A WARM LIQUID CALORIMETER CONCEPT FOR THE SUPERCONDUCTING SUPER COLLIDER


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1. INTRODUCTION

The advantages of liquid ionization calorimetry are well known. Direct collection of charge leads to a stable, well calibrated and uniform response. There is flexibility and ease of segmentation in both depth and surface area, relatively high resistance to radiation, and, with the development of the electrostatic transformer, insensitivity to magnetic fields. A vigorous R&D program pursued world wide in the past few years has shown that some organic liquids at ambient room temperature (so-called "warm liquids") can make excellent calorimeters. The yield of electrons, taking into account $dE/dx$, electron lifetime and drift velocity is comparable with that for liquid argon; and the relatively short drift times are an advantage in suppressing pile-up. Warm liquids can provide superior detectors, because they require neither cryogenic equipment nor thermal insulation; this encourages simplicity, flexibility, and hermeticity. Furthermore, as hydrogenous materials, organic liquids can provide a compensated response - equal sensitivity to hadronic and electromagnetic particles.

The conceptual design for an SDC calorimeter based on warm-liquid technology has made considerable progress since the completion of the EG&G engineering study in September, 1989. Although some of this comes from a sharpening of the overall concept of the SDC detector, most springs from a deeper understanding of the capabilities of warm-liquid calorimetry resulting from an aggressive and successful R&D program. The improved design and construction detail presented here is the result of work done in three particular areas of the R&D program:

1. Results in the investigation of handling, purity requirements, and material compatibility issues have indicated that there are many standard construction materials and devices that can be used in the calorimeter, and have indicated the cleaning procedures that should be used.

2. The investigation of the electrostatic transformer readout has shown that it can attain the required charge transfer speed if employed in a proper design.

3. The work done for the Test Beam Module has resulted in a practical detailed design for the tile assembly and support, high voltage distribution, and signal readout consistent with compatible materials, good hermeticity, and inexpensive assembly. The TBM is scheduled to be tested in beam in mid-1991.

A successful warm liquid SSC calorimeter will offer superior physics research capabilities by virtue of its high hermeticity, full compensation, fine grain structure, and excellent resolution. It will have adequate speed, signal to noise ratio, and radiation hardness to meet or exceed all of the SDC requirements.
2. CALORIMETER DESCRIPTION AND ASSEMBLY

2.1 OVERALL DESCRIPTION: The SDC calorimeter comprises barrel and end cap assemblies, each of which has separate electromagnetic (EM) and hadronic volumes. For scale, the complete calorimeter is shown in elevation side view in Fig. 2-A. A quadrant showing somewhat more detail, and marked in rays of constant pseudo-rapidity is shown in Fig. 2.B.
The eight meter long barrel calorimeter is assembled in three almost identical bays, each, with support structure, weighing about 1400 tons, resting on moveable cradles that are permanent parts of the detector. Each bay is assembled from 20 wedge modules. About nine absorption lengths of active material, primarily Pb and TMP, are enclosed in a welded and leak-tight shell of aluminum. Each wedge module has a 40 cm. thick slab of steel joined to its outside radius for structural support. When the calorimeter is fully assembled, this serves as the magnetic return yoke. The inner EM volume of each barrel bay is a monolithic cylindrical module to maximize hermeticity, and is supported from the surrounding hadronic assembly.

The hadronic end caps are assembled similarly in bays, two per end cap of 10 wedge modules. The return-yoke steel is part of each end-cap wedge. Again, for hermeticity reasons, the EM module is a single monolithic disk supported from the hadronic end cap assembly.

The internal structure of the wedge modules in both the barrel and end caps is semi-projective in polar angle. The hadronic module walls are projective in azimuth; to avoid projective cracks, the EM modules are not. The design is such that each wedge is made up of sub-assemblies that can be fabricated and tested at a remote location, so that the assembly of the large wedges involves the handling of a relatively small number of pre-fabricated parts. All of the cabling and plumbing is internal to the wedge modules and is accessible from the outer perimeter. In total, there are seven calorimeter bays comprising 100 hadronic modules and five electromagnetic modules. The following sections describe the design and assembly procedure of the calorimeter in more detail.

2.2 INTERNAL STRUCTURE: In designing the Warm Liquid TBM, we have developed the simple and reliable internal structure of lead absorber/electrodes, insulators, tie rods, and ground plates shown in Figure 2-C. This internal structure has good hermeticity and full compensation, while allowing voltage gradients of 50 kV/cm. or more. Only materials known to be compatible with the tetramethyl pentane ionizing liquid are used, and each part is designed for efficient cleaning, assembly, and vacuum pumpdown.
This progress on the design of the internal structure has taken place since the EG&G engineering study was completed and has been a by-product of our work on the Test Beam Module.

2.3 BASIC BUILDING BLOCK: Drawing upon our experience with the TBM, the basic hadronic "building block" assembly will be a planar array of electrostatic transformer cells faced on both sides with a continuous stainless steel ground plate. Short aluminum tie rods provide the internal structure to support the absorber/electrode plates and their insulators. The lead plates are die castings, requiring no machining. Each EST cell comprises 10 capacitively coupled active liquid gaps (two parallel sets of 5 in series). The planar arrays are assembled in a clean room facility and are individually tested for voltage holding. Many of these assemblies can be built in parallel to meet schedule demands. The "2-wide" array from a hadronic barrel section shown in Figure 2-D is typical. The electrical connections are accomplished with flat ribbon cables at DC ground running up the outside of the two-wide arrays. High voltage is distributed horizontally using large resistances to de-couple neighboring tiles. This design is essentially identical to the TBM in internal construction, support structure, and cabling.
2.4 WEDGE MODULES: In the hadronic section of the barrel calorimeter, these planar assemblies are combined to form "wedge modules" built up structurally on a segment of the steel flux return yoke, as shown in Figure 2-E. Each module weighs about 62 tons, including 14 tons of return steel. The active calorimeter structure, but not the return steel, is enclosed in an aluminum box containing a single liquid volume. All of the high voltage and signal cables are routed internally to the radially outside wall, where they penetrate with vacuum tight feedthsrs. Plumbing connections and other penetrations also are through the back wall.

Each module is filled with TMP and subjected to complete testing before assembly into the calorimeter. The 62 ton module can be assembled, transported, pumped and purged, and installed without the use of extraordinary equipment. It can be lifted, moved, and placed accurately with a standard crane in the collision hall.
2.5 HADRONIC BARREL SECTION: The hadronic barrel section is divided axially into three 2.67 meter long bays, each built up of 20 of the 62 ton wedge modules described above. The assembly into bays can be accomplished with an overhead crane and a holding fixture that picks up each wedge module near its center of gravity, as shown in Figure 2-F. A rigid, self-supporting cylindrical structure is created by joining the wedge modules to each other with bolted joints at their outer and inner diameters, as shown. The wedge modules are supported at both their outer and inner radii; they are not cantilevered as they were in the EG&G design. By avoiding mechanical overconstraint, the present design minimizes the azimuthal cracks between modules. For a discussion of the structural stresses in this design, see section 6 of this report.

The bays are built up on cradles that move along the floor on rails or plates as permanent parts of the detector. This assembly procedure, and the use of floor space to accomplish it, has been studied in some detail by a group from the SSC Laboratory, LBL, and RTK Engineering. A report will soon exist from this study.
Figure 2-F  Assembling the Hadronic Barrel

2.6 EM BARREL: Supported in the inner bore of each hadronic barrel section is a separate 2.67 meter long EM barrel module. Although it would be possible to incorporate this inner EM layer as an extension of each of the 20 hadronic wedge modules as done in the EG&G study, the resulting 20 pairs of azimuthal walls would be detrimental to the hermeticity of the EM section. For this reason, each bay is a single-liquid-volume, $2\pi$ annular structure weighing about 60 tons.

The relatively thin EM calorimeter (18 cm, 24 radiation lengths) is structurally supported by its aluminum outer shell, with a thin inner shell as a liquid boundary. The electrostatic transformer is not used. Instead, the signal lines at high voltage are brought through feedthrus in the outer shell into an enclosed inert gas layer where they are capacitively coupled through a second set of feedthrus to external pre-amps in the annulus between EM and hadronic calorimeters. (See Appendix A).
Plumbing connections to the EM section share a similar routing, which is aided by the reduced outer diameters of the EM barrel end sections, made possible by the obliquity of the particle trajectories (see Figure 2-B). The fine-scale structure of the EM section is shown in Fig. 2-H. Three or four layers of lead absorber tiles, each acting as a sampling depth, are supported by tie rods, ceramic insulators, and structural ground plates. (For improved spatial resolution, the center layer may be composed of perpendicular "strip" electrodes. This option is described in Appendix A.)

![SQUARE CAPSTONE ASSEMBLY](image1)
![TRAPEZOIDAL CAPSTONE ASSEMBLY](image2)

Figure 2-H  EM Capstone Assemblies

To form the barrel geometry, 64 of these 2.67 meter long, open assemblies are mounted on the inside surface of the aluminum outer shell. A "capstone" pairing of cross-sectional shapes makes it possible to assemble these radially outward, as shown in Figure 2-I. That is, alternate assemblies of trapezoidal cross-section are first installed, followed by intervening assemblies of rectangular cross-section. This geometry also eliminates projective boundaries between assemblies.
Figure 2-I  Insertion of Capstone Assemblies into EM Shell

The capstone assemblies are held to the outer shell by a row of special feedthrus incorporating a substantial threaded nut fastener and a metal seal. Small screws through the end bulkhead walls secure the full-length ground plates. These are then seal-welded to the bulk heads. Finally, the thin aluminum inner skin wall is welded in place, followed by helium leak testing.

Figure 2-J  EM Barrel Insertion into the Hadronic Barrel
2.7 END CAP MODULES: The design and construction of each end cap calorimeter section uses most of the concepts already described. Each wedge is a single liquid volume. Ten 1.4 meter thick wedges are used to complete each of two bays per end cap. These wedge modules, shown in Figure 2-K, are also assembled on segments of the steel flux return yoke, leaving an outer radius access space in an open support structure. The planar array subassemblies are normal to the beam axis. As in the barrel section, short aluminum tie rods between continuous stainless steel ground plates provide structural support for the lead plates and ceramic insulators.

In a manner similar to that in the barrel sections, high voltage and signal lines are routed normal to the absorber plates, this time exiting through backside bulkhead walls to inert gas layers, from which they are connected through a second set of feedthrus to pre-amps in the outer radius access space.
The design of each end cap EM module is analogous to that of a barrel module. The 30 ton, 4 sampling depth, $2\pi$, single liquid-volume module avoids projective wall structures. It uses a relatively thin aluminum front wall, with a thicker aluminum structural back wall supported by the adjacent hadronic end cap modules, as shown in Figure 2-L. Internal tie rods join the walls to prevent bulging under liquid head.

Figure 2-L  End Cap EM Module

Towers close to the beam line have very small areas for constant delta eta - delta phi. The strip electrode option discussed in Appendix A may be relevant in this region of the calorimeter.
2.8 PROJECTIVE GEOMETRY IN HADRONIC BARREL TOWERS: The "basic building block" electrostatic transformer fits easily into the semi-projective geometry desired for hadronic towers. For uniform charge collection, the cross section of each 12 cm deep EST cell must be rectangular, but its overall dimensions may change with location in the module. Figure 2-M shows how an excellent semi-projective geometry for the towers is achieved with different cell variations. The azimuthal width varies in 16 radial steps, with 5 axial lengths: 10, 15, 20, 25, and 30 cm. The straightforward means of supporting and restraining the magnet is also apparent in this view.

Figure 2-M  Semi-Projective Tower Geometry Achieved with Quantized Cell Sizes
3. OPERATION

3.1 CLEAN ROOM ASSEMBLY: Successful operation of a warm liquid calorimeter requires highly purified TMP or TMS (tetramethyl silane) contained in modules that have been carefully assembled to avoid electronegative contaminants which would destroy the free electron lifetime. Clean room assembly of the modules is needed to eliminate electronegative contaminants. The halogens especially (fluorine, chlorine, and bromine) must be kept below tens of parts per billion in the TMP liquid. Our experience with small swimming-pool prototypes demonstrates that practical designs which meet the purity requirements can be built and operated successfully. The Test Beam Module under construction will tell whether final in-situ bake-outs are necessary before filling with TMP. Experiments with test assemblies indicate that two-day bakeout cycles of up to 130 C are possible with negligible mechanical creep of the lead absorber tiles. Inert gas purge and pump-down cycles also can be used to dilute contaminants to negligible concentrations.

3.2 MODULE TESTING: After fabrication, each module is tested under vacuum and pressure and then filled with TMP in a fixture for functional testing with cosmic rays. The module is then drained for handling and assembly into the calorimeter structure. Filling is always into a vacuum, using the large diameter vacuum pump-out lines. These large lines can also be used for draining the EM and all hadronic modules mounted in "down" positions. For modules in "up" positions, a full depth, minimum intrusion drain line of about 3/8" diameter is used.
3.3 MAINTENANCE AND RELIABILITY: The low-point drain lines, vacuum ports, and filling lines are accessible for each module in the installed position. These features allow remedial replacement of the entire liquid volume, and in-situ purge/pumpdown cycles to improve TMP ionization lifetimes. Continuous circulation of TMP within the modules is not planned; significant design compromises would be necessary for effective circulation. Finally, the relatively simple mechanical assembly of the calorimeter does not exclude access for removal and replacement of individual defective wedge modules. (see Figure 2-F)

Commercial, room temperature vacuum technology will be used. The calorimeter's electrical system is also designed for a high level of reliability. The large numbers of insulators used (see section 9) require careful test programs to assure excellent performance. The network of isolation resistors and distributed high voltage feedthrus provides assurance that high voltage breakdowns will disable only small volumes of the calorimeter.

4. HERMETICITY

One of the principal appeals of warm liquid calorimetry is excellent hermeticity. We have calculated the hermeticity for the design described in this report:

4.1 SIMULATION: Starting with a Hewlett Packard ME-10 CAD system scale drawing of the elevation section quadrant, an ME-10 "macro" program was created to explore the calorimeter volume along rays of constant eta (pseudo-rapidity). Eta steps of 0.02 were used, and the materials encountered were categorized as "dead" air, structural aluminum or stainless steel; and "live" lead/TMP/Kapton/ceramic/aluminum/stainless composite, each with specific interaction lengths and radiation lengths. The scanning technique uses the color of line boundaries to indicate the material beyond the boundary while moving out along a ray trace. The output of this ME-10 macro code is an input table for the Womersly Fortran program which has been traditionally used to compare design hermeticities. As a check, the information in this input table was then used to fill in the regions of the quadrant drawing with colored rays representing the materials that had been scanned. This result is shown in Figure 4-A.

In addition to accounting for structures in terms of cumulative radiation lengths and interaction lengths, a shower development algorithm is used in the Womersly code to weight the influence of materials at various distances from the interaction point. These results are the most significant, and are portrayed in the plots of resolution as a function of rapidity.

The ME-10 / Fortran code package we developed is available to anyone who wishes to assess the hermeticity of a calorimeter design. The input is a standard ME-10 elevation section drawing of the design, and no manual measurements are needed.
Figure 4-A  Hewlett Packard ME-10 CAD system scale drawing of the elevation section quadrant, with confirmatory color-coded eta ray traces.
4.2 RESULTS: Results from the hermeticity evaluation of the warm liquid
    calorimeter design described in this report are shown in Figures 4-B through 4-D.
    Although the hermeticity of this design looks quite good, time has not allowed us to
    iterate on module proportions; further optimization is possible on both large and
    small scale structures.

Figure 4-B  Live and Total
    Interaction Lengths as a
    Function of Rapidity

Figure 4-C  Resolution
    at 50 GeV as a
    Function of Rapidity

Figure 4-D  Resolution
    at 10 GeV as a
    Function of Rapidity
5. SIGNAL TO NOISE, PILE UP AND CHARGE TRANSFER

In liquid ionization calorimetry care is needed to minimize electronic noise and signal response time. Present design features recognizing this include:

a. The electrostatic transformer used in the hadronic section is insensitive to magnetic field. With negligible internal inductance it provides instantaneous current from the transformed charge.

b. Signal-ganging uses a low inductance strip-line matched to the tower without increasing significantly the total capacitance.

c. All preamplifiers are readily accessible for service. For Barrel signals, cable lengths from detector to preamp are ≤ 2m. The cable transit time is much less than the signal shaping time.

d. Where cables must be longer (i.e., 3.5m in Endcap Hadronic), tower capacitance is small. The preamp capacitance need not be 'matched' for a good signal to noise ratio; the cable can be terminated to preserve the rate of charge transfer.

5.1 SIGNAL TO NOISE RATIO: Based on standard circuitry and traditional components, the signal to noise ratios have been calculated for the present design for mips in TMP, TMS and LA as functions of gap width, high voltage and shaping time [J. Colas. "Speed of Response, Pile-up, and Signal to Noise Ratio in Liquid Ionization Calorimeters'. Tuscaloosa Workshop, 3/13-17/89; and W.A.Wenzel, "Electronic signal to Noise Ratio for LA, TMP, and TMS"; SDC-90-00071, 8/9/90]. The figure below shows these parameters for a 'standard' tower of area 0.01m$^2$ and total liquid depth 10cm. After correction for the differences in shaping time, tower volume and electric field strength, these calculated values are in good agreement with measured values from the TMP calorimeter in the test beam at FNAL (E795).

In the present design the calorimeter depth corresponding to this total liquid depth is 0.6m: the reference tower volume is then 0.006m$^3$. Showers are measured in an appropriately weighted 5.5 interaction lengths, which corresponds to the accumulated depth of the EM section and the first hadronic sampling. The noise associated with a shower measurement is proportional to the square root of the calorimeter volume needed for isolation, assumed in the SDC proposal to be a $\Delta\phi\Delta\eta$ cone of radius $\alpha=0.15$. Because the corresponding calorimeter volume is a strong function of $\eta$, we consider only small $\eta$ (worst case). Between the maximum and minimum radii in the Barrel, $\rho_2=3.4m$, $\rho_1=2.1m$, this volume is:

$$V(m^3) = \pi\alpha^2(\rho_2^3-\rho_1^3)/3 = 0.708$$
Relative to our standard tower the signal is doubled and the noise increased by a factor \((0.708/0.006)^{1/2}=10.9\). The energy lost by a mip in 1.2m is:

\[
\Delta E = \int \psi d\rho (dE/dx)_{\text{min}} = 7.9(120)(1.23) = 1170 \text{ MeV} = 1.17 \text{ GeV}
\]

Therefore, the noise energy in the conical calorimeter volume corresponding to a given signal to noise ratio \(S/N\) in the standard volume (see figure) is:

\[
E_{\text{noise}}(\text{GeV}) = 10.9(1.17)/2(S/N) = 6.4/(S/N)
\]
Referring to the figure: For TMP at 10keV (upper S/N curves) and $T_m=100\text{ns}$, $S/N=7.8$, giving $E_{\text{noise}}=0.82\text{GeV}$. With $T_m=50\text{ns}$, $S/N=5$, giving $E_{\text{noise}}=1.3\text{GeV}$. For TMS the optimized noise is less by a factor of $\sqrt{2}$.

5.2 PILE UP: This has been calculated by J. Colas for a standard tower with $\Delta \phi=\Delta \eta=0.05$, assuming a luminosity of $10^{33}\text{cm}^{-2}\text{sec}^{-1}$, 100mb inelastic cross section and a multiplicity of 100 particles with $<E_p>=0.5\text{GeV}$. Assuming that the ratio of drift time to shaping time is $T_d/T_m=2$, with $T_m=50\text{ns}$, the rms pile-up contribution to the transverse energy is $\approx 80\text{MeV per standard tower}$, or 0.425 GeV for the SDC standard cone of $9\pi$ standard towers, or $=10\text{GeV}$ for the entire calorimeter with $-3\leq \eta\leq 3$. For a given $T_m$, measured to the peak of the monopolar pulse, the pile-up goes inversely with $B=(1.27T_m/T_d)[1-\exp(-T_d/1.27T_m)]\leq 1$. $B$ is a ballistic factor which measures the effective charge utilization. For TMP and TMS, $B$ is always large near the peak in the signal/noise vs gap width.

5.3 CHARGE TRANSFER AND THE EFFECTS OF CABLES: The preamp input resistance $R$ is determined by the time constant for charge transfer to the preamp, $\tau=T_m/2=R(C_a+C_d+C_c)$, where subscripts $a$, $d$ and $c$ refer to preamp, detector and cable, respectively. The noise is proportional to $(r^{1/2}+r^{-1/2})(C_d+C_c)^{1/2}$, where $r=C_a/(C_d+C_c)$. For fixed values of $\tau$ and $t_c$ all capacitances scale; the electrostatic transformer ratio is chosen so that stray capacitance is negligible, preamp power is acceptable, and cable impedance is in a convenient range. Near the minimum noise (matched) condition $r=1$, it is impossible to terminate the cable with a resistive preamp input; in calculations it is convenient to use the lumped constant values, $C_c=t_c/Z$, $L_c=Zt_c$, where $t_c$ is the transit time of the cable ($5\text{ns/m}$) and $Z$ is its characteristic impedance.

The cables degrade performance in two ways, noise from the capacitance, and charge transfer delays from the inductance. These are small if:

$$C_c/C_{\text{total}}<1 \quad \text{or} \quad Z/R>t_c/\tau$$
$$L_c/R<<\tau \quad \text{or} \quad Z/R<<t_c/\tau$$

Though not quite optimum, $Z/R=1$ satisfies both conditions for short cables; For a 2m cable with $\tau=50\text{ns}$, the noise is increased by the factor $(1+t_c/\tau)^{1/2}=1.1$.

In the present design, cable lengths are $\leq 2\text{m}$ ($t_c=10\text{ns}$) for the Barrel hadronic modules. They are as long as $3.5\text{m}$ for the inner Endcap hadronic, where the towers are much smaller than at $\eta=0$. Hence the matched condition can be sacrificed, letting $C_a<<C_d+C_c$ ($r<1$), to permit termination at the preamp. This minimizes reflections and degradation of the charge transfer. The required sacrifice in signal to noise ratio, a factor of 1.74 for $r=10$, is more than offset by the smaller (a factor of $= 5$) tower capacitances near $\eta=3$. 
5.4 VOLTAGE GRADIENT: As can be seen in Figure 5A, the performance of organic liquid calorimeters improves generally with gap voltage. The maximum useable voltage can be limited by the gap itself, by insulator surface or volume breakdown, or, in the hadronic sections, by punch through of the Kapton insulating layers. At 50 kV/cm (10kV across 2mm of TMP) the liquid is expected to be safe by a large factor. In this design insulator surface leakage is inhibited by long path lengths (≥6mm). Because of microscopic imperfections (pinholes), the (5 mil) Kapton layer, nominally rated for 3900 volts/mil, may sometimes hold much less than 19.5 kV. The present design, therefore, calls for double layer (5mils+5mils) Kapton.

We have carried out voltage tests in both dry nitrogen and TMP using lead tiles, ceramic insulators, and single 5 mil layers of Kapton. The 2mm gaps held >5kV in dry nitrogen gas. After a week of operation in TMP at 11 kV there is no deterioration and leakage currents are ≤1nA.
6. STRUCTURAL DESIGN

6.1 BASIS: Wherever possible, structural member thicknesses have been calculated using simplifying assumptions and handbook methods such as those found in Roark and Young's Formulas for Stress and Strain, 5th edition. Factors of safety between 2 and 4 based on yield stress were used. A more rigorous structural analysis is needed. Structural optimizations may change the sizes of some members, but these changes will not have a large impact on the hermeticity of the design.

6.2 INTERNAL DESIGN: To give a basic understanding of the mechanical support of the distributed calorimeter mass, we trace the structure outward from a single lead absorber/electrode:

Figure 6-A Internal Structure in Cross-Section
A sectional view of the lead tiles is shown in Figure 6-A. This is the structure used in the TBM, which is designed to place minimum stress on the lead, which is a highly creep resistant calcium-tin alloy (9000 psi yield stress). This alloy is used because elevated temperature bake-out cycles greatly aggravate the creep deformation of stressed lead. As shown in Figure 2-A, each lead tile is supported at three points around its perimeter by ceramic insulators strung on an aluminum tie rod. Midway along the tie rods, a spring loaded aluminum signal tile compresses the assembly to eliminate any mechanical movement under shipping accelerations of up to 1g. These spring elements also act to take up the inevitable tolerance stack-ups of such an assembly of parts, thus avoiding the need for tight (expensive) tolerances. A special compact conical/variable pitch stainless steel spring has been devised to give a relatively constant load over the needed travel range. This results in maximum lead stresses of only 400 psi.

The aluminum tie rods are a readily available high strength alloy (6262-T9), so that the tie rods and ceramic insulators can be made as small as possible to maximize the active area of the lead absorber/electrode plates. In the TBM, there is a 90.4% active area over the lead plate array. The ceramic insulators and the aluminum tie rods transfer the weight of the lead tiles to the stainless steel ground plates (aluminum in the EM sections) which form the faces of each planar array of calorimeter cells (see also Figure 2-D). As will be seen, the relatively short tie rods also function effectively as compression columns with fixed end conditions. This internal structure is used throughout the calorimeter, in both barrel and endcap, hadronic and EM sections.

6.3 STRUCTURE OF WEDGE MODULES: Three representative orientations of the hadronic barrel modules are shown in Figure 6-B. In the 6 O'clock position, the weight of planar arrays is simply stacked, bearing most heavily on the lowest assembly, and ultimately on the steel return yoke segment. The relatively short, fixed-end tie rods function as compression columns in supporting this distributed load. Compressive stress in the bottom tie rods is about 7000 psi.
In the 12 O’clock position, the planar arrays are also stacked, but their weight bears on the aluminum strongback layers, which are well supported by the module’s aluminum face skins in tension. The strongbacks act as beams across their azimuthal widths only. The intermediate strongback layer bears two-thirds of the weight, allowing the inner strongback layer to be thinner for hermeticity reasons.

In the 3 O’clock position, the stainless steel ground plates of each planar array act as beams which transfer the lead weight to the trapezoidal end bulkheads. Any lateral instability of these thin beams is resisted by the close stacking of the planar arrays and the stiffness of the aluminum strongbacks.

For positions between the 6, 12, and 3 O’clock cases, internal loadings are linear combinations of these scenarios.

In all orientations, the internal structure of the modules supports the liquid walls against vacuum loads. The modules operate with internal pressures of about 6 Torr (TMP vapor pressure) plus liquid head. In all cases this is a partial vacuum. The modules are at positive pressure only during draining or gas purging, when the liquid walls are supported by neighboring modules or an assembly fixture.
6.4 BARREL ASSEMBLIES: The bolted assembly of the hadronic wedge modules to form the barrel section was illustrated in Figure 2-F. These modules have a bulk density equivalent to steel, although their strength and rigidity for support purposes exists only along the outer wall (composed of the steel yoke segment), at the aluminum end bulkheads, and along the inner strongback layer. In a 2D end view, the proposed bolting scheme joins the stacked trapezoidal end bulkheads at their four corners with joints that may be analyzed as pin joints; that is, each joint is expected to withstand shear stresses but not bending moments:

![Figure 6-C Hadronic Barrel End View](image)

A preliminary worst-case calculation indicates that a 3.5" diameter steel "pin" (or equivalent) at the outer radius is adequate. In 3D, the internal structure of strongback layers and the steel yoke segment prevent out-of-plane instabilities of the end bulkheads. Thin, full length axial tie rods buried in ground plane layers within the wedge modules pull the end bulkheads firmly against the ends of the planar arrays. These eliminate buckling instabilities in the end bulkheads, allowing them to be thinner and more hermetic. Independently, several calculations using simplifying assumptions indicate that 6061-T6 end bulkheads 4.0 cm. thick, stepping down to 2.0 cm. thick for the inner portion, are adequate to support the worst-case loads of hadronic barrel assembly with a factor of safety of two in the yield stress.
Appendix B gives an analytical calculation of stresses in the barrel assembly. This 3-D structure deserves a rigorous finite element analysis. A preliminary inspection does not reveal any weaknesses that cannot be remedied by minor adjustments to wall thicknesses and fastener sizes.

6.5 EM BARREL STRUCTURE: The assembled barrel EM sections have a relatively thin layer of active absorber mass supported mainly by the outer aluminum cylindrical wall. At the 12 O'clock and 6 O'clock positions, the lead weight is supported by the three layer tie rod structure in tension and compression, respectively. At the 3 O'clock position, the lead mass is supported by the continuous aluminum ground plates which run axially from one end bulkhead to the other. In the vertical plane, these act as horizontal beams transferring the load to the end bulkhead walls. Ground plate buckling is resisted by the tie rods.

Figure 6-D EM Module Structure

The EM barrel end bulkheads are stressed by the weight of submodules at the 3 and 9 O'clock positions. For EM hermeticity there is a strong incentive to keep these aluminum walls thin. We estimate that a wall thickness of 1.0 cm. is adequate.
The loading of the outer aluminum cylindrical shell is not simple. The largest component is the vacuum. For this azimuthally symmetric load, calculations indicate that buckling is avoided if the outer wall thickness is >1.25 cm. The vertical loading by the calorimeter mass is only about 1/6 atmosphere, and that of the liquid head is a maximum of 1/3 atmosphere. A careful analysis is needed to set the wall thickness of the EM outer barrel. Our assumption is that a 6061-T6 wall thickness of 3.0 cm. is adequate.

6.6 END CAP STRUCTURE: The end cap hadronic modules are inherently simpler in a structural sense. The orientation of the planar arrays and their stainless steel ground plates normal to the horizontal beam axis (Z) produces wedge modules which are very strong and rigid in the axial end view. The bays have bolted joints at each of the four corners of the 10 trapezoidal wedge modules similar to the barrel sections. Structural integrity in the axial dimension is assured by the thin aluminum radial wall "skins" in tension opposing the stacked internal structure of short tie rods in compression. In each end cap module the backside bulkhead wall is of thicker aluminum than the front. This provides a stable planar reference for signal feedthrus.

Figure 6-E  End Cap Wedge Module
7. AUXILIARY SYSTEMS

The full scale SSC warm liquid calorimeter is not dependent on extensive auxiliary systems. In common with other technologies, data acquisition electronics and high voltage (10 kV) distribution system are necessary.

7.1 TMP: No purification or processing of TMP on site is anticipated. Clean, tested TMP is furnished from the vendor in 5000 liter tanks. Removable piping allows back filling from these tanks into evacuated modules. Empty tanks are re-cycled to the vendor during the filling process (total TMP volume is about 170,000 liters in 105 modules). A two tank reserve of clean TMP (about 6 module's worth) is maintained during operation for use if a drain and refill treatment is needed for a contaminated module. A portable 10⁻⁵ Torr vacuum pump/gas purge system with a condenser for TMP vapor recovery is also needed for liquid exchange.

7.2 LEAK DETECTION/COLLECTION: Since electrical feedthrus are the most likely source of TMP leakage, feedthru walls will be covered with a sealed, thin walled, inert gas safety volume which also houses coupling capacitors, high voltage resistors and signal cabling. TMP leakage into these volumes is routed to empty 5000 liter TMP tanks. Such a leak is detected quickly, and an intentional draining into the TMP tanks is initiated to allow repairs to the emptied module. Catastrophic leaks in other than feedthru walls would be deflected by a full footprint, compact cylindrical drip pan barrier just above the solenoid magnet and below the steel magnet return yoke wall, and again routed to empty TMP tanks for eventual re-purification.
8. SAFETY ISSUES
Safety of the warm liquid calorimeter involves some general features arising from the use of large mass and high voltage, and some that are particularly associated with the flammable tetramethyl pentane. TMP is a clear hydrocarbon liquid with an odor similar to that of paint thinner. It has a vapor pressure of only 6 torr at 20°C, and a boiling point of 122°C. Ignited in an open container, it burns slowly with a low blue flame, similar to alcohol. Approximately 170,000 liters (170 m³) are required.

8.1 MODULE TESTING: Each of the modules is assembled resting on its outer radius steel base. After completion it is rigorously tested under vacuum and under pressure and when filled with liquid to assure that there are no weaknesses in the welds or feedthrus.

8.2 LEAKS AND SAFETY VOLUMES: The calorimeter structure is designed to channel any leaking liquid to an empty TMP container. In all modules, EM and Hadronic, Barrel and Endcap, the relatively fragile feedthroughts are protected by safety volumes on the back (from the origin) wall, which contain all the feedthroughts. In this location, the impact of the protective layer on performance is minimized. The sealed volume of inert gas is monitored continuously and can be changed or evacuated in the event of a feedthrough leak. The outside seal, from which contamination of the liquid is not an issue, is made with simple gaskets. The safety volume boundary is designed to contain leaks with a maximum pressure difference greater than the liquid head. The procedure in the event of a leaking module is to drain the module. Vacuum pump-down can remove all traces of liquid. A decision would then be made to repair or to operate without data from the defective module.

8.3 TMP VAPOR DISCHARGES: To avoid exhausting of TMP vapor into the atmosphere, the vacuum system is equipped with condensing coils to convert TMP vapors to liquid for recovery. This is necessary also to protect the vacuum pump’s lubrication system from TMP dilution.

8.4 TMP HANDLING: To minimize plant and safety considerations on site, we propose to fill and empty the (1500 liquid liter) modules from 5000 liter containers, which can be acquired and recycled as needed from the supplier (e.g., Wiley Organics Co., Coshocton, Ohio). Recent tests of smaller containers have shown acceptable quality, which can be improved, especially in large quantities. To maximize the effectiveness of the liquid transfer, while minimizing the pressures at the modules, the liquid supply and recovery system is located the level of the lowest modules. Storage of liquid normally uses similar containers, with no more than a few on site at a given time.
9. COST AND SCHEDULE

9.1 COST: The following quantities derive from the design shown in this report:

<table>
<thead>
<tr>
<th>Component</th>
<th>Hadronic Barrel</th>
<th>Hadronic End Cap</th>
<th>EM Barrel</th>
<th>EM End Cap</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid modules</td>
<td>60</td>
<td>40</td>
<td>3</td>
<td>2</td>
<td>105</td>
</tr>
<tr>
<td>Planar tile arrays</td>
<td>48x60</td>
<td>6x10x40</td>
<td>64x1x4</td>
<td>4x2</td>
<td>5,544</td>
</tr>
<tr>
<td></td>
<td>=2,880</td>
<td>=2,400</td>
<td>=256</td>
<td>=8</td>
<td></td>
</tr>
<tr>
<td>Lead absorber tiles</td>
<td>x2x12x18</td>
<td>x2x13x18</td>
<td>x2x6x52</td>
<td>x2700x6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>=1.2 mil.</td>
<td>=1.1 mil.</td>
<td>=0.16 mil.</td>
<td>=0.13 mil.</td>
<td>2.6 mil.</td>
</tr>
<tr>
<td>lead weight:</td>
<td>48 tons/ mod</td>
<td>54 tons/ mod</td>
<td>60 tons/ mod</td>
<td>35 tons/ mod</td>
<td></td>
</tr>
<tr>
<td>total lead:</td>
<td>2880 tons</td>
<td>2160 ton</td>
<td>180 tons</td>
<td>70 tons</td>
<td>5,290 tons</td>
</tr>
<tr>
<td>gross weight:</td>
<td>62 tons/ mod</td>
<td>70 tons/ mod</td>
<td>66 tons/ mod</td>
<td>38 tons/ mod</td>
<td></td>
</tr>
<tr>
<td>total gross:</td>
<td>3720 tons</td>
<td>2800 tons</td>
<td>198 tons</td>
<td>76 tons</td>
<td>6,794 tons</td>
</tr>
<tr>
<td>Insulators</td>
<td>1.9 million</td>
<td>1.8 million</td>
<td>0.7 million</td>
<td>0.5 million</td>
<td>4.9 mil.</td>
</tr>
<tr>
<td>Isolation resistors</td>
<td>1.2 million</td>
<td>1.1 million</td>
<td>N.A.</td>
<td>N.A.</td>
<td>2.3 mil.</td>
</tr>
<tr>
<td>High voltage channels</td>
<td>3,000</td>
<td>2,500</td>
<td>N.A.</td>
<td>N.A.</td>
<td>7.500</td>
</tr>
<tr>
<td>Signal channels</td>
<td>13,000</td>
<td>10,800</td>
<td>39,000</td>
<td>21,600</td>
<td>84,400</td>
</tr>
<tr>
<td>TMP (25% of volume)</td>
<td>80,000 liters</td>
<td>78,000 liters</td>
<td>6,000 liters</td>
<td>6,900 liters</td>
<td>171,000 liters</td>
</tr>
</tbody>
</table>

A more detailed preliminary costing exercise was then conducted as a large EXCEL spreadsheet. Parts costs are estimated based on weight and complexity, and manhours are estimated and costed for all phases of the effort. The cost estimate includes all design and construction of the calorimeter, including support structure and the complete magnet yoke, but without power supplies or data acquisition system. Benchmark rates used were: fabricated aluminum, $12.50/lb, fabricated stainless steel, $8.00/lb, lead absorber tiles, $1.00/lb, steel magnet yoke, $1.00/lb, TMP, $85/liter, engineering and QA, $50.40/hr, design, $29.25/hr, administration, $14.90/hr.
A summary of the cost estimate is given in the following table:

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>CLEAN ROOM</th>
<th>ENG/DES</th>
<th>FACILITIES</th>
<th>ADMIN/QA</th>
<th>TOTALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROTOTYPE DEV. &amp; TESTING</td>
<td>$300,000</td>
<td>$112,000</td>
<td>$100,000</td>
<td>$2,296,560</td>
<td>$2,808,560</td>
</tr>
<tr>
<td>HADRONIC BARREL</td>
<td>$14,758,513</td>
<td>$3,236,251</td>
<td>$1,400,000</td>
<td>$2,668,003</td>
<td>$22,062,767</td>
</tr>
<tr>
<td>HADRONIC END CAPS</td>
<td>$12,905,038</td>
<td>$3,374,134</td>
<td>$1,300,000</td>
<td>$2,316,968</td>
<td>$19,896,140</td>
</tr>
<tr>
<td>EM BARREL</td>
<td>$2,294,198</td>
<td>$730,945</td>
<td>$1,600,000</td>
<td>$2,307,399</td>
<td>$6,932,542</td>
</tr>
<tr>
<td>EM END CAPS</td>
<td>$1,211,138</td>
<td>$404,523</td>
<td>$1,100,000</td>
<td>$622,088</td>
<td>$3,337,749</td>
</tr>
<tr>
<td>TMP &amp; TMP SYSTEM</td>
<td>$16,095,000</td>
<td>$52,200</td>
<td>$95,690</td>
<td>$16,242,890</td>
<td></td>
</tr>
<tr>
<td>TOTALS:</td>
<td>$47,563,887</td>
<td>$7,910,053</td>
<td>$5,500,000</td>
<td>$10,306,707</td>
<td>$71,280,647</td>
</tr>
</tbody>
</table>

Of the total estimated cost of $71 million, the ten million pounds (5000 tons) of lead absorber tiles represent 14%, and the 187,000 liters of TMP represent 22%.

9.2 SCHEDULE: The modular design of the warm liquid calorimeter shown in this report offers important construction schedule advantages. A large portion of the assembly work will be done in parallel, saving considerable time.
10. CONCLUSIONS:

When R&D on warm liquid calorimetry began, the spectre of unavoidable contamination at unmeasurably low levels dominated concerns about the technique. Our growing experience and that of our colleagues around the world is that careful handling and cleaning avoids the pitfalls of contamination. The required procedures are far less formidable than those foreseen in the original UA-1 program, where stainless steel and ceramic, baked at very high temperatures were the only materials considered. Now we have dozens of acceptable metals and plastics, so that there is flexibility for optimization of performance and cost. Effective cleaning procedures are not far from standard (although some cleansers are not useable); and although it may save some time, it is not certain that any heating is necessary for cleaning.

A related development is that acceptably pure liquid can be obtained directly from the supplier, eliminating the need for the lengthy and expensive development of a major on-site purification system.

Another concern of the early R&D program was the voltage holding capabilities needed for fast response and low noise. Recent tests have shown that 10kV or more per 2mm gap is feasible.

A major advantage of the warm liquid approach, not fully appreciated in the early studies, is the effectiveness of modular construction using this technology. The detector is assembled from ≈100 complete and testable modules of only a few different types. The implied parallel operations in fabrication and final testing will save time. The assembly of modules into large subunits (bays) is straightforward. Accessible pre-amps located at or very near each module assure easy testing and excellent performance. Each module is equipped for liquid changes if and when needed.

The overall modular construction is highly compatible with the requirements of neighboring detector components. For example, the relatively light bays can be separated for access to the magnet coil, the central detector, or to each other. Another example is in the small angle region (eta > 3), where the thin end cap boundary preserves excellent hermeticity for the presently undefined forward calorimeter.
APPENDIX A:

STRIP TOWERS FOR ELECTRON MEASUREMENTS:

Square towers with $\Delta \phi = \Delta \eta = 0.05$ are too large to localize electrons and photons accurately. This can be accomplished with a high resolution pre-radiator, but here we consider the alternative of narrow projective ($\Delta \phi, \Delta \eta$) strip towers in the EM section. These are included as part of the depth sampling, covering shower maximum for best signal and resolution, and alternating in direction from layer to layer. At front and back of the 24rl EM section are 6rl square subtowers, in the middle are two interleaved strip towers of 6rl each. The figure shows schematically how the front and back subtowers are arranged in semi-projective geometry. The strip subtowers are more nearly projective.

Since the strips are used for position measurements, their widths are essentially independent of $\eta$. The strip lengths are $\Delta \phi$ (or $\Delta \eta$) = 0.2, the widths are 1.5cm. The dimensions are somewhat arbitrary; the optimum solution must take into account resolution, channel capacitance, ambiguities and assembly problems. In the present design there are an average of 1.5 strip channels per square channels. The totals are summarized in Section 9.

All signals are carried to the backs of the modules (see figure). The $\eta$-cracks in the back square subtower carry the signals from the $\phi$-strips, which are ganged in the $\eta$-cracks of the strip channels. Ganging and extraction of signals from the front square subtower and $\eta$-strips are easiest in the $\phi$-cracks.
APPENDIX B:

MECHANICAL ANALYSIS OF HADRONIC BARREL ASSEMBLY

The Barrel(Endcap) Hadronic calorimeter is formed from azimuthal wedge modules of 18(36) degrees assembled into three(two) $\Delta\phi=2\pi$ rings. Each includes a matching section of the outer radius steel magnet yoke, to which the module is rigidly joined. There are 100 Barrel and Endcap Hadronic module-yoke assemblies weighing $\leq 70$ tons each. Each, including pre-amps nested in holes in the steel yoke, is thoroughly tested before assembly. The rings are built up from the bottom, supported at the outer radius on cradles which are then rolled axially into operating position. Azimuthal rotation of this support structure during assembly is not needed.

The modules could be cantilevered from a strong outer radius steel yoke, with sections joined into a rigid $\Delta\phi=2\pi$ beam. Assembly is easier, however, if the yoke sections are simply pinned together with joints supplying radial and azimuthal forces. At the inner radius azimuthal but not radial forces are provided. In contrast with a cantilevered design the outer radius pins do not constrain the azimuthal orientation of each module; hence a small azimuthal force at the inside radius closes the gaps between modules. The large forces are at the outside; the inner structure can be thin, as required for good hermeticity.

With the simplifying approximation that the wedge modules are of infinitesimal width (Figure 1) a zero order structural analysis of the radial and azimuthal forces on each end of the ring is carried out below. With density $\psi(\rho)$, the weight $W\Delta\phi$ and radial center of gravity $b$ of an infinitesimal module of (half) length $l$ are:

$$W = \int \psi(\rho) \rho \, d\rho \quad \quad b = \int \psi(\rho) \rho^2 \, d\rho / W$$

where $l$ is the (half) length and $W$ is the weight of one radian of (half length) modules. For the Barrel(Endcap) $W = 100(50)$ tons.

In Figure 1 the azimuthal forces (tension is positive) at inner and outer radii $\rho=a,c$ are $t$ and $T$, respectively. Azimuthal stability of each infinitesimal module requires:

$$\frac{dt}{d\phi} = f \cos\phi; \quad \frac{dT}{d\phi} = F \cos\phi; \quad f = (c-b)/(c-a); \quad F = (b-a)/(c-a); \quad f+F=1$$

$$t = f \sin\phi + k \quad T = F \sin\phi + K$$

where $k$ and $K$ are constants of integration, and we normalize all forces to $W=1$. $R(\phi)$ represents the radial force on the pins between modules, opposing the gravitational and $\phi=\pi/2$ tangential forces on the section of the ring above $\phi$.

Figure 1 shows also a set of external forces $V$, $H$, and $A$ to provide three point support of the total ring. There is symmetry around $\phi=\pm \pi/2$. Balancing the horizontal and vertical forces and the moments around the center of gravity at $\phi=0$, $\rho=2b/\pi$: 
Figure 1. Half of L-R symmetric hadronic ring. Arrows show forces, normalized to $W=1$, acting on pins at inner and outer radii $\rho=a,c$. $\rho=b$ is the center of gravity of individual modules, assumed for simplicity to be infinitesimal.

(3) provides three constraints for seven free parameters: $V, A, H, K, J, k, \alpha$. Note that a single constant $k$ describes the force at the important inner radius, while two are needed at the outer radius to account for the external tangential force at $\phi=\alpha$.

Whatever the distribution of external support at the outer radius, the absolute magnitude of the force at the inner radius is minimized ($-f \leq t \leq f$) for $k=0$. In the simplest case, a single (per side) support point with $\phi=\alpha$ and $A=H=k=0$ gives:

$$V=\pi \quad J=-K=(\pi/2)\cos\alpha$$

$$t=fsin\phi \quad T_+ (\phi>\alpha)=Fsin\phi-(\pi/2)\cos\alpha \quad T_- (\phi<\alpha)=Fsin\phi+(\pi/2)\cos\alpha$$

$$R_+ (\phi>\alpha)=[1-(\pi/2)\cos\alpha]cos\phi+(\pi/2-\phi)sin\phi \quad R_- (\phi<\alpha)=[1-(\pi/2)\cos\alpha]cos\phi-(\pi/2+\phi)sin\phi$$
The tangential and radial force distributions from (4) are shown in Figure 2 for the Barrel Hadronic rings with $\alpha=0$ and $\pm \pi/6$, $A=H=k=0$, and $f=0.25, F=0.75$.

• With $k=0$, $|t| \leq 25$ tons for the Barrel. Distributed over the inner radius strongback of thickness 2cm and half-length 133cm, the stress is $\leq 0.1$ tons/cm².

• $\alpha=0$ gives the smallest R-forces – up to $= 50$ tons.

• The peak tangential forces are nearly 150 tons, but less sensitive to $\alpha$.

• We have not yet attempted to minimize T and R with a broader support base, e.g. $A \neq 0$.

Figure 2. Azimuthal dependence of $t$, $T$, and $R$ forces. Outer radius external support is at $\phi=\alpha$, where $\alpha=0, \pm \pi/6$. $A=H=k=0; f=0.25, F=0.75$. Arrows show paths through discontinuities at $\phi=\alpha$. 