EXECUTIVE SUMMARY

The ES&H design criterion for vacuum windows is addressed in the Design Reference Data section of FESHM chapter 5033-TA which specifically references Mechanical Safety Subcommittee Guidelines for the Design of Thin Windows at Fermilab, TM-1380 (SCN 0121.585). This TM (latest revision dated March 1993) provides General Guidelines which state that the allowable stress shall be the most stringent of $S= 0.5\ F_u$ or $S = 0.9\ F_y$, where S= the allowable stress (psi), F_u = the ultimate tensile strength (psi), and F_y = the yield strength or stress to produce 5% elongation (psi). These ratios are calculated based on the theoretical material properties, not necessarily the actual material properties. No portions of FESHM 5033 other than TM 1380 explicitly address criterion for the design of vacuum windows.

To meet the criterion set forth in FESHM 5033, the following work has been performed:

1) Andrew Szymulanski and Ron Currier (retired) of RD/MSD/MSG designed the 71 inch vacuum window and the vacuum window test fixture. This effort drew upon existing designed used on previous 48 inch vacuum windows for E731, E773 and E799I. See the calculation in Section 1. Ang Lee of RD/MSD/EAG provided finite element analysis of the window material stresses and deflections in a report dated 13 August 1992. Refer to Section 2.

2) Results of these calculations were reviewed by the then existing KTeV Mechanical Safety Review Panel chaired by Joel Misek. A letter sent by Joel Misek to Roger Dixon on 19 January 1993 included the statement that "the window design appears to be consistant with existing window design and the upcoming test program should provide assurances to its safety and design limitations". See Appendix 4.

3) Fred Renken, a coop student in RD/MSD, performed tensile testing on Kevlar material samples from the roll destined to be used to fabricated KTeV vacuum window. These tests provided a qualitative measure of the clamping effectiveness and provided ultimate tensile strength values. See Section 3.

4) A window assembly procedure was drafted by Dave Erickson of RD/MSD/MSG and is in Section 5.0, Part A. (See Appendix 5 for the final version). Procedures for the test program were written by Andrew Szymulanski, and Ron Currier (retired) and reviewed by the KTeV ES&H/QA Review Panel chaired by Wes Smart (which superseded the KTeV Mechanical Safety Review Panel). A letter sent by Joel Misek and Wes Smart to Roger Dixon on 21 March 1994, (included in Section 6) concluded "sound engineering practices have been employed" and indicated that the Fermilab Pressure Testing Permit procedure would be followed. The letter indicated that one permit would suffice for all vacuum testing and a second permit would cover the hydrostatic tests. The letter concluded by recommending approval of the testing program. Roger Dixon approved it on 22 March 1994.

5) A puncture test was conducted on the first window on Thursday 21 April 1994 in MAB. See Section 5, part C. The local puncture propagated across the full diameter of the window. Ang Lee analyzed the failure in a

report dated 13 May 1994 to understand the failure mode. Conclusions reached in this analysis provide an understanding of the puncture process. See Section 4.

6) Four hydrostatic tests (with the appropriate Fermilab Pressure Testing Permits) were performed in MAB with failure occurring at ultimate pressures of 28, 24, 28, and 28 psig. The low value was recorded for a window fabricated by a different pair of technicians and is not considered to be representative of the actual ultimate pressure of the window. See Section 5.0 Part B

7) A long term creep test of a sixth window was initiated in TSB during November 1994. Results indicate that the initial increase in the deflection was approximately 0.1 inches during the first week with decreasing additional deflection increases measured thereafter. The test continued until May 1995 and additional measurements indicate that a creep related failure is not probable. Refer to Section 6.0

Results of the above described processes indicate the following:

1) The *calculated* ratio of design stress (F_d) to ultimate tensile strength is $F_d/F_u = 0.5$. Because of the very high Young's modulus for Kevlar, this value rather than the ratio of $F_d/F_y = 0.9$ sets the allowable stress. This result is in accordance with the FESHM criteria. However, the examples cited in TM-1380(SCN 0121.585) do not include a mylar / Kevlar composite design. Therefore, finite element techniques were used to determine the calculated design stress in the Kevlar material.

   This design is very close to the minimum allowable ultimate tensile strength. Approaching the minimum allowable ultimate tensile strength is appropriate because of the detrimental effects material in the window has on multiple scattering in the experiments and because window material thickness are not infinitely adjustable as metal sheet thickness are. It must be remembered that all of these fabrics are "step function" materials. The next thicker or stronger weave will have significantly more material because the factory does not offer material 5% stronger.

2) The *measured* ratio of the actual stress (F_a) to ultimate tensile strength (F_u), $F_a/F_u = 0.5$ for the three hydrostatically tested windows believed to be representative of the one to be used in the KTeV experimental hall. This result is in accordance with the FESHM criteria. The calculation is as follows: The stress is proportional to the applied pressure and the ratio F_a/F_u can be replaced by P_a/P_u where P_a is the actual pressure in service and P_u is the ultimate pressure at failure. Per the US. Standard Atmosphere Data, the atmospheric pressure at 734'-0 elevation is 14.29 psia. The average ultimate pressure at failure for the three representative windows was 28 psig. In both cases, these values also represent the differential pressure across the window. Substituting the pressure values and solving for the ratio gives $F_a/F_u = P_a/P_u = 14.3/28 = 0.5$.

   This value is based on a *measured* ratio, not a theoretical value. Potential errors due to differences from batch to batch variations in material ultimate strength, errors due to stress risers omitted from the analysis, and variations from the design conditions in the applied load have been implicitly included in determining this ratio.

The construction and test-to-failure of four vacuum windows exceed the requirements of FESHM 5033 and the documents referenced therein.

3) Long term creep tests, which far exceed any written FESHM requirement, have been performed. The results indicate that 50% of ultimate load measured on the window is sufficiently low to prevent creep related failure. Specifically, these test results show that the creep-time curve is safely within the second stage of the curve (secondary creep) for the loads and durations the window will encounter in service. From this curve the expected window lifetime will be extrapolated. It is this lifetime compared to the required lifetime of the window used in the experiment that is the most relevant way to quantify the safety factor of the window.

The creep test data presented here is based on an initial creep test of six months, a period equal to the scheduled duration of the first leg of the next fixed target run. It is possible to continue the creep test indefinitely (provided a second window flange set was purchased) to experimentally determine the window lifetime. It is also possible to simply replace the window in the experiment every six months. Either course will ensure that window used in the experiment is operated within its design lifetime.

There are three possibilities which would cause the window to fail; puncture, overpressure, and creep related failure. Puncture of the window will be prevented by a vacuum window safety barrier discussed in Section 7. A doubling of the absolute atmospheric pressure, which would cause failure, is very improbable. This leaves creep related failures as the sole remaining plausible possibility. For this reason, considerable effort was expended to perform the creep tests. Conducting this test exceeds any stated requirements in FESHM or documents referenced therein but is considered necessary by the engineers responsible for designing the window.

Hazard assessment:

Since there are inherent dangers with thin vacuum windows, the KTeV project has always recognized the need for a vacuum window safety barrier. This barrier was designed by engineers in RD/MSD/MSG with the following criteria:

1) The vacuum window safety barrier has been designed for remote operation. It will be closed (placed in front of the vacuum window) whenever it is necessary for people to enter the experimental hall while the vacuum system is under vacuum.

2) The vacuum window safety barrier will be interlocked to prevent putting beam on the target while the vacuum window safety barrier is in the closed position. This is necessary to prevent the accidental loss described in section 6.5.2.iii in the KTeV Beam Systems Design Report Version 1.1 dated June 1994.

3) The vacuum window safety barrier has been designed using ASME pressure vessel allowable stresses, to take the differential pressure resulting from full vacuum on one side and atmospheric pressure on the other side. It is designed to be forced against the vacuum window flange

in the event of a window failure. A clearance is provided to allow air into the vacuum vessels, repressurizing them.

4) The primary functions of the vacuum window safety barrier are to prevent access to the front of the vacuum window (thereby eliminating the potential for accidental window puncture) and to isolate people from the pressure wave which would occur during a window failure.

5) The vacuum window safety barrier is NOT designed to protect equipment in the experimental hall should the vacuum window fail while the shield is in the open position.

The vacuum window safety barrier described above is being provided to mitigate potential hazards to personnel.

In the event of a vacuum window sudden failure occurring while the vacuum window safety barrier is in the open position, the potential equipment damage is estimated to include:

1) Drift Chamber 1 (DC-1) is located immediately downstream of the vacuum window. Its close proximity to the vacuum window is necessitated to optimize the physics. In the event the window fails while the vacuum window safety barrier is in the open position, it is reasonable to assume that all of the drift chamber wires and windows would be destroyed. Additionally, one may assume that the entire drift chamber and chamber mounted electronics is damaged beyond repair. The value of DC-1 is estimated to be $50,000. This risk is acceptable to the KTeV collaboration.

2) Helium Bag 1 (HB-1) fills the space around the vacuum window and the upstream face of DC-1. It is reasonable to assume that HB-1 would be a total loss in the event of the window suddenly failing while the vacuum window safety barrier is in the open position. The value of HB-1 is estimated to be $3000. This risk is acceptable to the KTeV collaboration.

3) Spectrometer Anti 2 (SA2) is located 6 meters downstream of the vacuum window. The support for this detector is designed to accommodate a 3600 pound lateral force at the top of the detector due to lateral loads such as earthquake and window failure. Although the net area of the SA2 frame is approximately 200 square feet, sufficiently detailed analysis has been completed to quantify the loading on the detector frame resulting from a window failure while the vacuum window safety barrier is in the open position. It is calculated that the detector frame is capable of withstanding the loading imposed by the a vacuum window failure. That analysis was prepared by Zhijing Tang of RD/MSD/EAG. Please refer to Section 8.

4) Drift Chamber 2 (DC-2) is located immediately downstream of SA2 and would be exposed to the effects of a window failure since there is a large aperture in SA2. It is reasonable to assume that all wires and windows in DC-2 would need replacement after a window failure. Since the DC-2 electronics are behind SA2, it is not believed that they would be damaged. The cost of repairing DC-2 is estimated to be $35,000. This is acceptable to the KTeV collaboration.

5) Helium Bag 2 (HB-2) fills the space between the downstream face of DC-1 and the upstream face of DC-2. It is reasonable to assume that HB-2 would be a total loss in the event of the window suddenly failing while the

vacuum window safety barrier is in the open position. The value of HB-2 is known to be $3000. This risk is acceptable to the KTeV collaboration.

6) The sudden repressurization of the vacuum vessels would cause the building pressure to theoretically drop by 0.21 psi if the building was hermetically sealed. While this is a conservative assumption, the pressure reduction is equivalent to an external pressure of approximately 30 psf on the outside of the building. This building is designed to accommodate comparable loads due to wind (30 psf minimum) and snow (25 psf). During CDR and Title I building design, the building was volumetrically larger which reduced the building pressure drop in the event of a sudden repressurization. As the building was trimmed to control costs, the effect of a sudden repressurization of the vacuum vessels on the wall and roof loads increased but were not included in the design. A large frangible panel could be added to the north facade of the building to provide make up air and reduce the static pressure to within the design values. However, such modifications to the building may not be necessary due to the very conservative assumption of a hermetically sealed building.

7) The sudden unbalanced load due to the presence of atmospheric pressure on one end of the string of vacuum vessels and the absence of it on the other will place a net force on the vacuum vessels of approximately 57,000 pounds. The puncture testing of the first vacuum window resulted in the same force being applied to the much less massive vacuum window test table, but the video tape of this test does not show evidence of the table moving, although a slight displacement of the table was noted after the test ended. One can conclude that the force existed for such a short length of time that the vacuum window test table did not have an opportunity to accelerate before the pressure wave hit the bottom of the table, thereby restoring a balanced force condition. The ratio of volume to weight for the KTeV vacuum decay region is a factor of four greater than the same ratio for the vacuum window test table and sufficient calculations. Zhijing Tang has evaluated the effect on the KTeV Vacuum Vessels in the decay region and has determined that the existing vessel supports are sufficient to restrain vacuum vessel movement during a vacuum window failure. See Section 8.

8) The sudden repressurization of the vacuum vessels would cause the diffusion pump oil to be exposed to oxygen while hot. Although a silicone based oil is being used, this may degrade the oil. Replacing the pump oil will cost $5000. This is acceptable to the KTeV collaboration.

9) The sudden repressurization of the vacuum vessels would cause the ion gauge on the vacuum vessels to burn out. A replacement gauge will cost less than $200. This is acceptable to the KTeV collaboration.

In conclusion, the Research Division's Mechanical Support Department has methodically designed a large diameter vacuum window which exceeds the requirements of FESHM. This window is based on previously used 48" diameter windows for E731, E773, and E799I and a 36" diameter vacuum window used in Brookhaven which were constructed in the same manner with the same materials. The work has been performed with the full knowledge of both the KTeV ES&H/QA Review Committee and the Research Division Office. While this window does present some hazard, personnel hazards are mitigated by the vacuum window safety barrier. The identified hazards to equipment (which can not be mitigated through use of a vacuum window safety barrier) that have been analyzed are deemed acceptable. The window is categorized as a low hazard consistant with the KTeV Safety Assessment Document.