For the generalized 4π detectors they will be indispensible; for most of the specialized detectors[48] calorimeters will play important roles in particle identification, jet reconstruction, quark flavor tagging etc. Although the working group has not seen specific areas where currently known calorimetric techniques are totally inadequate for the job at SSC, there are clearly worries about some of the performance and cost figures.

Calorimeters can be judged on many different bases: EM and hadronic energy resolution, response ratio for EM and hadronic showers, position resolution, time resolution, signal collection time, effective density, segmentation ability, calibration control, stability, radiation hardness, ease of packaging, intrinsic noise, linearity, ability to operate in magnetic fields and of course cost. No single choice of method is ideal from all points of view. It is perhaps a failure of this workshop that new ideas for calorimetry media and readout were not forthcoming.

For many of the discussions, the standard choice for SSC calorimetry of uranium liquid argon was made. This choice has clear advantages in that it has been demonstrated to work, has superior density, EM to hadron response, energy resolution, calibration and ease of segmentation. Its primary drawbacks are the difficulty of working with the cryogenic liquid containers and the signal collection times. The characteristic integration times (≈100 nsec) inherent in liquid argon schemes allow substantial overlap of events within the resolution interval. Although no clear case has been made that interesting physics will be jeopardized by these overlaps, we are by no means sure that some crucial topology of rare event will be lost due to the background from several overlapped events. Thus it seems crucial to extend studies of this problem through more complete simulations than have been reported here. It must be true that at some level (e.g. a signature involving 1 e^-, 2 μ^+ and three jets) the backgrounds swamp the signal when 10 events are overlapped. We need a better guide to the acceptable limits of time resolution for a range of physics.

Other techniques offer specific advantages. Substitution of liquid argon with room temperature liquids (TMS, TMP, etc.) relieve the cryogenic difficulties but raise new hazards associated with flammability. There is also a loss in signal size and a gain in signal speeds. Requisite purity is hard to achieve. Sampling with scintillator may give timing improvements at the risk of excessive radiation damage. Potential new cerium doped heavy glasses may give superior energy resolution, but will pose difficulties in calibration and stability and in ability to segment finely. The use of BaF_2 should yield excellent time resolution but may have difficulties owing to non-uniformities, stability and construction problems. The idea of sampling with silicon wafers could be very attractive and straight forward to build, but cost, cracks for readouts and radiation damage are problems. The existing techniques using gas sampling are viable but give reduced energy resolution, less overall density and difficulties in calibration. It is clear that further R and D on all of these possible choices should have a high priority in the coming few years. For some there are major unknowns with regard to radiation damage, energy resolution and EM/hadronic response which need to be measured. For all, there needs to be demonstration that calculations and small scale prototype performance can be translated into workage large scale devices.

Somewhat orthogonal to the question of evaluating the various calorimeter sampling materials is the issue of how well uranium absorber works to reduce energy resolution widths and equalize EM and hadronic response. This issue is not wholly decoupled from the choice of samples, as it is expected that conversion of fission decay products in the sampler will be better in low Z than in high Z materials. The role of the transition effect in reducing EM response is also understood to depend in a known quantitative way upon the critical energies, and hence on sampling medium Z. The major unresolved issues here are in the size of the compensation effect due to fission of uranium relative to other non-uranium properties such as albedo, leakage and transition effect. Test calorimeters of nearly identical construction should be studied. Of particular interest are comparisons of uranium liquid argon, lead liquid argon, uranium scintillator and lead scintillator calorimeters of equivalent depth, radius and segmentation.

The ability to trigger on calorimetric information was studied here[7] and found to be sufficient to the task (barely). The schemes envisioned involve multi-level triggers in which a series of more sophisticated cuts are applied at each succeeding stage. An approximation to such trigger schemes are now being built for the 2 TeV Fermilab Collider where instantaneous luminosities will be at least a factor 10 below the SSC design. Experience with the detectors and triggers should provide very useful experience in handling noise and overlapping events, making fast jet finding algorithms and missing p_T calculations, and in incorporating triggers for special particles. Additional simulations and studies of the trigger problems for the SSC, together with advances in implementation, should continue.

Studies of the performance parameters required to do the range of SSC physics need amplification in several areas. Much of this can be accomplished through combinations of analytic calculations and Monte Carlo simulations. Among the topics needing further work we note: (1) proper calculation of the effect of beam holes upon missing p_T resolution; (2) much more extensive modelling of the deleterious effects of dead regions in calorimeter coverage; (3) measurement of hadronic shower containment depths; (4) the benefit to be found from tagging the time of individual energy deposits; (5) the ability of calorimeters to aid in identifying specific jet or particle types; and (6) the effect of time overlapped event backgrounds on interesting physics signatures.

It is, in our opinion, essential that much of R and D, simulation and calculation exercises be carried forward as rapidly as possible. We have perhaps five years available before construction of the real SSC detectors is initiated and the sort of program outlined here is necessarily an iterative and recursive process. Although we may count on the efforts of those collaborations now building detectors for LEP, SLC, TeV I and HERA to answer some of the questions, it is clear that these initiatives will not address all of the new territory that should be expored for SSC detectors.

The mechanism for stimulating this research program is a legitimate concern in itself. Although it may be ideal to call for the establishment of dedicated detector R and D groups[5], such arrangements have not been wholly successful in the past. It is however clear that the major laboratories in this country and abroad do have an opportunity, and perhaps responsibility, to dedicate some fraction of their resources to such unrestricted research. It has been most useful in providing focus and talent for these enterprises in the past and should be expanded. A corollary is that access to test beams must be preserved (enlarged?) in order to facilitate rapid and repeated tests of specific new realizations of calorimeter prototypes. Finally, it seems appropriate that the SSC R and D phase not lose sight of the need to foster research on detector issues as well as on accelerator questions. The time scale for the detector buildup is not so much shorter than for the SSC itself.

A radical alternative would be to call for proposals as early as possible, organize the proponents into perhaps 2 groups, appoint a manager to take on the responsibility of developing the detector which would include the detector R&D relevant and necessary. This is essentially the example followed in LEP. It would mobilize experimental groups to treat the SSC as a reality and therefore commit themselves to the project. The R&D would be naturally directed towards tasks relevant to that project. It would also force an early interaction between builders of the accelerator and the detector.

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