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Thermo-Mechanical Analysis of the White-Beam Slits for a Wiggler/Undulator Beamline at the Advanced Photon Source

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Abstract

A set of precision, vertical, white-beam slits has been designed for an undulator/wiggler beamline at the Advanced Photon Source (APS). The slit, a knife-edge-type precision device, is required to have very small thermal distortion during operation with beam. The traditional slit consists of a cooling block and an OFHC cooling channel inside the block.

Our design consists of one large block and an OFHC cooling tube (filled with copper mesh) brazed inside the large block. This design will accommodate the x-ray source from both undulators and wigglers. Due to the powerful x-ray heat flux coming from APS Undulator A, it is an exceedingly difficult problem to reduce the thermal distortion to less than 50 microns as required by some users.

1 Introduction

A set of precision, vertical, white-beam slits has been designed [1] for an undulator/wiggler beamline at the Advanced Photon Source (APS). The design consists of one large block and an OFHC cooling tube (filled with copper mesh) [2] brazed inside the large block. This design will accomdate the x-ray source from both undulators and wigglers.

Dealing with the heat flux from Undulator A [3] is a major engineering challenge. At normal incidence, the peak power is about $175\frac{W}{mm^2}$ at 27.5 m, with a total power of 3.8 kW. The Gaussian deviation is about 1.22 mm, and the parabolic deviation is about 3.8 mm. The footprint of the x-ray beam is very small, which induces a very high thermal stress. Due to such an powerful x-ray heat flux coming from APS Undulator A, it is an exceedingly difficult problem to reduce the thermal distortion to less than 50 microns as required by some users. A FORTRAN code allows the element (in the ANSYS finite element code used) subjected to the x-ray beam to get the power distribution automatically at its coordinate position.

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Enhanced heat transfer technology [2] was used to increase the convective heat transfer coefficient with water from 1 $\frac{W}{cm^2 \cdot {}^\circ C}$ to about 3 $\frac{W}{cm^2 \cdot {}^\circ C}$ for the OFHC tube. However, we assumed a convective heat transfer coefficient of 2$\frac{W}{cm^2 \cdot {}^\circ C}$ in conservative calculations.

2 Material Considerations

It is very important that the slit body be made of a material having a very low thermal expansion coefficient and a high thermal conductivity. Both TZM (vacuum arc-cast molybdenum-0.5% titanium-0.1% zirconium alloy) and tungsten alloy (HD18) [4] were considered for the block material. OFHC is the material for the cooling tube. During operation, both the HD18 and TZM will reach temperature levels of about 400°C. Therefore, the material properties at such elevated temperatures were considered in the analysis. Table 1 shows the properties of the materials considered for the slit.

Table 1. Properties of the Materials Considered for the Slit

			Room Temperature (°C)			400°C	
Properties			TZM	HD18	OFHC	TZM	HD18
Conductivity	K	$\frac{W}{cm\ {}^\circ K}$	1.45	1.65	3.95	1.3	1.35
Young's Modulus	E	MPa	3.15×10^5	3.65×10^5	1.19×10^5	3.0×10^5	3.1×10^5
Thermal Exp. Coef.	α	$\frac{1}{{}^\circ C}$	5.4×10^{-6}	4.5×10^{-6}	17.7×10^{-6}	5.6×10^{-6}	4.6×10^{-6}
Poisson Ratio	ν		0.293	0.28	0.307	.361	.28
Yield Strength	σ_y		1000	580	300	800	380
Ultimate Strength	σ_u	MPa	1000+	1500+	350	1000+	1500+

3 Conceptual Design of the Vertical Cooling Block

The vertical cooling block is made of HD18 and is placed 27.5 m from the x-ray beam source, and the size is about 560 × 33 × 45 mm (x, y, and z coordinates, respectively). It intercepts the x-ray beam in such a way that the horizontal direction of the beam will stretch out in the x-axis. Figure 1 depicts the geometry and the modeling of the original design used in this analysis. One pair of the cooling blocks will be built.

The critical surface shown in Fig. 1 is $\Diamond ABCD$ which causes a clear cut of the x-ray beam in the horizontal plane. The displacement of the knife edge ($\overline{AD}$) along the z axis, U_z, is the only displacement that is important at this surface.

If the location of the x-ray beam center is a function of z, the worst possible case for the thermal distortion and stress occurs when z is 3 mm from the knife edge ($\overline{AD}$) in the negative z direction (as shown in Fig. 1). The maximum calculated temperature is about $589°C$ in such a case.

When a set of vertical slits is moving around the vacuum chamber, one of the cooling blocks must have a recess from $\angle EJG$ to $\angle FKH$ (as shown in Fig. 2) to allow the other block (without the recess) to move around the space from $\angle EJG$ to $\angle FKH$. Due to the large recess from $\angle EJG$ to $\angle FKH$ (shown in Fig 1), the x-ray beam hitting on $\Diamond ABCD$ is a problem of "wedge heating" in heat transfer. A cooling block without the recess will perform much better under the same boundary conditions.

The design has been reviewed to see if it is possible to reduce the recessed volume (from $\angle EJG$ to $\angle FKH$ in Fig. 1). A new cooling block was then developed with less recess volume (as shown in Fig. 2). With such a reduction in recess volume, the distance between the cooling tube and the knife edge $\overline{AD}$ could be reduced to about 14 mm. Figure 2 shows the calculated temperature contour of this design. The maximum surface temperature was reduced to $400°C$. This design shows huge progress in the temperature field. The maximum effective stress is about 400 MPa. The maximum distortion will occur when the x-ray beam center is located at the center of the cooling block in the longitudinal direction (x-axis), which is about 76 microns.

The footprint of Undulator A (k=2.3) is much less than that of Wiggler A (k=7.94) in the horizontal direction. Because the slit design [1] has to accommodate the footprint from both sources, the length of the cooling block is extremely long for the footprint for the undulator x-ray beam; only about one fifth of the total length (690 mm) is needed. It is a good idea to eliminate the recess for one fifth of the total length, which can be used for the undulator beamline. In this case, not only is the "recess effect" reduced, but also the undulator beam center is away from the center of large block in the longitudinal direction (x-axis). Because the heat flux from the wiggler results in less temperature gradient and thermal stress for the cooling block, the recess area is not as big a problem. The total power of the wiggler is larger than that of the undulator, so the thermal distortion of the large block is larger for the wiggler.

The final design [1] was developed along these lines. The size of the final design is about 690× 31.75 × 63.5 mm (x, y, and z coordinates, respectively) as shown in Fig. 3. By using surface $\diamond ABZY$ for the undulator beamline, the "recess effect" is eliminated. Besides, the center of the x-ray beam is away from the center in the longitudinal direction (x-axis), which induces less thermal distortion U_z than that induced by the x-ray beam at the center. The final design also allows the cooling block to expand freely in the longitudinal direction (x-axis), which reduces the stress component σ_x of the large block and ceramic plate. Ideally, the ceramic plate is stress free, except at the area around the pin-hole, which has very localized stress due to constraints in the y-axis and the z-axis.

Table 2. Calculated Results from ANSYS Finite Element Code for the Vertical Cooling Block

	Final Design				Original Design		
h($\frac{W}{cm^2\ ^\circ C}$)	1	1.5	2	3	1	2	3
Max. Temperature on $\diamond ADEF$ (°C)	414	391	376	361	621	589	576
Max. Effective Stress on $\diamond ADEF$ (MPa)	351	365	372	380	500	495	495
Max. Temperature at Interface (°C)	152	126	112	96	134	99	84
Max. Effective Stress at Interface (MPa)	261	200	160	112	200	122	91
Max. Displacement U_z at Knife Edge (micron)	66	56	50	46	130	123	120

The calculated displacement component U_z was further reduced to 50 microns (from 56 microns in the intermediate design). The displacement component U_z contour is shown in Fig. 4. The temperature contour is shown in Fig. 5. The calculated results for the final design subjected to the heat flux from Undulator A are shown in Table 2.

The calculations show that increasing the h (the convective heat transfer coefficient) from 1 $\frac{W}{cm^2 \cdot {}^\circ C}$ to 2 $\frac{W}{cm^2 \cdot {}^\circ C}$ for the final design will:

1. Reduce the maximum thermal distortion from 66 microns to 50 microns.
2. Reduce the maximum effective stress at the interface from 261 MPa to 160 MPa, which insures that the OFHC cooling tube remains in elastic deformation during application.

3. Reduce the maximum interface temperature from 152°C to about 112°C.

4. Reduce the maximum temperature of tungsten from 414°C to about 376°C, which will help to keep the HD18 from annealing.

The component that benefits the most by this enhancement [2] is the OFHC cooling tube, which will cool better resulting in much lower temperatures and longer life and reliability.

When the center of the x-ray beam moves toward $\overline{BZC}$ as shown in Fig. 3, the maximum temperature at surface $\diamond ABZY$ decreases, while the maximum temperature and stress at the interface (between the HD18 large block and the OFHC cooling tube) remain about the same. The maximum temperature difference between the heating surface $\diamond ABZY$ and the cooling tube was reduced because the distance between them was reduced. The stress at the interface is not a concern, even for the case in which the x-ray beam center is located at 15 mm (in the negative z-axis) from the knife edge ($\overline{AYD}$ in Fig. 3). In this case, the maximum temperature at $\diamond ABZY$ is about 250°C; the maximum temperature at the interface is about 125°C; the maximum effective stress at the interface is about 210 MPa.

4 Conceptual Design of the Horizontal Cooling Block

The horizontal cooling block will intercept the x-ray beam in such a way that the vertical direction of the x-ray beam stretches out in the x direction as shown in Fig. 6. The size of the design is about 190 × 75 × 18 mm (x, y, and z coordinates, respectively). The original design consists of a face plate made of OFHC bonded to a 3-mm-thick HD18 face plate, which results in very high shear stress at the interface. The material for the base plate was then changed to TZM and bonded to a 3-mm-thick HD18 face plate. The critical surfaces (for the undulator beamline) shown in Fig. 6 are :

1. $\diamond ABCD$ (part of $\diamond ABMN$ to be used on the wiggler beamline), which causes a clear cut of the x-ray beam in the vertical plane. The displacement of knife edge ($\overline{AD}$) along the y-axis U_y is the only important displacement at this surface.

If the location of the x-ray beam center is a function of y and x, the worst possible case for the thermal distortion and stress occurs when y is 4.5 mm from the knife edge ($\overline{AD}$) in the negative y direction (as shown in Fig. 6), and x is 20 mm from $\overline{AB}$ in the positive x direction (as shown in Fig. 6).

Table 3 lists the calculated results from ANSYS finite element code. The calculated maximum surface temperature of the face plate is about 464°C as shown in Fig. 7. A face plate made of HD18 will anneal somewhat in areas with a temperature 400°C or higher. The calculated maximum effective stress for the face plate is about 300 MPa. The HD18 will remain in elastic deformation because the yield strength is about 350 MPa at 450°C. The maximum calculated effective stress of the OFHC tube is about 255 MPa. The calculated maximum temperature of the tube is less than 175°C; in other word, the OFHC will not anneal and will retain its high yield strength (300 MPa).

Table 3. Calculated Results from ANSYS Finite Element Code for the Horizontal Cooling Block

	Final Design'				Original Design		
h($\frac{W}{cm^2\,°C}$)	1	1.5	2	3	1	2	3
Max. Temperature on $\diamond ADEF$ (°C)	526	486	464	438	390	350	333
Max. Effective Stress on $\diamond ADEF$ (MPa)	294	297	300	307	200	200	200
Max. Temperature on Base Plate (°C)	435	396	375	348	264	223	206
Max. Temperatufe on Tube (°C)	234	192	165	139	200	150	130
Max. Eff. Stress on Base Plate (MPa)	250	236	234	232	800	600	470
Max. Effective Stress on Base Plate (MPa)	400	290	255	190	150	120	100
Max. Displacement U_y at Knife Edge (micron)	47	39	33	28	151	123	99

The calculations show that increasing h (the convective heat transfer coefficient) from 1 $\frac{W}{cm^2 \cdot °C}$ to 2 $\frac{W}{cm^2 \cdot °C}$ for the final design will:

1. Reduce the maximum thermal distortion from 47 microns to 33 microns.

2. Reduce the maximum effective stress at the interface (between the TZM base plate and the OFHC cooling tube) from 400 MPa to 255 MPa, which insures that the OFHC cooling tube remains in elastic deformation during application.

3. Reduce the maximum temperature of the OFHC cooling tube from 234°C to about 165°C, which will help to keep the OFHC from annealing.

4. Reduce the maximum temperature of tungsten from 526°C to about 464°C.

5 Slit Performance

The above discussion considers the worst possible conditions for both the vertical and horizontal cooling blocks. The maximum thermal distortion, maximum surface temperature, and maximum thermal stress of the cooling blocks under regular application will be discussed below.

5.1 Vertical Slit

In most applications, for each vertical cooling block, the worst case is intercepting 50% of the total power (3.8 kW) from Undulator A. In this case, the x-ray beam center will be located at the knife edge of the cooling block (in Fig. 3).

The following boundary conditions are used for the vertical slit performance studies:

1. The x-ray beam center is located at a fixed x-coordinate, which is at the center of $\overline{AY}$ (in Fig. 3).
2. The location of the x-ray beam center is a function of the z-coordinate only.

Figure 8 shows the displacement component U_z vs the knife-edge location (on the z-axis) related to the x-ray beam center. For example, if the knife edge of the cooling block is 2 mm from the x-ray beam center in the z direction (in Fig. 3), the displacement component U_z is about 4 microns. If the knife edge of the cooling block is 1 mm from the x-ray beam center in the z direction (in Fig. 3), the displacement component U_z is about 10 microns. If the knife edge of the cooling block is at the x-ray beam center in the z direction (in Fig. 3), the displacement component U_z is about 24 microns.

When the knife edge of the cooling block moves from 4 mm to the x-ray beam center, the slot of the displacement component U_z changes rapidly at 1.25 mm (in Fig. 8). This can be explained as follows. When the cooling block moves from the location of Gaussian (vertical) deviation, which is 1.22 mm at 27.5 m, toward the center of x-ray beam, the absorbed power increases rapidly.

Figure 9 shows the maximum surface temperature of the cooling block vs the knife-edge location related to the x-ray beam center. Figure 10 shows the maximum effective stress of the cooling block vs the knife-edge location related to the x-ray beam center. The maximum surface temperature of the cooling block will stay below 300°C, and the maximum effective stress will stay below 350 MPa under most of the slit applications. If all the missteered x-ray beam can be blocked by the fixed mask [5], the vertical cooling blocks have a safety factor of 2.5 (see Table 1).

5.2 Horizontal Slit

In most cases, the worst condition for each horizontal slit occurs when each absorbs 50% of the total power (3.8 kW) from the undulator source. In this case, the x-ray beam center will be located at the knife edge of the cooling block (in Fig. 6).

The following boundary conditions are used for the horizontal slit performance studies.

1. The x-ray beam center is located at a fixed x-coordinate, 30 mm from $\overline{AM}$ (in Fig. 6), which represents the worst case if one is taking the x-coordinate as a variable.
2. The location of the x-ray beam center is a function of the y-coordinate only.

Figure 11 shows the displacement component U_y vs the knife-edge location related to the x-ray beam center. For example, if the knife edge $\overline{AD}$ of the cooling block is 2 mm from the x-ray beam center in the y direction (in Fig. 6), the displacement component U_y is about 8 microns. If the knife edge of the cooling block is 1 mm from the x-ray beam center in the y direction (in Fig. 6), the displacement component U_y is about 12.5 microns. If the knife edge of cooling block is at the x-ray beam center in the y direction (in Fig. 6), the displacement component U_y is about 17 microns. The maximum surface temperature of the cooling block will stay below 370°C, and the maximum effective stress will stay below 300 MPa under most of the slit applications.

6 Acknowledgments

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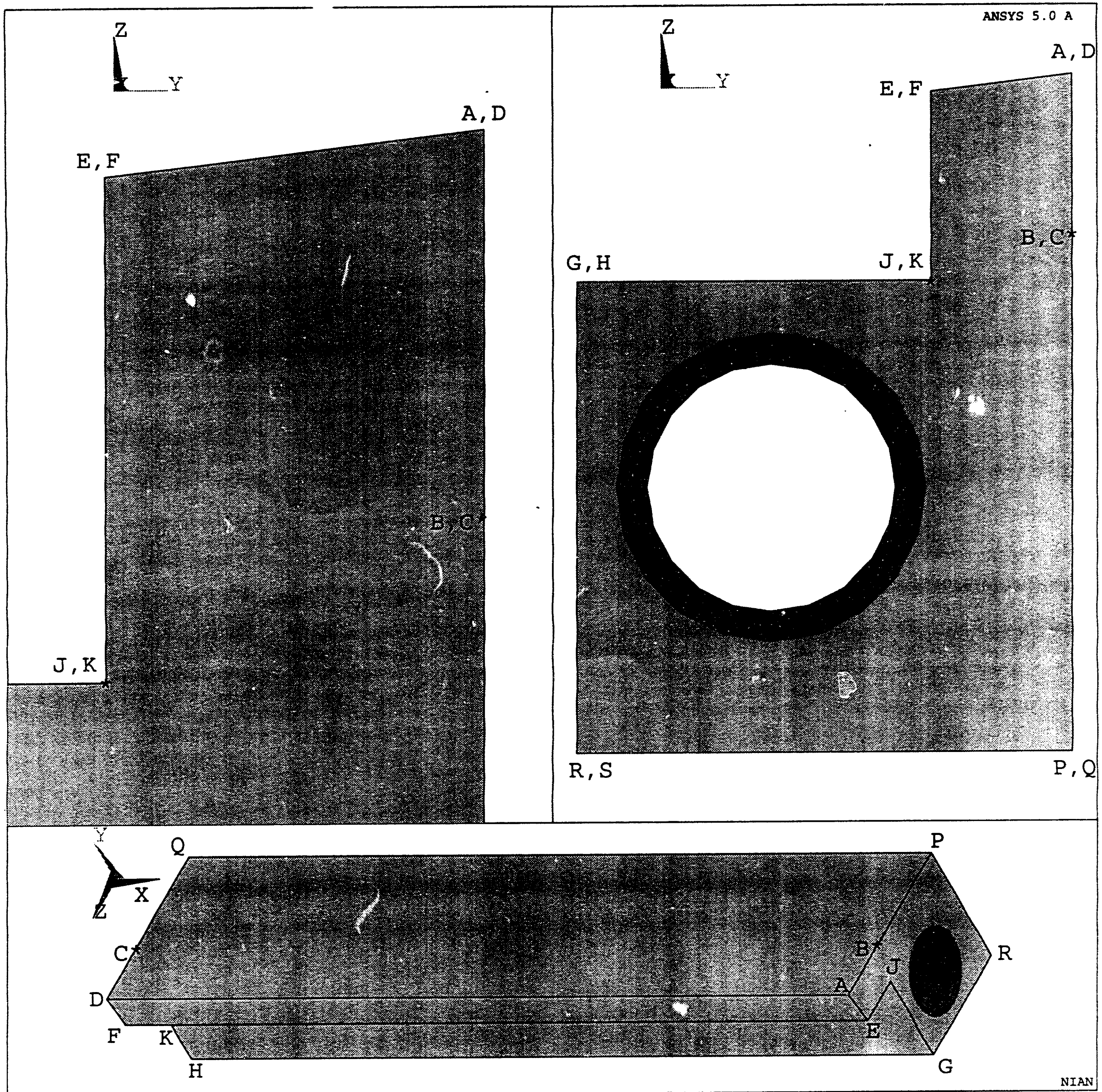
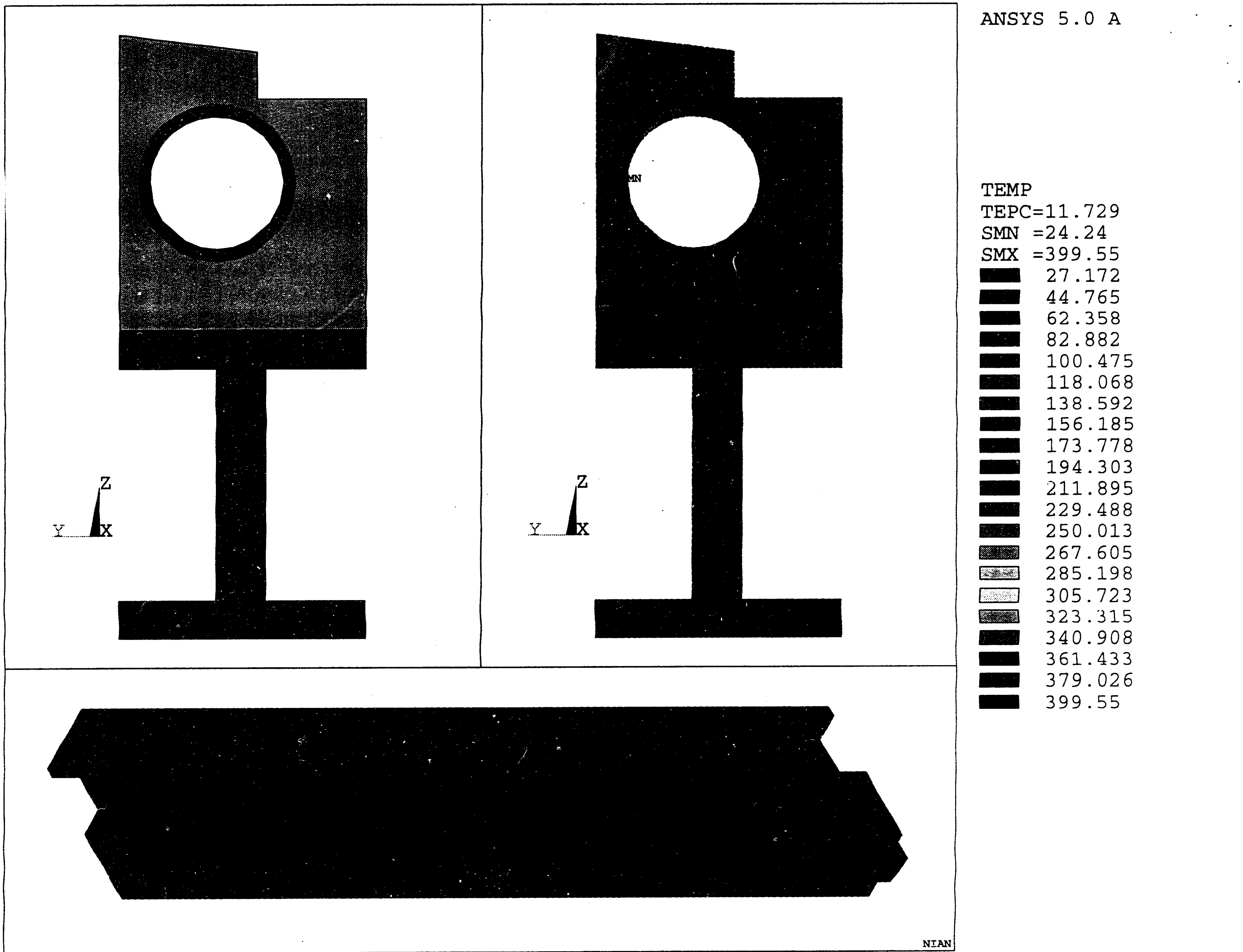


Figure 1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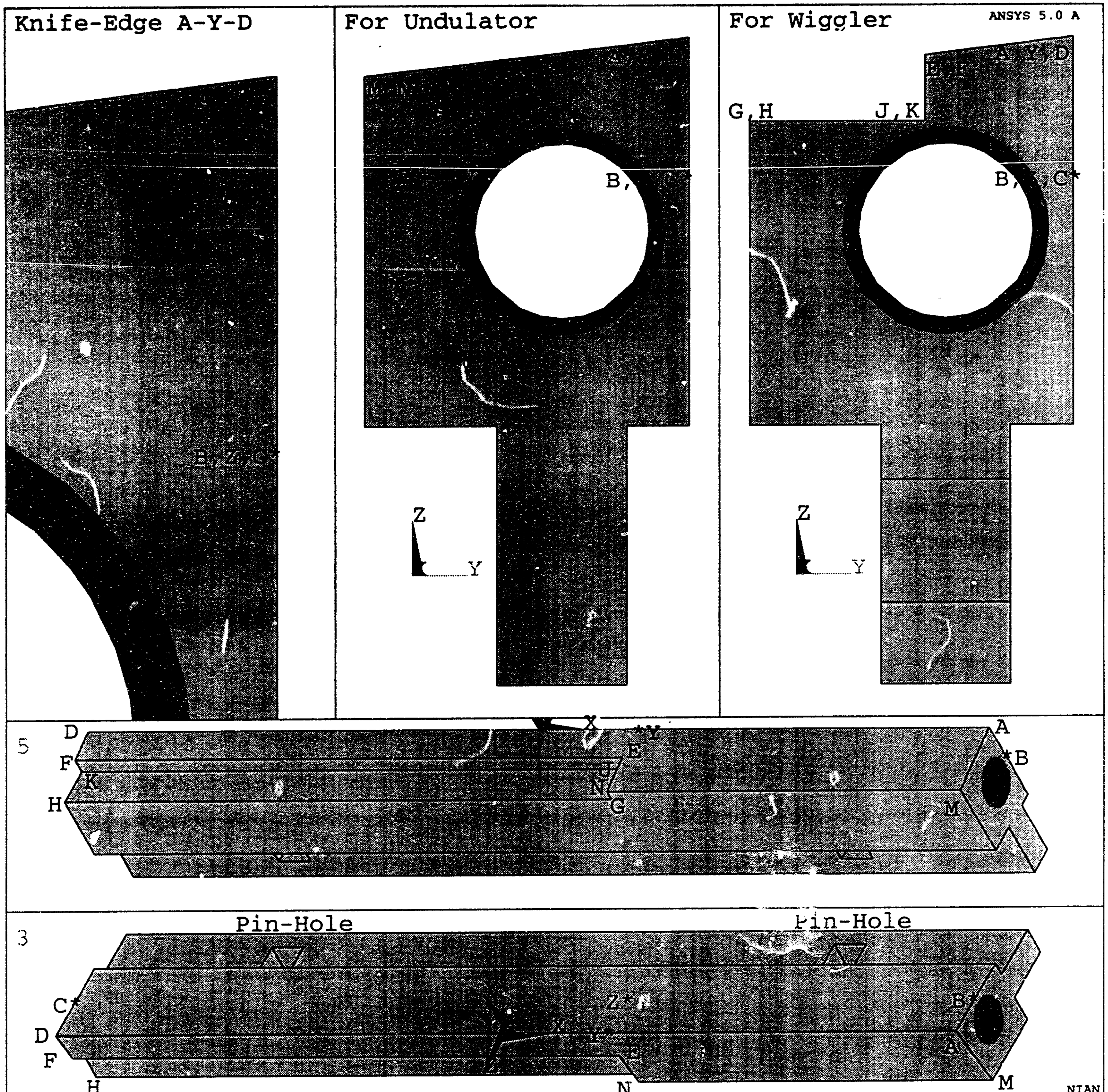
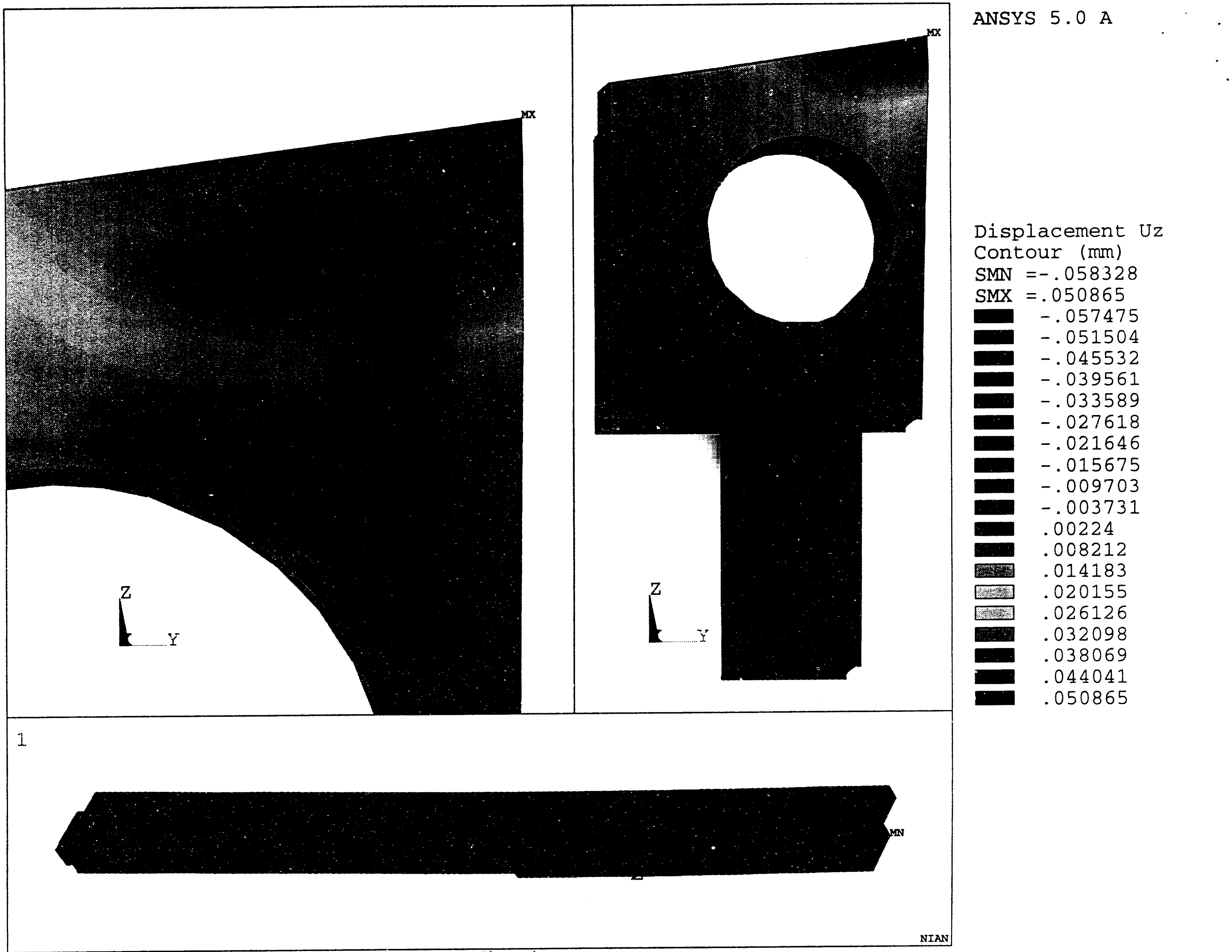
MN
Z
Y
X
NIAN

Figure 2



Knife-Edge A-Y-D
For Undulator
For Wiggler
ANSYS 5.0 A
G,H
J,K
B,
Z
Y
Pin-Hole
Pin-Hole
NIAN

Figure 3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MX
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SMX =.050865
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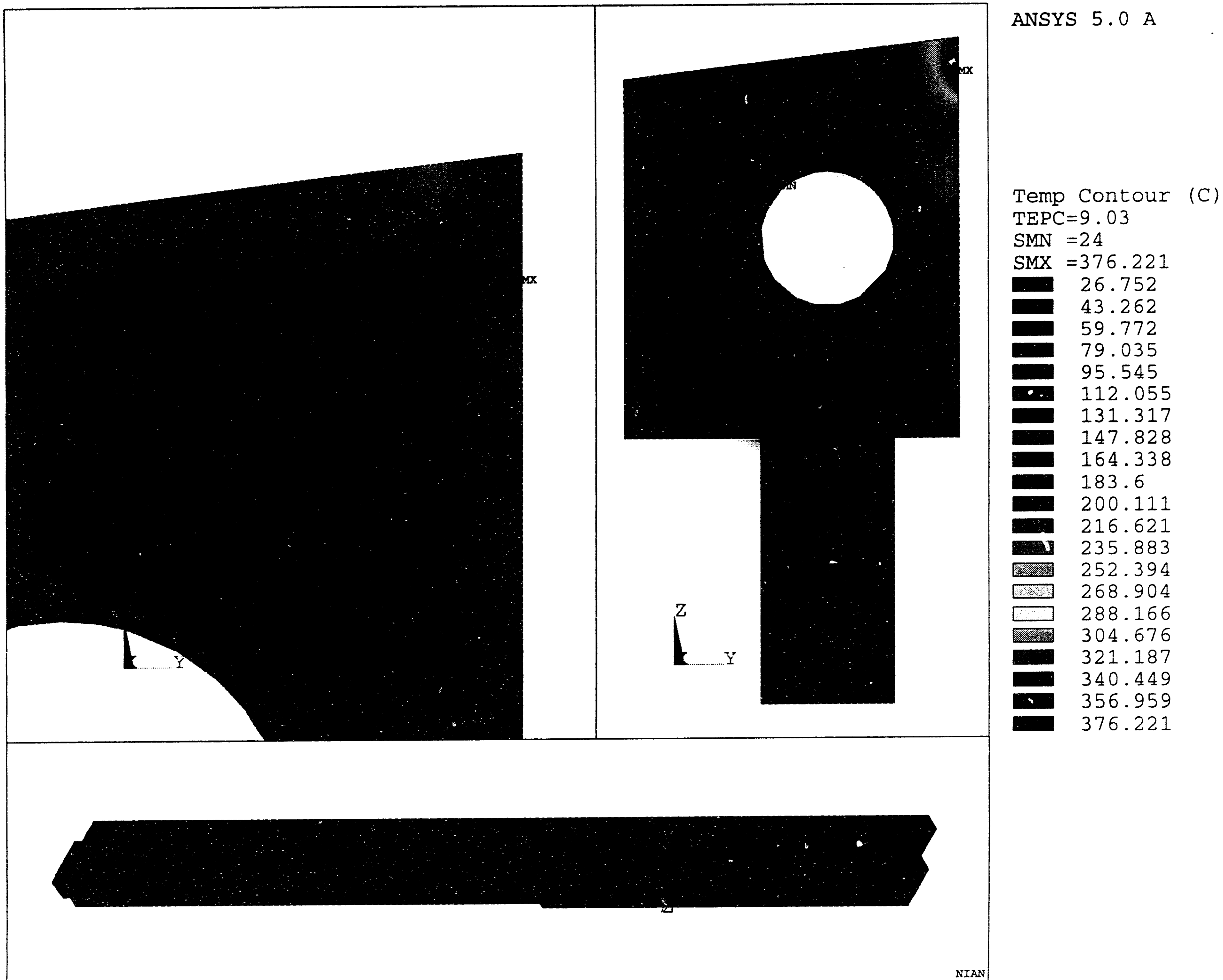
Z
Y
Z
Y
1
MN
NIAN

Figure 4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MX
Z
Y
NIAN

Figure 5

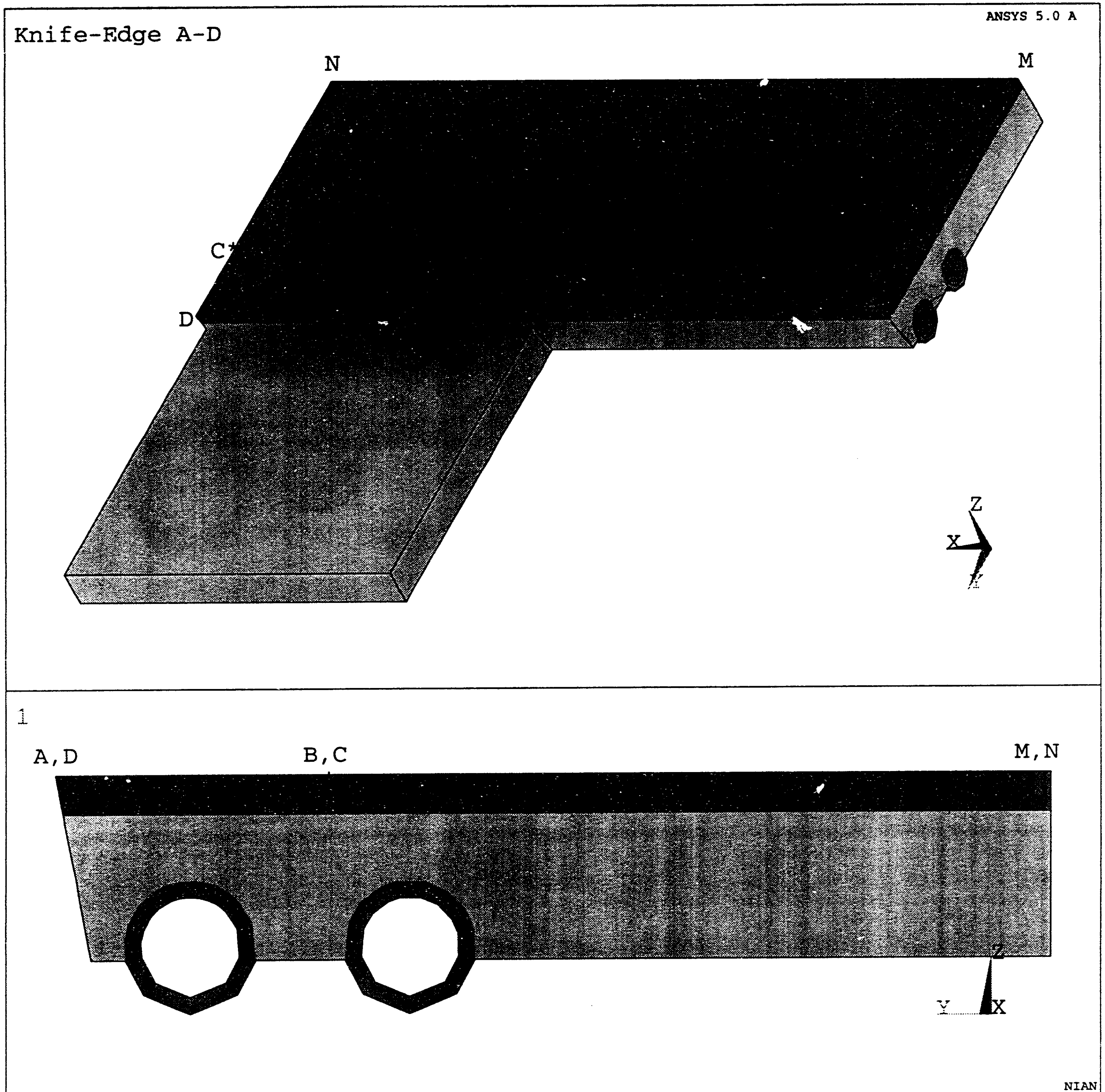
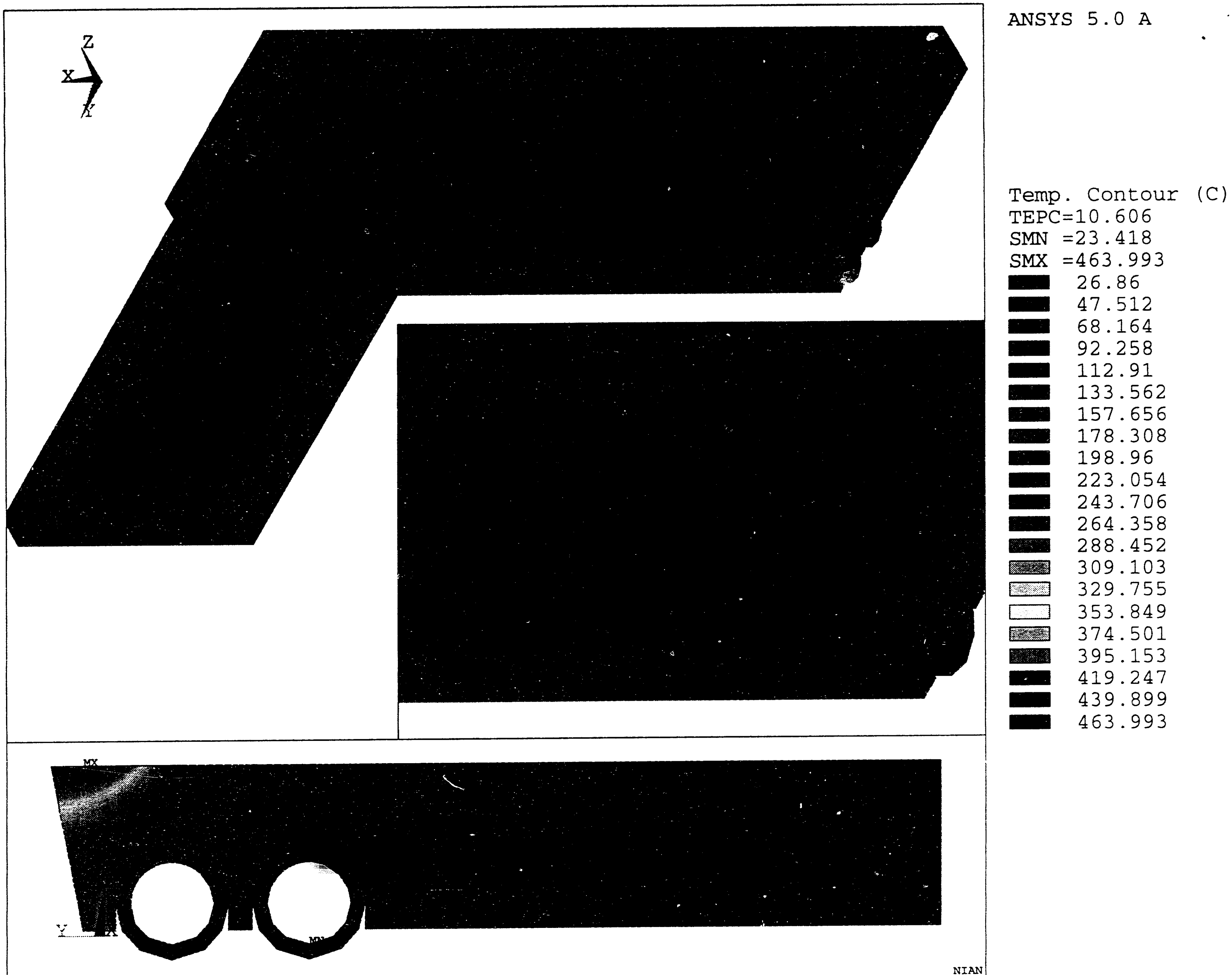


Figure 6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288.452
309.103
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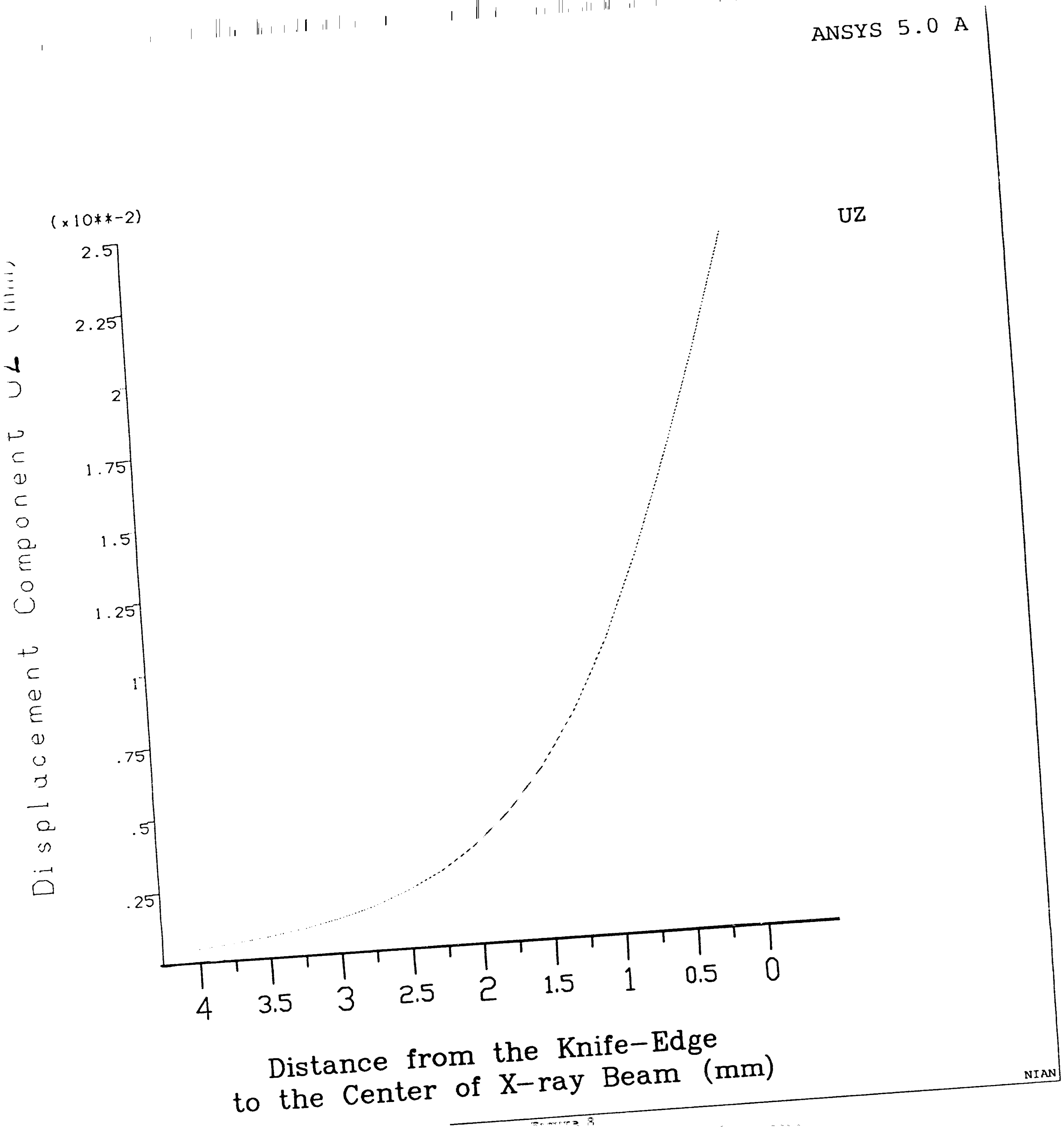
Z
X
Y
MX
MN
NIAN

Figure 7


ANSYS 5.0 A
UZ
(x10**-2)
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2.25
2
1.75
1.5
1.25
1
.75
.5
.25
Displacement Component UZ (mm)
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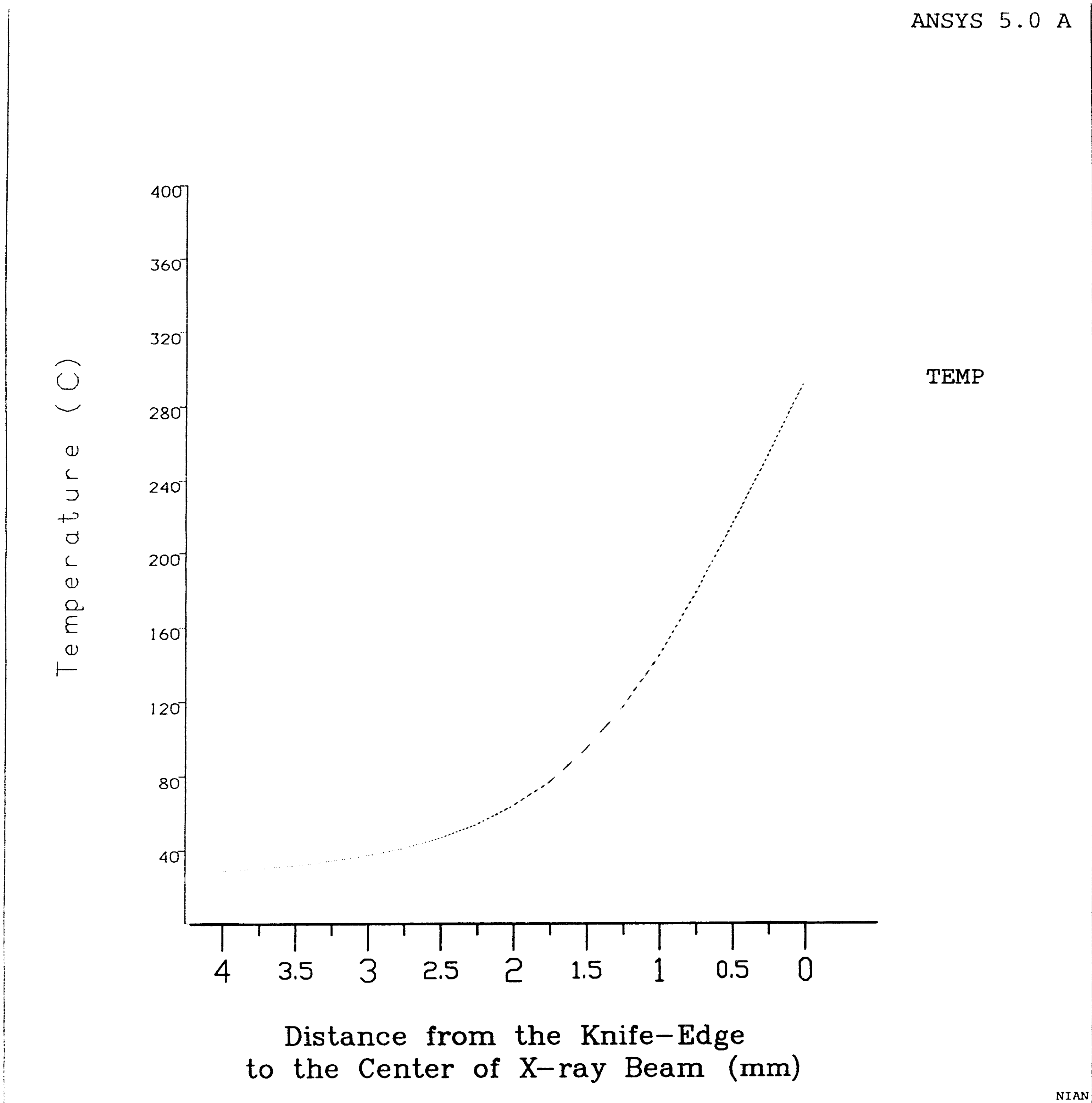
3
2.5
2
1.5
1
0.5
0
Distance from the Knife-Edge
to the Center of X-ray Beam (mm)
NIAN



ANSYS 5.0 A
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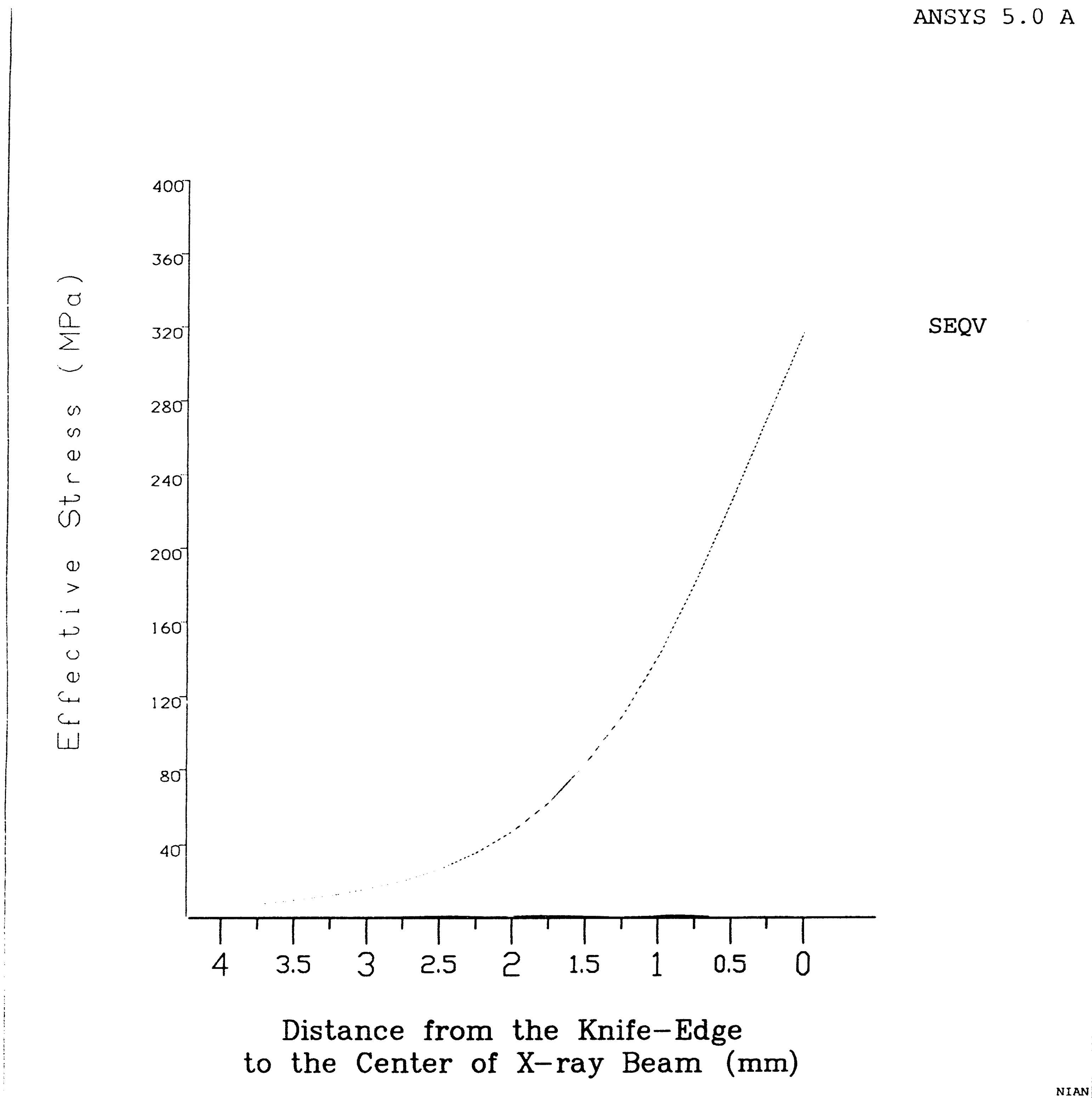
360
320
280
240
200
160
120
80
40
Temperature (C)
TEMP
4
3.5
3
2.5
2
1.5
1
0.5
0
Distance from the Knife-Edge
to the Center of X-ray Beam (mm)
NIAN

Figure 9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200
160
120
80
40
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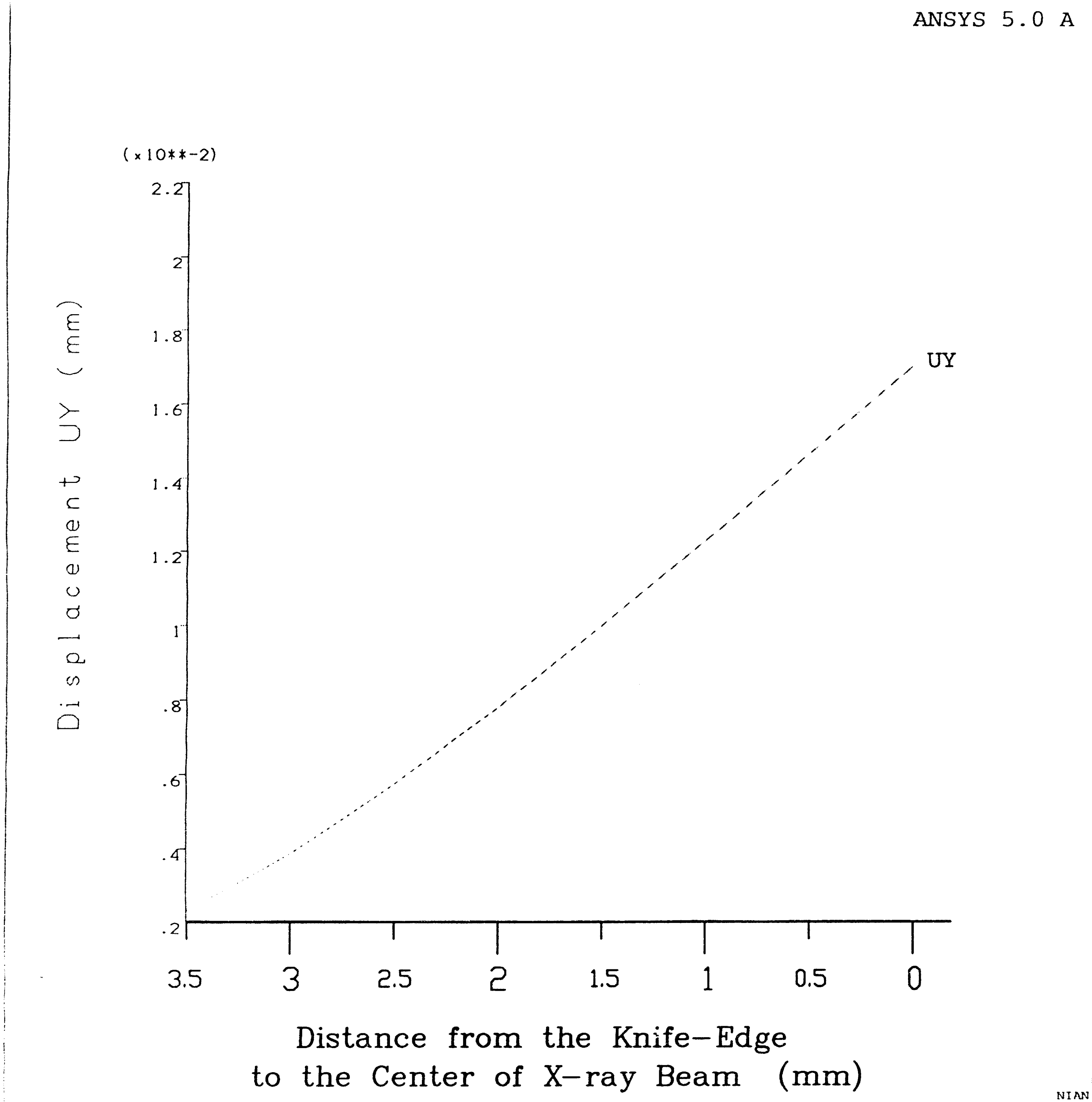
3.5
3
2.5
2
1.5
1
0.5
0
Distance from the Knife-Edge
to the Center of X-ray Beam (mm)
NIAN

Figure 10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1.2
1
.8
.6
.4
.2
Displacement UY (mm)
UY
3.5
3
2.5
2
1.5
1
0.5
0
Distance from the Knife-Edge
to the Center of X-ray Beam (mm)
NIAN

Figure 11

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