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Beryllium Window for Synchrotron Light Sources

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ABSTRACT

As part of an on-going upgrade program at the National Synchrotron Light Source, a parametric study of rectangular flat and curved beryllium windows of varying thickness and heights and under varying thermal loading was undertaken. The study consisted of a series of 2D and 3D thermal stress finite element analyses to determine the relative benefit of various combinations of parameters with respect to the windows' ability to withstand thermal loads.

This study includes evaluation of fixed versus flexible mounting of flat and curved beryllium windows. Buckling analyses for both types of mountings are also included.

Keywords: Beryllium, X-ray Vacuum Windows, Thermal Stress

1. INTRODUCTION

The properties of beryllium with respect to transmissibility of x-rays, thermal conductivity, and strength make it well suited as an x-ray window vacuum separator for x-ray synchrotron beam lines. Beryllium is nearly transparent to shorter wavelength x-rays, has relatively high thermal conductivity and a high strength-to-weight ratio. These factors allow thin narrow strips of beryllium foil to be used as vacuum separators between the NSLS machine vacuum and various beamline environments. Some of the x-rays produced by the NSLS X-Ray Ring will be absorbed by the beryllium, however, consequently heating the windows. Appropriate design of an actively-cooled x-ray window may allow a window to operate indefinitely in such an environment. Beryllium windows have been in use without failure on most of the beamlines at the NSLS since its inception.

The original plans for the x-ray ring at the NSLS specified a ring current of 500 mAmps and beam energy of 2.5 GeV. Until recently, the ring RF cavities were able to reliably support a maximum ring current of 250 mAmps. Recent upgrades to the RF cavities and other improvements have made operation of the ring at 500 mAmps feasible. As part of this upgrade process, all components of the x-ray ring were analyzed to determine the impact of the higher operating current. These analyses determined that many of the NSLS windows violated criteria established by Thomlinson[1] prior to the NSLS x-ray ring commissioning. The Thomlinson criteria provided for a maximum temerature rise in the beryllium of 80°K. This report revisits Thomlinson's calculations and investigates the merits of alternative window designs.

2. METHODOLOGY

In order to insure consistency and conservatism in the calculations, a baseline set of parameters was set up, using the NSLS existing beryllium window closest to its source point, under thermal load from bending magnet synchrotron radiation. The parameters thus chosen were as follows:

distance from source	5.48 meters
vertical opening angle	0.198 mrad
incident power (from bending magnet)	40 W/mrad
power absorbed	dependent on window thickness (see figure 1)
window width	123 mm
intentional window curvature	none
window material	beryllium, Brush-Wellman IF-1

filters	none
window mounting	fixed boundaries

In addition, it was assumed that the cooled support for all window designs presented a fixed temperature heat sink at 37.8 °C (100 °F). Although the properties of beryllium vary with temperature, it was determined reasonable to analyze the windows using constant properties. Existing correlations[2,3] show thermal stress to be proportional to the quantity

$$E \alpha \Delta T$$

where:

E is the material's modulus of elasticity
α is the material's thermal expansion coefficient
ΔT is the characteristic temperature difference.

Under examination, the product $E\alpha$ was found nearly invariant with temperature. The thermal conductivity used was an average value for the range of temperatures encountered in this analysis. Finally, it was assumed that the incident power density is linearly related to the distance from the source point.

Having established these parameters, the next step in the analysis consists of a series of finite element analyses wherein the window thickness, window height, window mounting (fixed or free edges), and distance from the source were varied, and the combined stress profile (von Mises stress) is calculated for each case. Because of symmetry in these analyses, only 1/4 of each of the windows neede to be modeled. They were modeled as plate elements, with fixed-temperature heat sink thermal boundary conditions on the 2 outer edges, either fixed or free mechanical boundary conditions on these same edges and symmetry thermal and mechanical boundary conditions on the symmetry edges. In order to use this type of element, the power absorbed from the x-rays was assumed to be absorbed along the horizontal centerline, uniformly across the window thickness. This assumption is slightly more conservative than distributing the power across the vertical opening angle on the upstream face of the window. The percentage of total power absorbed vs. beryllium window thickness is shown in figure 1.

Considering only the window in the analysis, and setting the edge boundary conditions to either fixed or free, while keeping these edges as a constant temperature heat sink, the window problem is effectively bounded, so that these two conditions represent a worst case and best case for any given set of window parameters. Linear static finite element analysis (FEA) calculations were then performed to calculate some characteristic value for each set of window parameters. In the present case, the characteristic value for each analysis is the maximum von Mises stress in the window. The maximum von Mises stress value for both cases (fixed and free edges) could then plotted against any other set of variables to establish a range between the two curves where any real window must fall for the given parameters, with the assumption of linear static stress.

Criteria for determining allowable stresses in a beryllium window were obtained by performing a Goodman analysis[4] (for non-reversible stress). To be conservative, the number of thermal cycles to be experienced by a typical window was taken as 100,000. Properties for Beryllium are taken from Brush Wellman data. The allowable stress thus determined may now be used as a criteria to evaluate window parameter combinations.

In order to establish the reasonableness of using a linear stress FEA calculation, a set of calculations is performed to determine the relationship between buckling stress and window dimensions. Roark (Table 35, cases 2a and 2b) relations were used to find the critical buckling stress vs. window dimensions (height). These calculations correspond to a simply-supported and a clamped window, which in turn approximate the free or fixed boundary conditions, respectively, for FEA calculations. These analyses determine (conservatively) the stress at which a flat plate subjected to compressive stresses due to thermal loading will buckle.

The effects of buckling on the development of stress was assessed by using FEA to examine the thermal stresses developed in a window which has a small degree of curvature imposed on it. Using plate elements, it was also relatively easy to examine the effects of doubly-curved windows (i.e. rectangular windows with distinct radii of curvature for both the horizontal and vertical directions.

The data generated by the above analyses was combined to bound the ranges where suitable window designs may be found. The data is also examined qualitatively to determine how the nature of the stress profile on a given set of window parameters varies when one or more of those parameters is varied. This information was then be used to determine a range of window parameters wherein an acceptable solution for a given duty may be found. In the present case this corresponds to the requirements imposed by the individual beamlines at the NSLS.

Finally, once the territory where a solution may be found was "staked out", and once a set of common parameters was imposed, 3D thermal stress models were created representing more realistic boundary conditions. This analysis then determined the best solution(s) for a given set of parameters.

3. ANALYSES

In order to find the linear elastic bounding solutions for windows of varying height, thickness and power density, a series of finite analyses (using 3D plate elements) were performed for both fixed and free edge boundary conditions. In all cases the material properties were evaluated at a representative (average) value and assumed constant. The boundary temperature was assumed fixed at 37.8 ° C (100°F). One quarter of the window was modeled with symmetry conditions imposed on the symmetry planes. The maximum von Mises stresses vs. height, window thickness and power density (absorbed at the window centerline) for both fixed and free edges are presented as figures 2, 3 and 4 respectively.

A Goodman analysis was performed to determine the failure criteria for the beryllium windows. Figure 5 shows the Goodman diagram used. The resulting allowable stress is 290 MPa (42,000 psi).

A set of calculations was then performed to find the critical buckling stresses for windows with either fixed or free mechanical boundary conditions. Since beryllium window dimensions typically have low aspect ratios (height/width), the width of the window is of lesser significance and was assumed constant for purposes of this analysis. The resultant buckling stresses for fixed and free windows of varying window heights and window thickness are presented in figures 6 and 7.

FEA calculations on slightly curved windows were then performed to examine the effects of buckling on beryllium windows and to examine the mode shapes. Using linear calculations on curved windows, it was found that, although the compressive stresses were greatly reduced, large bending stresses at the window edges and symmetry planes were created. Using non-linear FEA to examine mode shapes indicated that a multi-period waviness along the longitudinal symmetry plane was developed after buckling. Attempts at minimizing this effect by examining a doubly-curved window with differing radii of curvature in the longitudinal and transverse directions seemed to be somewhat effective. Examination of the temperature profiles on typical windows indicate that the temperature was more uniform in the longitudinal direction and approximately linearly decreasing from the centerline to the upper and lower boundaries. This suggested that the overall rate-of-growth in the horizontal direction should be about twice that in the vertical direction, and accordingly the ratios of the respective radii of curvature might be adjusted. Linear FEA on the resulting doubly curved windows, however, indicated marginal improvements in maximum total stresses for free edges, and considerably greater total stresses (due to large edge bending stresses) for fixed-edge windows. In addition, manufacturing difficulties for fabricating and joining such windows to their cooling blocks made this approach undesirable to pursue for NSLS purposes, and further investigation into curved windows was abandoned.

At this point, it was decided that further investigation would be limited to flat windows, and that the maximum von Mises stress in the window would not be allowed to exceed the buckling stress. Furthermore, in order to preserve existing throughput of x-rays in NSLS beamlines, the window thickness was fixed at .254 mm (.010 in).

The data compiled above can then be used to establish an upper and lower bound to the maximum von Mises stress for a .254 mm (.010 in) thick beryllium window of any given height, at any power density. It has been suggested by Hu[5], that a thin flexible frame attaching the beryllium window to its cooling block might significantly reduce stresses in a beryllium window. 3D Finite element analyses (linear) were performed on a variety of frames and on a typical conventional block to determine if such improvement could be verified. Figures 8 and 9 show the results of the best "flexible frame" solution and the typical conventional cooling block for 5 mm (.197 in) and 10 mm (.394) high beryllium windows compared with fixed and free conditions on the window edges.

Figure 10 provides the maximum temperature rise (for windows at the baseline conditions) plotted against window thickness and window height.

CONCLUSIONS

Analysis of beryllium windows , as encountered in synchrotron light sources, involves a synthesis of techniques in order to understand the response of the windows to the particular thermal environment created by absorption of synchrotron radiation. The thermal response of such windows to the narrow zone of heat absorption is a highly two- dimensional temperature profile which in turn results in a mostly two-dimensional stress profile. Two-dimensional thermal stress FEA models, however, do not adequately reflect real stresses for specific window designs, though they can be very useful to find bounds to potential solutions and to examine specific design characteristics. Two-dimensional elements formulated in three dimensional space (i.e. plate elements) are useful in characterizing designs in which curvature and bending play a significant role. Finding bounding solutions to problems by formulating simple models which over and under estimate real conditions can significantly reduce the analytical tasks by limiting the range of potential solutions.

Full three-dimensional models for beryllium windows become necessary when the range of solutions has become significantly narrowed and the effects of more realistic boundaries are to be studied. In the present case, the two-dimensional (plate element) models were most useful in assessing the effects of the window material stiffness on the window growth in both the vertical and horizontal directions and the resulting stresses, when imposed with either fixed or free edges. These models formulated in three-dimensional space with curvature can also be used to examine the effects of bending and buckling.

The examination of buckling in the above efforts leads to the conclusion that allowing windows to buckle in attempt to reduce stress is undesirable, due to unacceptable bending stresses thus generated, and because flat window buckling leads to very complex mode shapes which are not well understood. (For more on buckling, see Wang[6]). Using curvature to prevent buckling of windows was also found to be undesirable for the NSLS for the reasons given above, although more investigation may be warranted, especially with non-linear models. Curved windows were found to significantly reduce stresses due to a differential pressure atmosphere, and therefore might be attractive if the thermal loading can be reduced (e.g. by the use of filters[7]). Such considerations, however, are beyond the scope of the present discussion.

The investigation of a "flexible frame" leads to the conclusion that, at least for the NSLS design considerations, the effects of reduced overall thermal conductance through the frame are not sufficiently overcome by the flexibility at the boundaries. Furthermore, for the frame as considered, there is significant flexibility only in one direction while there is thermal growth in the window in two perpendicular directions. Moreover, the greater stiffness of beryllium when compared to copper manifests itself as a certain degree of edge flexibility, even in the conventional solid block design.

Finally, the analyses presented herein validate the original findings of Thomlinson[1] with respect to appropriate window heights for NSLS beamline beryllium windows. The present analyses show that NSLS beamlines subject to bending magnet radiation should be sized for a maximum height of 1 mm for each meter of distance from the source point. In order to limit the number of design variations for NSLS beryllium windows, and with consideration to the actual beam opening angle and hardware alignment issues, the NSLS has adopted the policy that bend magnet beamline beryllium windows closer than 10 meters shall have a window height of 5 mm. All bend magnet beamline windows further that 10 meters from the source shall have a window height of 10 mm. Beamlines with other sources are treated on an individual basis. The NSLS has instituted an upgrade program to identify and replace any windows which violate this policy.

ACKOWLEDGEMENT

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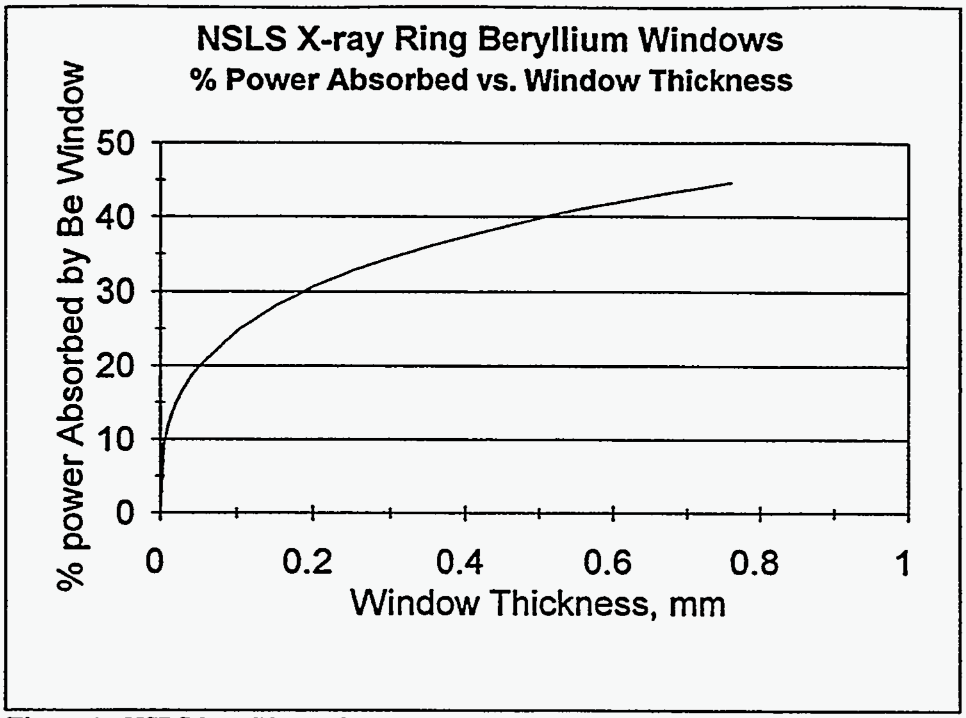

Figure 1: NSLS beryllium windows, % x-ray power absorbed vs. window thickness
(Critical photon energy 5.56 keV)

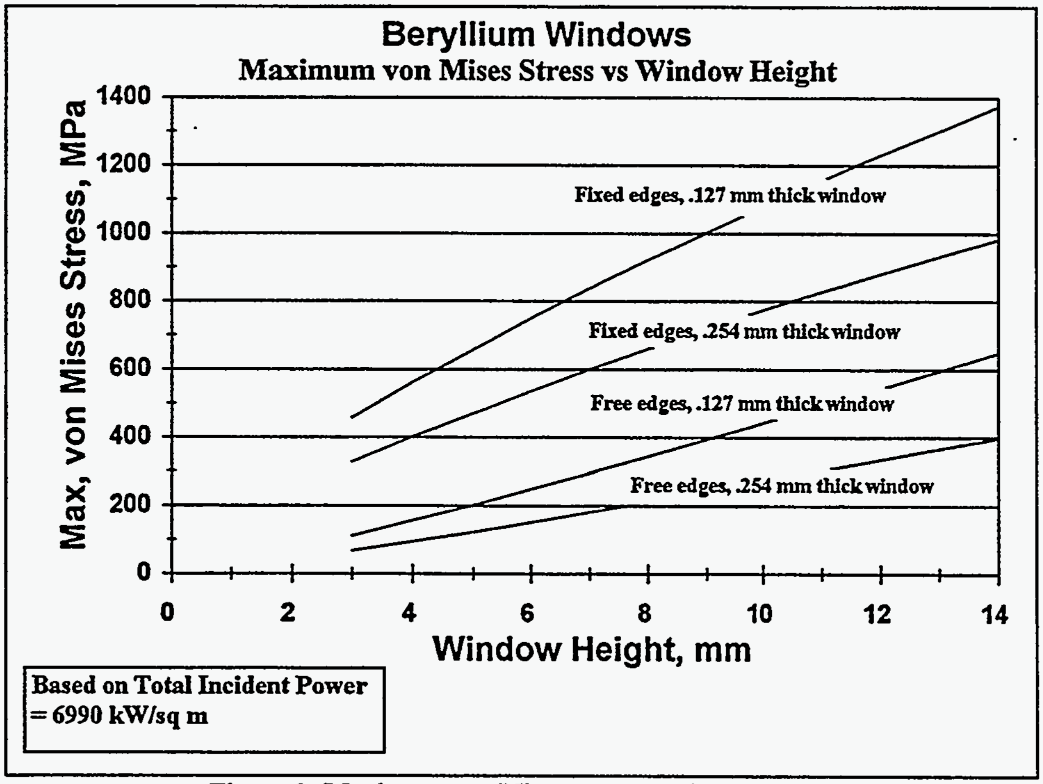

Figure 2: Maximum von Mises stress vs window height
The various curves correspond to different edge boundary conditions, and Be window thicknesses.

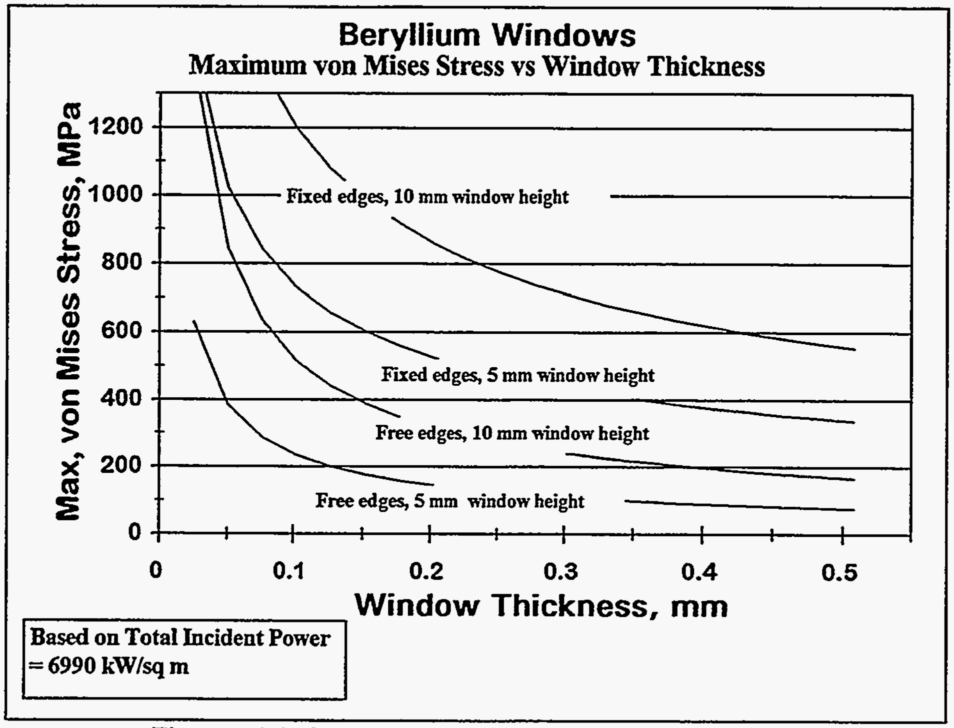

Figure 3: Maximum von Mises stress vs window thickness
The various curves correspond to different edge boundary conditions, and Be window heights.

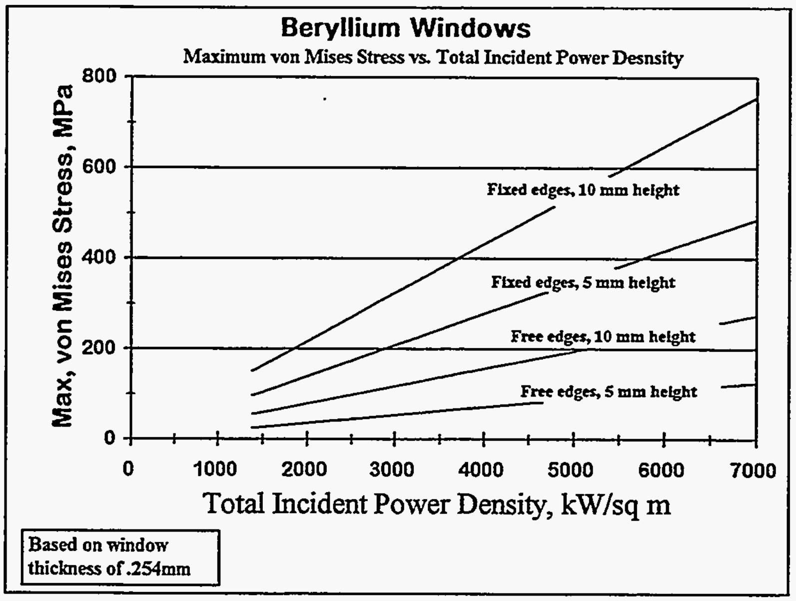

Figure 4: Maximum von Mises stress vs incident power density
The various curves correspond to different edge boundary conditions, and Be window heights.

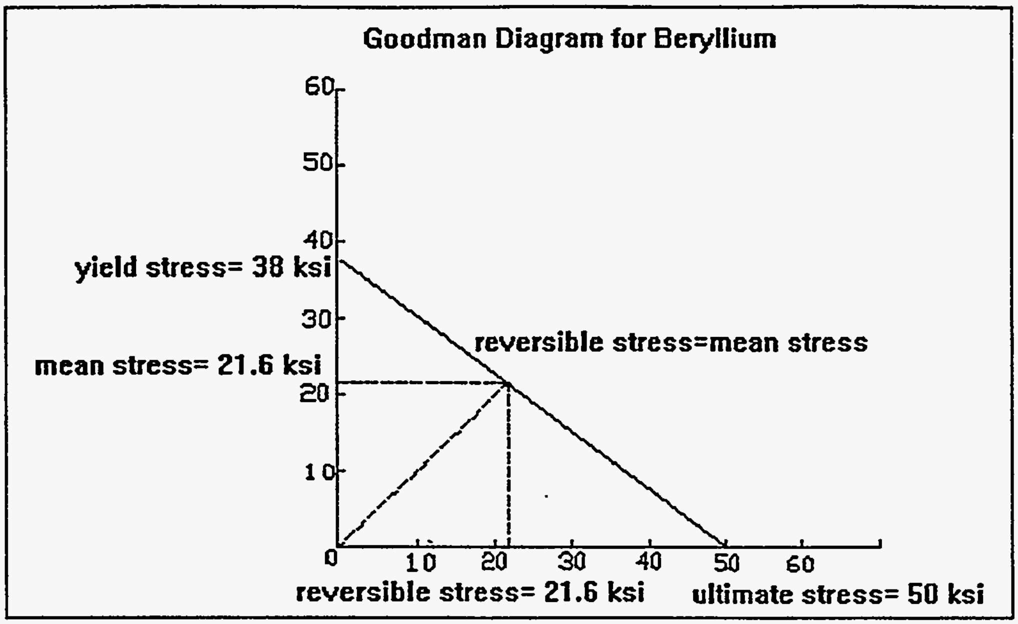

Figure 5: Beryllium Goodman diagram

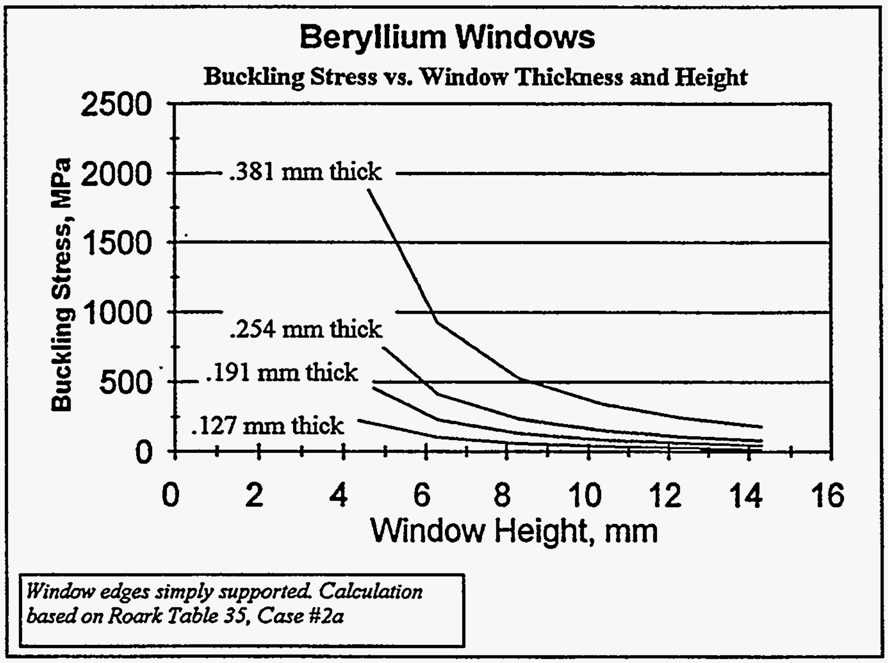

Figure 6: Critical buckling stress, beryllium windows with simply supported edges (free)

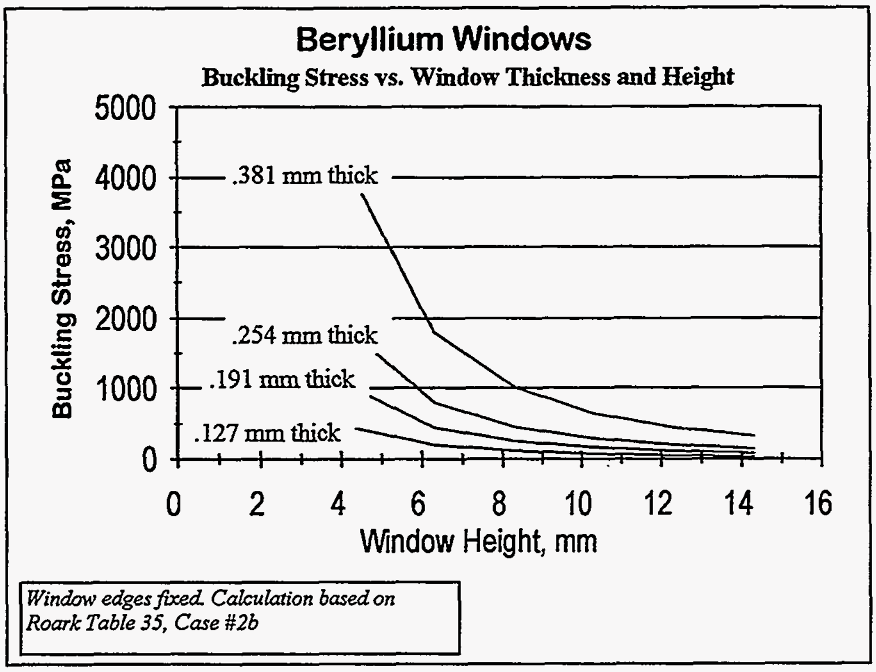

Figure 7: Critical buckling stress, beryllium windows with clamped edges (fixed)

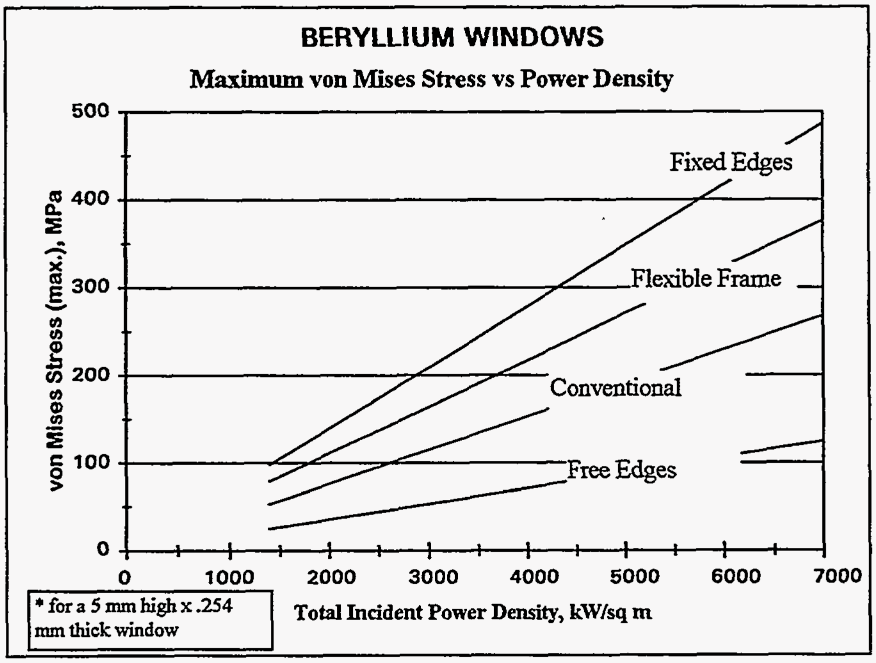

Figure 8: Maximum Stress vs incident power density, 5mm high windows

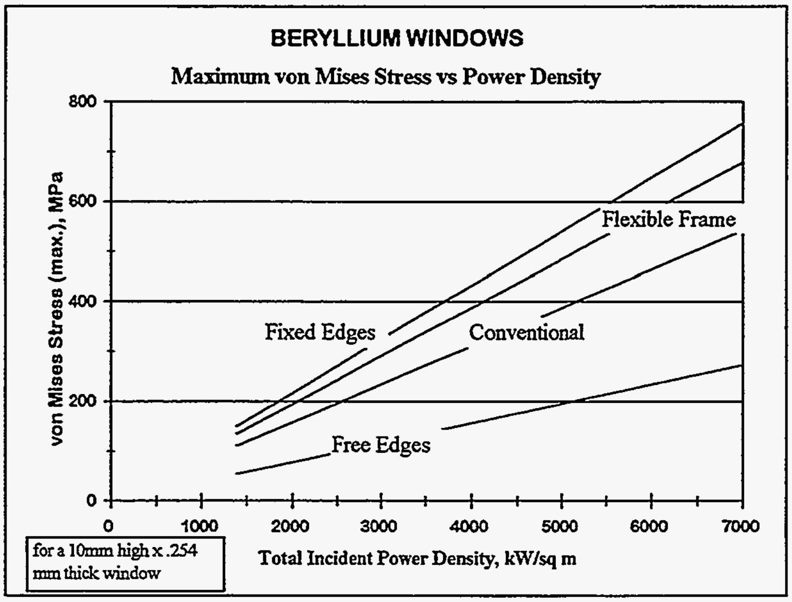

Figure 9: **Maximum Stress vs incident power density, 10 mm high windows**

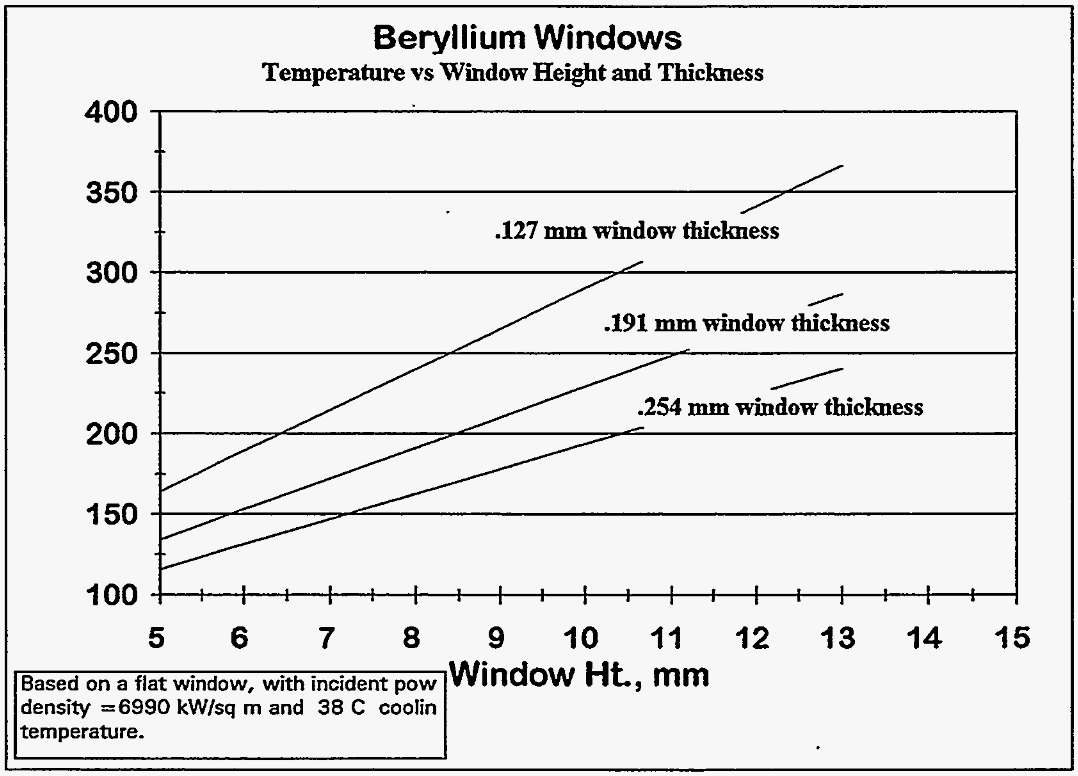

Figure 10: **Temperature vs. window thickness and window height**