

Y-12

Y/AMT-264

**OAK RIDGE
Y-12
PLANT**

MARTIN MARIETTA

**CRADA Final Report
for
CRADA Number Y-1293-0200**

**Development Of A Cooled Microwave
Window**

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COMPLETION REPORT
CRADA Y93-0200

With
ASTeX Applied Science and Technology, Inc.
For
Development of a Cooled Microwave Window

G. L. Bell, T. S. Bigelow, R. M. Leitch, L. A. Berry (MMES)
W. M. Holber (ASTeX)

INTRODUCTION

The objective of this Cooperative Research and Development project (CRADA) was to generate a new design for a microwave vacuum window to be used with ASTeX Corporation plasma processing equipment. This vacuum window allows transmission of microwave power from an input waveguide into a vacuum chamber for creation of plasma using the electron cyclotron resonance process. Requirements for the window design are: higher power capability, improved resistance to chemical attack, and physical compatibility with previous window models. In these applications, a significant portion of the input power is deposited in the window by plasma bombardment so the window must remove a great deal of heat to remain at a reliable operating temperature. A power level increase from 1.5 kW to 5 kW is desired by ASTeX for the new window which must have ~120 mm diameter and be compatible with existing hardware. New applications for these processing systems are being developed by ASTeX; these require the use of highly reactive fluorine plasmas which can rapidly etch some window materials. Therefore, the use of a fluorine compatible window ceramic is required.

This CRADA project between ASTeX and the Fusion Energy Division (ORNL - Y-12) was undertaken due to the participant's common interests in microwave generated plasma applications and their complementary experience and capabilities in high power microwave systems development. Design of a new window with capabilities significantly beyond the existing design requires good modeling tools, access to improved materials and new window cooling techniques. During the project, microwave engineering tasks and microwave tests were performed in the Microwave Development Laboratory at Martin Marietta Energy Systems, Inc. (MMES) Fusion Energy Division and high-power window data from existing window designs was obtained with actual plasma tests at ASTeX. The MMES Mechanical Engineering group performed thermal and stress modeling which proved quite valuable in checking power capability of new designs. Chemical compatibility was investigated through literature searches and consulting. ASTeX will generate a commercial design and perform tests with a fluorine plasma.

COMPLETION OF OBJECTIVES

The objectives of the CRADA were met in principle. Two possible window designs were investigated and both appeared to satisfy the requirements based on thermal-stress modeling and low-power laboratory tests. Thermal-stress modeling of both designs was performed; low-power microwave tests were made on a mock-up of the second design; manufacturing techniques for each design were investigated. High-power tests of a final window design were not performed due to difficulties in obtaining suitable window ceramic disks in the time available. However, the second window configuration investigated appears promising and requires ceramics readily available at this time with

slightly more difficult manufacturing techniques. Tests will be performed at a later date by ASTeX Corporation.

TECHNICAL SUMMARY

The microwave window is used to launch microwave power from a circular waveguide into a vacuum chamber having an applied magnetic field as shown in Figure 1. Plasma is generated by the microwaves from gas injected into the vacuum by exciting electrons with the electron cyclotron heating process. In the ASTeX system, a TM_{01} circular waveguide mode is generated and launched which generates a nearly uniform plasma in front of the window. The TM_{01} mode has a purely radial electric field with a field null on axis. The plasma and window combination introduce a large impedance mismatch and a significant reflected power level which is tuned out by an external matching circuit. The window must be transparent to the high microwave power level, withstand atmospheric pressure, and remove heat generated by plasma-flux incident on the window. Window disks are made from low dielectric loss-fused quartz or alumina ceramic in the present designs. Most of the heat flux on the window is removed by air cooling the pressure side with a jet of air from a small tube positioned on the axis of the circular waveguide where the electric field level is zero. Additional cooling is provided through the water-cooled window flange.

The greatest factor affecting the survivability of the window at high power levels is thermal stress caused by temperature gradients between the window center and the cooled areas where heat is removed. Excessive temperature in the window disk leads to thermal expansion, high stress, and eventually window failure. Existing window models using ceramic material work quite well at the 1.5 kW level but become unreliable at higher power. The new window design is intended to handle three times the heat load of previous designs. Two methods of approaching the design problem were taken: (1) using a more advanced ceramic with higher thermal conductivity with the existing window cooling scheme; (2) develop a significantly improved cooling technique with existing materials. In either case, the chemical compatibility issue between the window material and a fluorine plasma had to be addressed. The use of thin buffer layers bonded to the plasma side was proposed as an option if a high thermal-conductivity ceramic was selected which was not chemically resistant.

The first design investigated utilizes aluminum nitride (AlN) ceramic which has much higher thermal conductivity than alumina or quartz materials used in existing designs. The high thermal conductivity reduces the thermal gradients in the window. A design objective was to utilize existing hardware wherever possible so existing windows could be upgraded by simply replacing the ceramic with an improved type. Investigations indicated that AlN was chemically resistant to fluorine and would likely be able to be used directly exposed to the plasma. A detailed thermal model was setup using the P-THERMAL finite element code with appropriate material parameters and boundary conditions to simulate the window. The calculated 3-dimensional temperature data is input into the ABAQUS code to analyze stress levels in the ceramic to predict the power level at which failure will occur. It was determined that adding additional cooling around the window mounting flange and increasing the air flow rate by opening the flow passages was required to handle the higher power level. Modeling results shown in Figures 2 and 3 indicate that the AlN window with improved cooling was able to handle significantly higher power. For example, the maximum stress level in the AlN disk is 23,700 psi with 2.5 kW incident on the window (assuming half the 5 kW deposited in the plasma region is returned to the window). This stress level is well below the 41,000 psi flexural strength of AlN indicating reliable operation is likely at this power level.

Originally, a high power test of the window design generated was proposed as one of the project tasks. Unfortunately, it was not possible to obtain large disks of AlN ceramic with suitably low microwave loss in the time available for the project. Several AlN vendors were contacted who expressed interest in providing the disks. These vendors provided several small samples which had acceptably low microwave loss. However, none of these vendors have yet been able to sinter AlN in this large size with suitably low loss and impurity levels. Early on in the project it was believed that an AlN window would be built and tested at high power to prove the design. Due to significant delays in finding acceptable AlN (which resulted in two no-cost extensions of the project), this was not possible in the end. It is likely, due to the significant commercial interest in AlN driven by electronic packaging requirements, that a large, high-purity disk will become available in the near future which will make this window design a success. The Kyocera Corporation was able to supply AlN disks of appropriate size; however, the microwave loss factor was 2-3 times higher than desired.

A second approach to the high-power window design was devised which utilizes conventional alumina or sapphire window materials. The design uses advanced cooling techniques that are slightly more difficult to manufacture however the predicted performance results are quite encouraging. Thermal and stress modeling was performed on the new configuration using the same thermal stress code used for the AlN case. The results show the new design with an alumina disk to be easily capable of operating at 5 kW, even assuming that all of the input power is incident on the window. Alumina and sapphire are capable of operating at stresses up to 80,000 psi. The calculations show, for the case where the plasma facing surface of the window receives a total heat flux of 5 kW, that the maximum stress is about 53,000 psi. Low-power laboratory tests were performed using a simulated version of the new window design and a graphite foam to simulate the absorbing and reflecting plasma load. Measurements of the reflected power showed that this configuration introduces only a very small perturbation to the original configuration and the difference was easily accounted for by slight adjustment of one tuning screw in the matching network.

Asymmetries on the window surface can introduce conversion of power to other modes which could disrupt the symmetry and uniformity of the plasma produced. A set of low-power measurements of the power pattern launched by the TM₀₁ mode converter/window system was made using the standard window with a mock-up of the new configuration. The measurements revealed that the mode purity was quite high in both cases. The ultimate test of uniformity will require actual plasma operation.

Some aspects of the new window design make it slightly more difficult to manufacture. These details must be studied further to assess its potential for commercial success. It is also likely that the new window and cooling configuration could be patentable since the configuration does not appear to have been previously used and provides significantly greater window capability. At the present time, funds for pursuing a patent are not available.

CONCLUSION

Two new window designs were investigated using advanced window-modeling techniques and low-power laboratory testing. It was determined that both concepts were capable of operating at significantly higher power levels than present commercial windows and would meet the CRADA design objectives. The compatibility of the window materials considered with fluorine plasmas are believed to be acceptable. ASTeX has a continuing interest in

pursuing these window designs and will likely begin manufacturing design work of the improved design in the near future. There will also be a continuing effort to keep AlN ceramic manufacturers interested in improving the quality of large AlN disks. Additional window tests and development work could be performed by ORNL/MMES if a suitable funding source is available.

APPENDIX

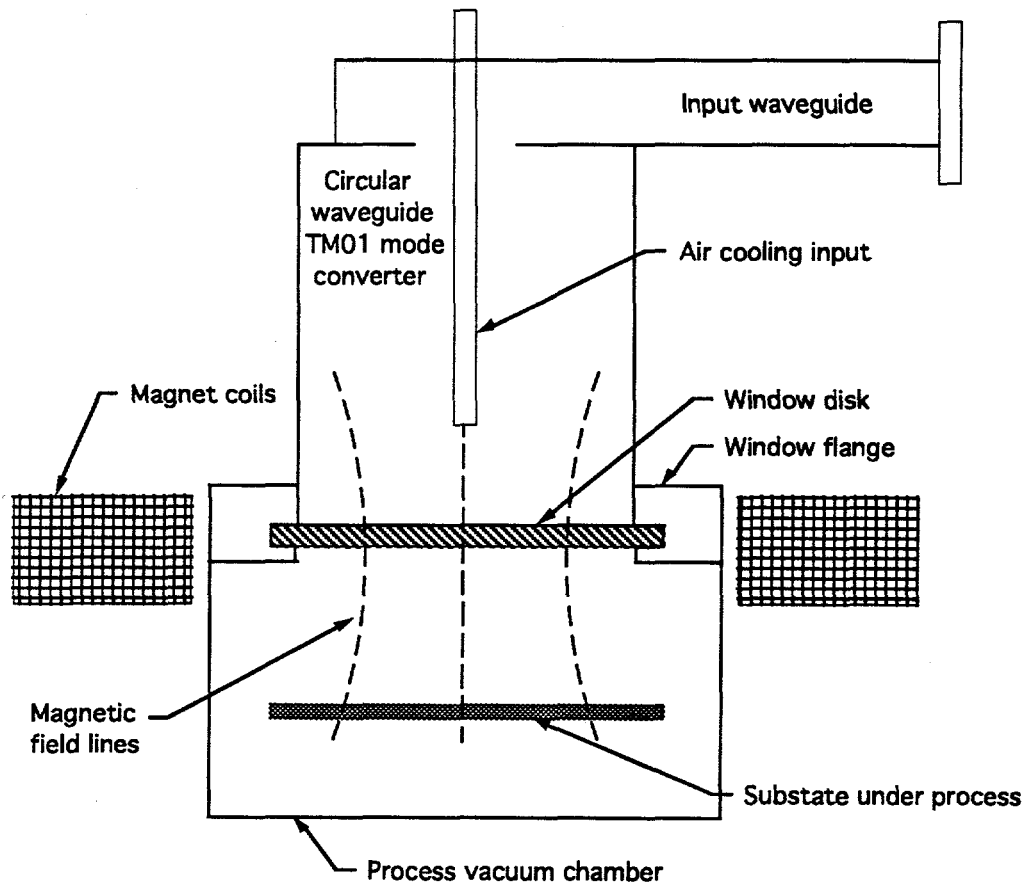
The scope of work adopted for this CRADA included four tasks:

Task 1 (6 weeks) Determine window specifications and operating environment. Identify plasma process system constraints, candidate materials and candidate designs. Microwave design of the window including material selection, matching, calculation of power deposition. ASTeX and ORNL will identify candidate materials and candidate designs. ORNL will perform microwave power deposition calculations.

Task 2 (8 weeks) Determine vacuum sealing technique. Thermal design, including temperature distribution and cooling analysis. Generate numerical models for mechanical and thermal stress analysis in the window ceramics. ORNL will generate the numerical models and perform the thermal and mechanical stress analyses. ASTeX and ORNL will determine the vacuum interface design, consistent with mechanical constraints.

Task 3 (2 weeks) Selection of materials and cooling techniques, and agreement on final design.

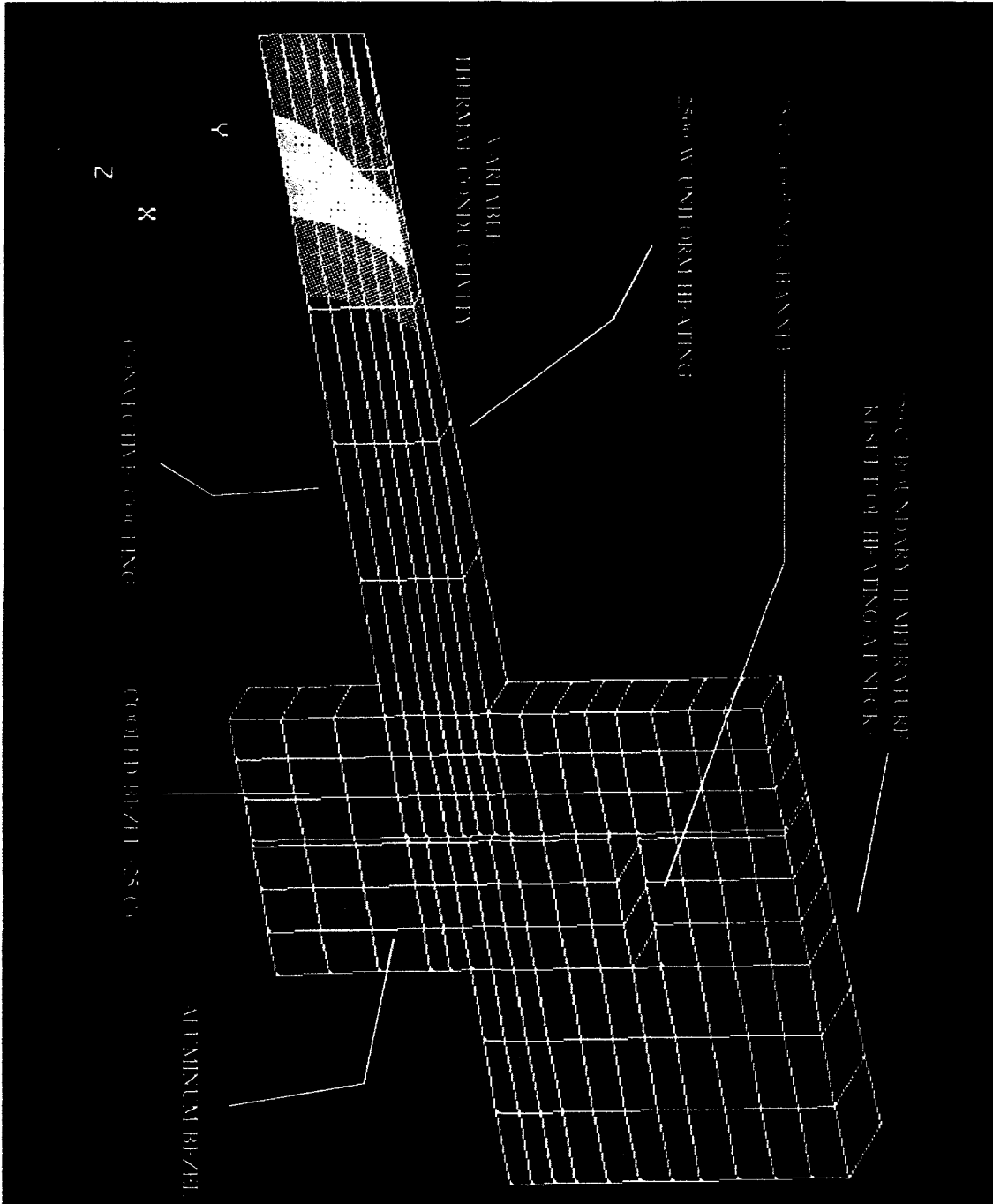
Task 4 (8 weeks) Build a test window and verify its performance. ASTeX will purchase and/or fabricate test components. Test facilities at ORNL and ASTeX will be used to test the product. ASTeX will demonstrate the performance of the product on an operational plasma processing system.



ASTeX ECR PLASMA PROCESSING CHAMBER

Figure 1. Configuration of the ASTeX ECR plasma reactor chamber

ALUMINUM BEZEL WINDOW



Time: 15:15:26
Date: 01/26/94

Contour
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Color Index

Degrees C



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Max= 0.3874E+03
Min ID= 86
Max ID= 43
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al_cool_beze1

Figure 2. Results of thermal modeling for the ALN window with 2.5 kW incident power

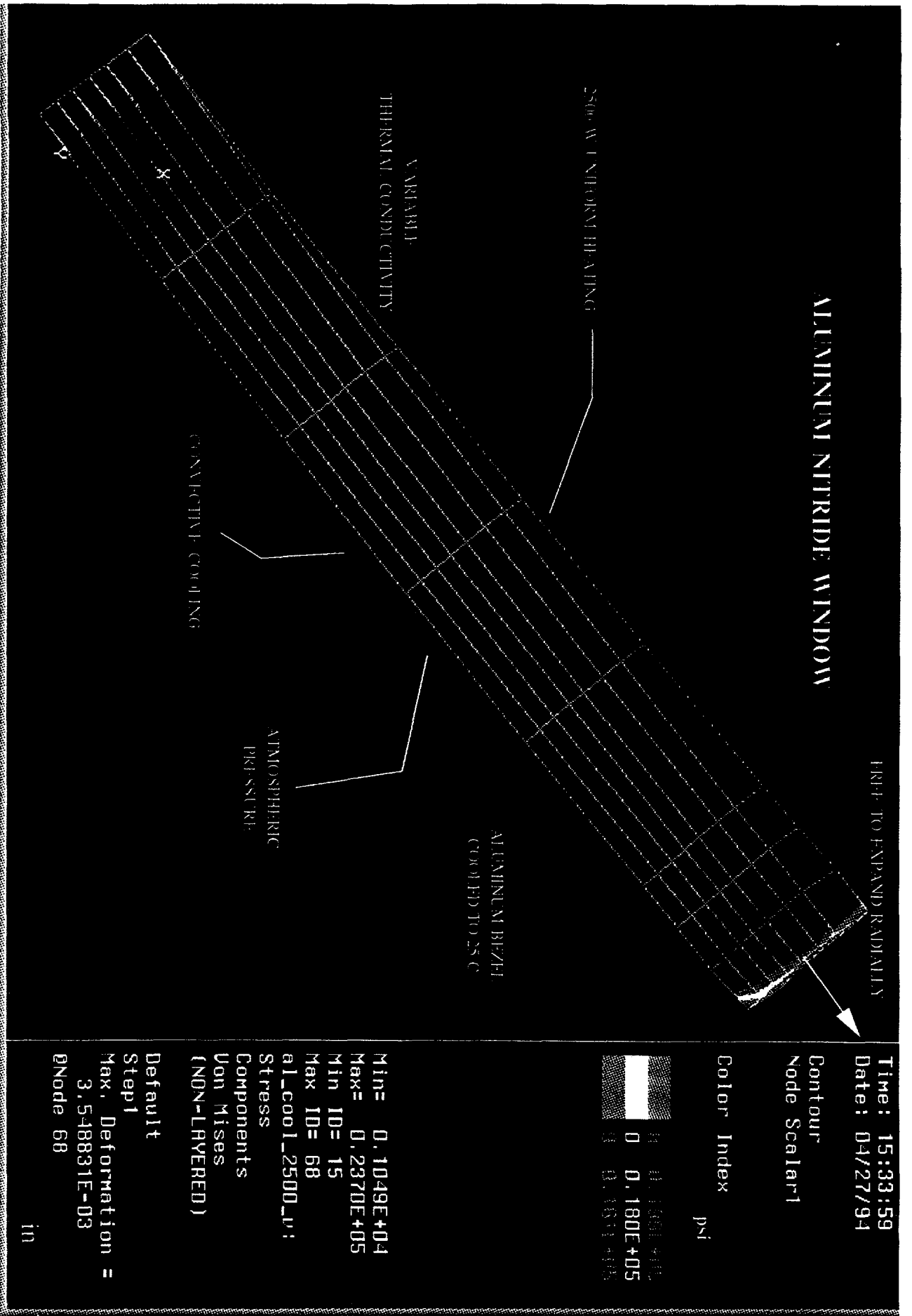


Figure 3. Results of stress modeling for the AlN window with 2.5 kW incident power

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