PS/AA/ACOL Note - 13 15th August 1984
AP/mp

ACOL Pulsed target

Some Calculations with the DOT[1]) Heat Transfer Program.

A. Poncet

1) Introduction:

DOT solves the planar bidimensional or axisymetric non linear heat transfer equation

$$\nabla^2 T + \frac{Q}{K} = \frac{1}{d}\,\frac{\partial T}{\partial t}$$

(with K thermal conductivity, d thermal diffusivity $= \frac{K}{\rho c}$)

through an isoparametric finite element formulation. Transient heat propagation with time dependent boundary conditions can be treated, in the non linear case where material constants vary with temperature.

This note describes the results of a first attempt to solve for the onedimensional axisymetric case the following problem:

> Current and field radial propagation inside the target, with and without beam energy deposition, with temperature dependent material properties such as electrical and thermal conductivities and heat capacity.
> Quasi static thermal and magnetic induced stresses are calculated as a by product.

1) DOT: Determination of temperatures - R. Polivska and E. Wilson
Berkeley 1976

2) Method:

To resolve the above problem, one has to solve simultaneously two coupled second order non linear differential equations, one for the field or current distribution, the other one for heat propagation.

The Field $\vec{H}$ inside the target is solution of the equation (no displacement currents)[3]:

$$(1) \qquad \vec{\nabla}^2 \vec{H} - \sigma \mu \frac{\partial \vec{H}}{\partial t} = 0$$

with the proper classical boundary conditions:

$$H(r,o) = 0$$
$$H(o,t) = 0$$
$$H(r_0,t) = \begin{cases} \dfrac{I_0 \sin \omega t}{2\pi r_0} & 0 < t < \dfrac{\pi}{\omega} \quad \text{(from Ampère's Law)} \\ 0 & \text{for} \quad t > \dfrac{\pi}{\omega} \end{cases}$$

for a half current sine wave of height I_0 and length $\frac{\pi}{\omega}$, r_0 being the outer radius of the target.

σ, the electric conductivity is related to the temperature T by

$$\sigma = \frac{\sigma\emptyset}{1 + \alpha T}$$

α being the target material temperature coefficient.

The temperature T is solution of the heat diffusion equation

$$(2) \qquad K \nabla^2 T + \frac{J^2}{\sigma} + Q_{beam} = \frac{K}{d} \frac{\partial T}{\partial t}$$

with $T(r,o) = T_{ambient}$ (ambient temperature)

$Q_{beam} = 0$ for $t \neq t_{beam}$

$= $ beam power for $t = t_{beam}$

t_{beam} is the time at which the beam hits the target,

$\frac{J^2}{\sigma}(r,t)$ is the power density in the target material resulting from joule heating,

$\vec{J}$ being related to $\vec{H}$ by:

$$\vec{J} = \vec{\nabla} \times \vec{H}$$

which in the axisymetric case and notations of figure 1 is :

$$J_z = \frac{H}{r} + \frac{\partial H}{\partial r}$$

For a transient heat transfer problem with time dependant boundary conditions and internal heat generation, DOT uses a step by step integration method of the tangent matrix type (see reference 1) unconditionally stable, the precision of which depends on the size of the mesh and the integration time step ∂t. Since there is no iteration process on the nodal heat flow equilibrium equations interleaved with the step by step integration, some cumulative errors exist, and this may turn out to be a problem, as we shall discuss briefly in the example to come.

There are 2 practical methods to solve step by step the problem with DOT:

a) Solve at each time step both equations (1) and (2) with proper initial and boundary conditions using the restart capabilities of the program, the solution of one equation being used to modify the input to the second equation.
b) Modify slightly the source of the DOT program by incorporating a routine which solves equation (2) by finite differences at the end of each calculation step.

Solution (a) is as accurate as the finite element formulation can be, but very lenghty and trouble some.
Solution (b) is less accurate due to finite difference approximations (and can even lead to instabilities) while being much faster in practise.

For these reasons solution (b) has been chosen, and incorporated in a new version of DOT, called DOT1.

For the one dimensional axisymetric case, $\vec{H}$ has only one tangential component H and equation (1) reduces to

$$\frac{\partial^2 H}{\partial r^2} + \frac{1}{r}\frac{\partial H}{\partial r} - \frac{H}{r^2} = \sigma\mu \frac{\partial H}{\partial r} \qquad \text{(1 bis)}$$

which, with abstraction of the term H/r^2, is simply the scalar diffusion equation.The term H/r^2 can be interpreted as an internal field sink, by similitude with heat sinks (negative Q in equation (2)). Since the program DOT provides temperature dependent heat sinks and sources, integration of equation (1 bis) is possible, giving for each time step i the field value Hi.

The calculation proceeds then as follows:

At the end of each evaluation time step i of H, one performs the following calculations:

$$J_i = \frac{Hi}{r} + \frac{\partial Hi}{\partial r}$$

j being the radial node numbering (see figure 1) this is finite difference approximated as:

$$J_i^j = \frac{H_i^{j+1} - H_i^{j-1}}{rj+1 - rj-1} + \frac{Hi^{j}}{rj}$$

Using the previously calculated element electrical conductivity σ_i^j , one calculates the joule power as:

$$P_{vi}^{j} = \frac{(J_i^j)^2}{\sigma_i^j}$$

the temperature field T is then obtained from equation (2) written as (uni-dimensional axisymetric case):

$$K\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) + P_v + Q_{beam} = \frac{K\partial T}{d\partial t}$$

that is:

$$T_{i+1}^{j} = T_i^j + \Delta T_i^j$$

with:

$$\Delta T_i^j = d_i\left[A_i^j + \frac{1}{k_i}\left(P_{vi}^j + Q_{beam\,i}^j\right)\right]\Delta t$$

A_i^j being a centered finite difference approximation of

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}$$

and di, Ki respectively the thermal diffusivity and conduction at temperature Ti.

T_{i+1}^j is then used to calculate the electric conductivity σ_i^j for the next DOT step calculation of H:

$$\sigma_{i+1}^{j} = \frac{\sigma_\emptyset}{1+\alpha T_i^j}$$

the radial magnetic volume force F is obtained as a by product:

$$F_i^j = J_i^j \quad \mu H_i^j$$

Also as a by product, the quasi static (i.e. with no inertia effect) elastic thermal and magnetic stresses are calculated at each step from the temperature and magnetic body force fields, and this according to the formulae of annex 2, the integrals involved being calculated at each step as simple summations over the radius of the relevant field function.

The calculation proceeds then to the next time step.

3) Application:

The case of a 3mm diameter, 9cm long copper target, loaded with a half sine wave shaped pulsed current of 250 KA of 30 μs duration, has been studied with and without radially gaussian beam energy deposition at the time of maximum current.

(see annex 1 for material constants)

Before going on to the results, some qualitative description of the different sources of errors, other than the physical model used, must be discussed.

Finite element model:

As already said in §2, inherent and classical to the axisymetric element formulation and method, a source of error is due to the fact that the center node lies on the axis of revolution where R=0. This leads to some systematic error in the calculation of the center element constitutive matrix, since terms in H/R have to be taken into account. A consequence found in the example treated herein is that, despite a small hole drilled in the target (center node put at 0.01 mm off the center), the field H is slithly over valued as one gets to near the center of the target. This would be of no importance if one would not take the square of the derivative in the calculation ! This error is cumulative as the integration proceeds, and adds up to the integration systematic error on the field, which depends critically on the mesh size and the time step.

Finite difference approximation:

The finite difference approach - centered differences - gives rise also to systematic and cumulative errors as the integration proceeds. The error is larger near to the center where one has to approximate the current density from finite differences of

$$\frac{H}{R} + \frac{\partial H}{\partial R}$$

keeping the second derivatives constants on the two extreme nodal points.

Material constants:

These are calculated for nodal points by taking the arithmetic average over the element.

All these computational errors can be made tolerable by decreasing the time steps (.1μs has been chosen in the example), choosing a large number of nodal points (100 elements over the radius in the example), and conducting the integration over a limited time (300 μs, i.e. 10 times the duration of the current pulse in the example below). For the integration to be processed further in time with enough precision in the neighbourhood of the target center, one would need to modify the program in order to introduce every integration steps some iterative scheme for basic nodal equilbrium conservation.

4) Results:

Figure 1: shows the magnetic field, current density and radial temperature distributions as a function of different values in time, with and without variation with temperature of the material constants (electrical conductivity, heat capacity).
At the end of the pulse the surface temperature is ~360° C (300°C with σ_T constant).

The effect of increasing resistivity with temperature is clearly visible also on the field and current density distribution. If anything, the current propagation toward the center of the target is faster when one takes into account increasing resistivity with temperature.

Figure 2: Energy density deposition as a function of time, with and without beam, showing the overwhelming effect of the beam.

Figure 3: Copper target temperature as a function of time (fictitious above ~1000°C since the model does not incorporate the true enthalpy of the copper at high temperature).
It shows that pure conduction in the target gives a time constant for temperature equilibrium of the order one ms.

Figure 4: Thermal stresses (No magnetic pinch) as a function of time, without beam, for a target free radially (contained axially). This calculation was done to cross check Timoshenko's formulae for a linear temperature field.

Figure 5: Stresses, without beam, for a target not contained radially. The strong negative pressure (radial contraction) is clearly seen at the end of the pulse. Also the contribution in stresses of the magnetic pinch is seen to be important when comparison is made with figure 4.

Figure 6: Stresses without beam, for a target totally constrained (radially and axially).
It is clearly seen that stresses become all compressive (closer to the hydrostatic state), apart of an initial thermal effect which for the first 15 µs tend to expand the outer target thus giving rise to high axial and circumferential shear strain.
Effect of cummulative errors is apparent, as the stress field should be flat with radius near to the center.

Figure 7: Same case as figure 6, but with a reduced mesh size and a smaller integration time step, showing better precision near the center. All 9 fields computed by the program are shown.

Figure 8: Temperature and stresses of an axially constrained, radially free target at Beam impact with latent heat of fusion of 2 x 10^5 Joules $m^{-3}\,^{\circ}C^{-1}$ (at atmospheric pressure) assuming the copper to be still elastic.
The strong expansion state of the outer target is clearly seen on the circumferential stress curve.

5) Some discussion ...:

a) Stresses and strain: (no beam)

One could ask if a "quasi static" calculation of radial stresses is valid, i.e. without taking into account inertia forces. Stress waves will propagate in copper at a speed of about 3500 m/s; the radial natural frequencies are all above 2.3 MHz, while the fundamental of the current loading is about 16 KHz, thus the radial inertia forces can be ignored concerning the current loading. However this is certainly not true axially (lowest natural frequency of 12 kHz) and dynamic calculations ought to be performed, which would probably show large axial strain and stress enhancement factors.

Calculation of stresses and strain has been done in the elastic case, which is certainly not valid in view of the temperature and strains reached. Nevertheless, knowing the thermo and elasto plastic properties of copper at high temperatures, some model could perhaps be developped and incorporated easily in the program, since it uses a direct step by step integration procedure, and thus does not require linearity of stress and strain.

If one were to define a design criterium based on the necessity to have a state of compressive (hydrostatic)
stress throughout the pulse and post pulse loading everywhere in the target, figure 6 shows that - obvious as it may seem physically - it needs to be constrained rigidly both axially and radially, with a rigid container. More over,
some externally applied axial precompression would help to reduce the differences in principal stresses, usually responsible for shear and deterioration of material lattice structure. Figure 6 indicates that for a 250 kA current pulse, some 20 kg/mm^2, i.e. about 140 kg of axial precompression force should be applied in order to get closer to a state of hydrostatic compression. But it also shows that the perfect hydrostatic loading cannot be achieved everywhere throughout the current pulse, even in the static approximation.

It could be that the dynamical behaviour of the container, itself subjected to stress and strain waves, makes the situation even worse from the point of view of hydrostatic loading; the possibility of simultaneous local container expansion and target contraction may exist.

In the elastic case, this problem can be treated with the Finite Element Program SAPV[2]) , available at CERN.

b) "Low density beam channel" with beam energy deposition

Figure 7 shows that the radial pressure in the center of the target hit by the beam is low, while the temperature is high due to instantaneous radial thermal expansion of the target material that the elastic analysis allows to take care of. With the appropriate equation of state, this means instantaneous target density reduction. Of course, although the effect is real for high energy deposition (workshop on targetting - Fermilab April 28 - 1980), the present analysis is not taking into account inertia forces and shock wave propagation phenomena, thus is not adequate and does not represent the true dynamics. To takle the problem of the conducting target behaviour with beam energy deposition, an hydrodynamic code like REXCO [2]) (also available at CERN) has to be used. This code would as well allow to solve the problem of the elastic dynamical behaviour of the container, which to my opinion is one of the keys towards understanding the physical behaviour of the target itself.

<u>References:</u>

1) DOT: Determination of temperatures. R. Polivska and E. Wilson Berkeley 1976

2) SAPV and REXCO are presented in: Note Technique LEP-IM/84-6

3) Skin Effect in Electrically Pulsed Cylindrical Conductor used as Focusing Devices. A.J. Lennox- Fermilab p note 269.

Annex 1

Cylindrical copper target - data used in the calculation

Target material: copper
diameter $d = 3 \times 10^{-3}$M
length $L = 9 \times 10^{-2}$M

electrical conductivity $\sigma = 5.5 \times 10^{7}$ Siemens (20°)

temperature coefficient $\alpha_\sigma = 4 \times 10^{-3}$
permeability $\mu = 4\pi \times 10^{-7}$ H/M

thermal conductivity $k = 380$ W (°C m)$^{-1}$ (20°)
density $\rho = 8900$ kg m^{-3}

heat capacity $Cp = 380$ J (m^{3}°C)$^{-1}$ (20°)

case where C_p varies
with T $C_p = 5.41 + 1.5 \times 10^{-3}$ T (°K) [Jm^{-3}°C^{-1}]
Modulus of elasticity
$E = 1.1 \times 10^{11}$ N m^{-2} (20°)
poisson coefficient $\nu = 0.33$
Coefficient of thermal
expansion $\alpha = 17 \times 10^{-6}$ [°C^{-1}] (20°)

Radial beam energy density deposited in the target

+ energy deposited uniformly along the length
+ gaussian beam of $\pm\,\sigma = 0.7 \times 10^{-3}$ M RMS
+ $Q_{beam} = Ae^{-\frac{r^2}{2\sigma^2}}$ [Joules m^{-3}]

A is calculated as follows:
Integral of energy density over the target:

$$2\pi L \int_0^\infty Ae^{-\frac{r^2}{2\sigma^2}} r \, dr = \text{Total Beam Energy} = 1300 \text{ Joules}$$

$$= 2\pi L A \sigma^2$$

Thus $A = 4.6 \times 10^{9}$ [J m^{-3}]

Annex 2

Determination of the quasi static elastic

Thermal and Magnetic stresses in the Target

The derivation below follows Timoshenko's (Theory of elasticity - Mac Graw Hill - 3rd edition) for thermal stresses, and is extended to include magnetic forces.

The first case studied is the one dimensional axisymetric plane stress case, with temperature and magnetic body forces symetric about the center of the target, which gives only normal stresses along u, v and w (radial, targential, axial), all shear stresses being zero due to symetry of deformation.

The case of plane strain, more physical for a thin long cylinder, follows readily.

Notation: u = radial displacement

v = circumferential displacement = 0

w = axial displacement

σ_r, ε_r = radial stress and strain

σ_θ, ε_θ = circumferential stress and strain

σ_z, ε_z = axial stress and strain

E : modulus of elasticity

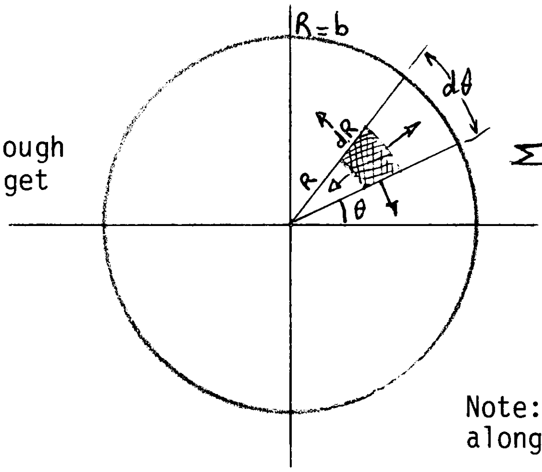
υ : poisson's ratio

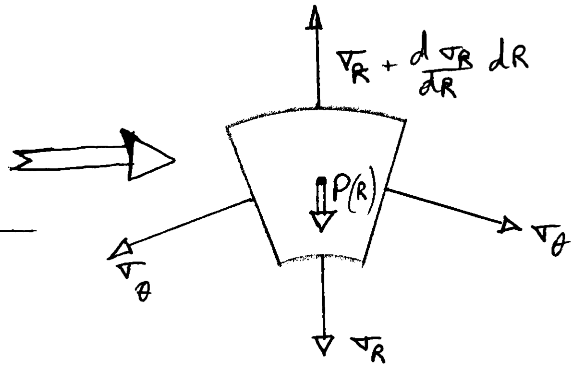
α : coefficient of thermal expansion

P(R) : magnetic volume force

Study of the equilibrium of forces applied to a small element of the target:

cut through the target





Note: forces are counted positive along these arrows.

yields the equation of equilibrium:

$$\frac{d\ \sigma_R}{dR} + \frac{\sigma_R - \sigma_\theta}{R} = P\ (R) \qquad (1)$$

A. plane stress case ($\sigma_z = 0$)

The stress strain relations, modified to take account of thermal expansion, write:

$$\varepsilon_r - \alpha T = \frac{1}{E}\ (\sigma_R - \upsilon\sigma_\theta) \qquad (2)$$

$$\varepsilon_\theta - \sigma T = \frac{1}{E}\ (\sigma_\theta - \upsilon\sigma_r) \qquad (3)$$

(2) and (3) give

$$\sigma_R = \frac{E}{1-\upsilon^2}\ [\ \varepsilon_R + \upsilon\varepsilon_\theta - (1 + \upsilon)\ \alpha T\ ] \qquad (4)$$

$$\sigma_\theta = \frac{E}{1-\upsilon^2}\ [\ \varepsilon_\theta + \upsilon\varepsilon_r - (1 + \upsilon)\ \alpha T\ ] \qquad (5)$$

(4) and (5) in (1) give

$$R\frac{d}{dr}\ (\ \varepsilon_r + \upsilon\varepsilon_\theta) + (1-\upsilon)\ (\varepsilon_R - \varepsilon_\theta) = (1+\upsilon)\,\alpha R\ \frac{dT}{dR} + RP\left(\frac{1-\upsilon^2}{E}\right) \qquad (6)$$

strains are related to displacement u by $\left(\frac{dv}{d\theta} = 0\right)$

$$\varepsilon_R = \frac{du}{dr} \quad ; \ \varepsilon_\theta = \frac{u}{R}$$

and (6) becomes

$$\frac{d^2u}{dR^2} + \frac{1}{R}\frac{du}{dR} - \frac{u}{R^2} = (1+\upsilon)\ \alpha \frac{dT}{dR} + P\ (\frac{1-\upsilon^2}{E})$$

$$\frac{d}{dR}\left[\frac{1}{R}\frac{d}{dR}(Ru)\right] = (1+\upsilon)\ \alpha \frac{dT}{dR} + P\ (\frac{1-\upsilon^2}{E})$$

integration of this equation yields:

$$u = (1+\upsilon)\ \alpha \frac{1}{R}\int_o^R TRdR + C_1R + \frac{C_2}{R} + (\frac{1-\upsilon^2}{E})\ \frac{1}{R}\int_o^R R\int_o^R PdRdR \qquad (7)$$

u being zero at the center of the target yields $C_2 = 0$, and C_1 will be obtained by the boundary condition at R=b (outside surface of the target)

σ_R and σ_θ are found from equations (4) and (5) with

$$\varepsilon_R = \frac{du}{dR} \quad \text{and} \quad \varepsilon_\theta = \frac{u}{R}$$

which are found by derivation of formulae (7):

$$\varepsilon_R = (1+\upsilon)\alpha\ T + \frac{1-\upsilon^2}{E}\int_o^R Pdr - (1+\upsilon)\alpha\frac{1}{R^2}\int_o^R TRdR$$

$$- \frac{1-\upsilon^2}{E}\frac{1}{R^2}\int_o^R R\int_o^R PdRdR$$

$$\varepsilon_\theta = (1+\upsilon)\ \frac{\alpha}{R^2}\int_o^R TRdR + C_1 + \frac{1-\upsilon^2}{E}\frac{1}{R}\int_o^R R\int_o^R PdRdR$$

This yields, for the plane stress case:

$$\sigma_R = -\alpha E \frac{1}{R^2}\int_o^R TRdR + \frac{E\upsilon C_1}{1-\upsilon^2} - (1-\upsilon)\frac{1}{R^2}\int_o^R R\int_o^R PdRdR + \int_o^R PdR \qquad (8)$$

$$\sigma_\theta = \alpha E \frac{1}{R^2}\int_o^R TRdR + \frac{E}{1-\upsilon^2}C_1 + (1-\upsilon)\frac{1}{R^2}\int_o^R R\int_o^R PdRdR + \upsilon\int_o^R PdR - \alpha ET \qquad (9)$$

Now, in order to find the coefficient C_1, one has to consider 2 cases:

a) the solid cylinder is free radially (not constrained)

$$\sigma_b = 0$$

b) The solid cylinder is blocked radially (constrained)

$$u_{(b)} = 0$$

Case (a): target unconstrained radially:

C_1 is found by equating expression (8) for R = b to zero this yields:

$$\sigma_R = \alpha E \left(\frac{1}{b^2}\int_o^b TRdR - \frac{1}{R^2}\int_o^R TRdR\right)$$

$$+ (1-\upsilon)\left[\frac{1}{b^2}\int_o^b R\int_o^R PdRdR - \frac{1}{R^2}\int_o^R R\int_o^R PdRdR\right]$$

$$+ \int_o^R PdR - \int_o^b PdR$$

$$\sigma_\theta = \alpha E \left(\frac{1}{b^2}\int_o^b TRdR + \frac{1}{R^2}\int_o^R TRdR\right)$$

$$+ (1-\upsilon)\left[\frac{1}{b^2}\int_o^b R\int_o^R PdRdR + \frac{1}{R^2}\int_o^R R\int_o^R PdRdR\right]$$

$$+ \upsilon \int_o^R PdR - \int_o^b PdR - \alpha ET$$

For a target rigidly constrained axially, away from the ends, the case of deformation is that of plane strain rather than plane stress and, as shown by Timoshenko, the equations above have to be modified simply by putting

$\frac{E}{1-\upsilon^2}$ instead E; $\frac{\upsilon}{1-\upsilon}$ for υ; $(1+\upsilon)\alpha$ for α

The stress strain relations are:

$$\varepsilon_R - \alpha T = \frac{1}{E}\left[\sigma_R - \upsilon(\sigma_\theta + \sigma_z)\right]$$

$$\varepsilon_\theta - \alpha T = \frac{1}{E}\left[\sigma_\theta - \upsilon(\sigma_R + \sigma_z)\right]$$

$$\varepsilon_z - \alpha T = \frac{1}{E}\left[\sigma_z - \upsilon(\sigma_R + \sigma_\theta)\right]$$

the target being constrained axially, $\varepsilon_z = 0$ and one gets

$$\sigma_z = \upsilon\,(\sigma_R + \sigma_\theta) - \alpha E T$$

So finally, for the case of a target constrained axially, but free to expand or retract radially, the stresses are:

$$\sigma_R = \frac{\alpha E}{1-\upsilon}\left(\frac{1}{b^2}\int_o^b TRdR - \frac{1}{R^2}\int_o^R TRdR\right)$$

$$+ \frac{1-2\upsilon}{1-\upsilon}\left[\frac{1}{b^2}\int_o^b R\int_o^R PdRdR - \frac{1}{R^2}\int_o^R R\int_o^R PdRdR\right]$$

$$+ \int_o^R PdR - \int_o^b PdR \qquad (10)$$

$$\sigma_\theta = \frac{\alpha E}{1-\upsilon}\left(\frac{1}{b^2}\int_o^b TRdR + \frac{1}{R^2}\int_o^R TRdR\right)$$

$$+ \frac{1-2\upsilon}{1-\upsilon}\left[\frac{1}{b^2}\int_o^b R\int_o^R PdRdR - \frac{1}{R^2}\int_o^R R\int_o^R PdRdR\right]$$

$$+ \frac{\upsilon}{1-\upsilon}\quad \int_o^R PdR - \int_o^b PdR - \frac{\alpha\, E}{1-\upsilon}\, T$$

$$\sigma_z = \upsilon\,(\sigma_R + \sigma_\theta) - \alpha\, E T$$

Case (b): Target constrained both axially and radially.

In that case, the coefficient C_1 in formulae (8) and (9) is found by equating expression (7) to zero, in the case of plane stress. The more physical case of plane strain is found as above by changing the coefficients E, υ, α by $\frac{E}{1-\upsilon^2}$, $\frac{\upsilon}{1-\upsilon}$, $(1+\upsilon)\alpha$ respectively in the equations so obtained.

All calculations done, this gives:

$$\sigma_R = -\frac{\alpha E}{1-\upsilon}\left(\frac{1}{R^2}\int_o^R TRdR + \frac{1-\upsilon}{1-2\upsilon}\int_o^b TRdR\right)$$

$$-\frac{\upsilon}{(1-\upsilon)\,b^2}\int_o^b R\int_o^R PdRdR - \frac{1-2\upsilon}{1-\upsilon}\frac{1}{R^2}\int_o^R R\int_o^R PdRdR$$

$$+\int_o^R PdR \qquad (11)$$

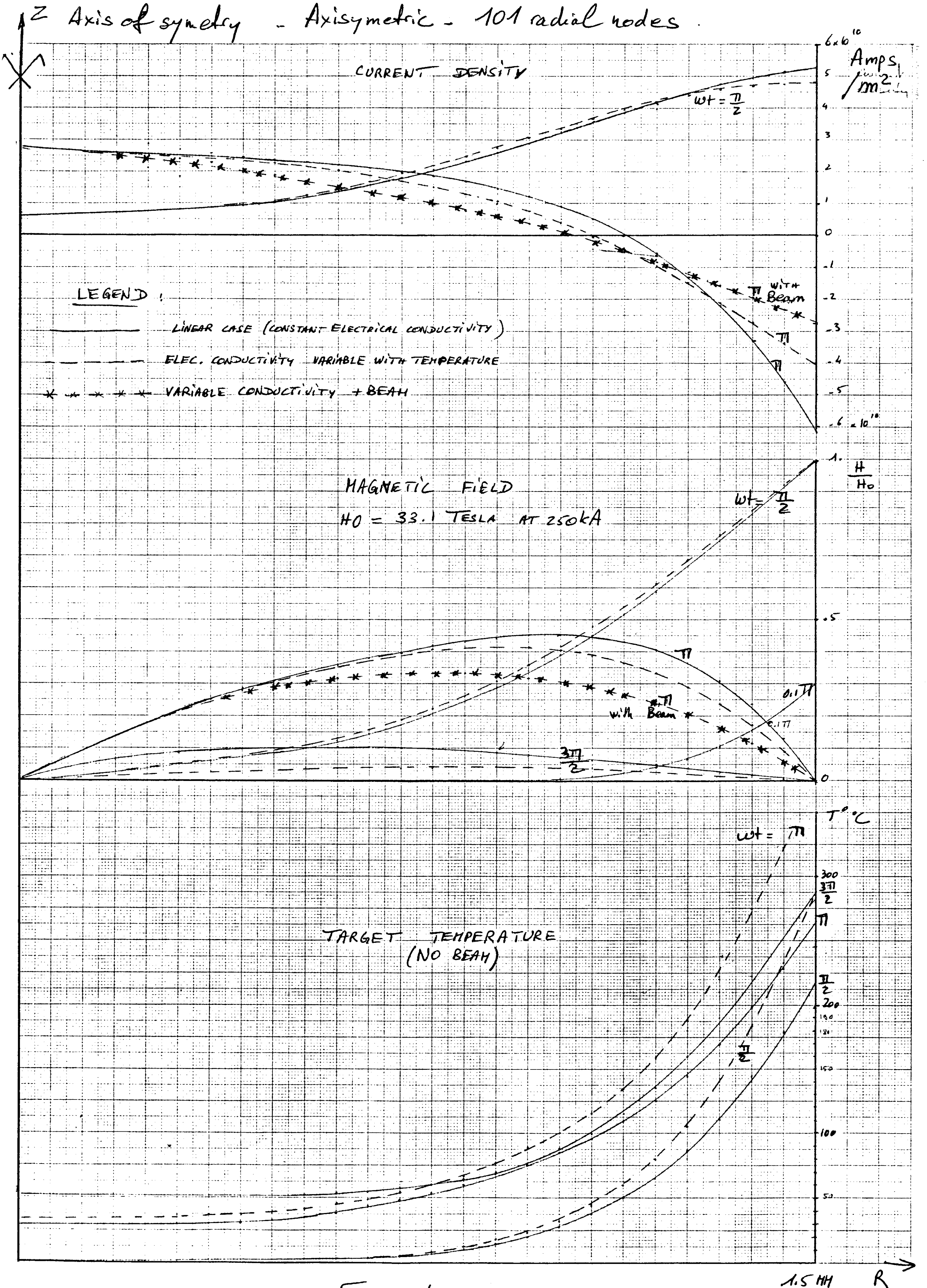
$$\sigma_\theta = \frac{\alpha E}{1-\upsilon}\left(\frac{1}{R^2}\int_o^R TRdR - \frac{1}{1-\upsilon}\quad\frac{1}{b^2}\int_o^b TRdR\right.$$

$$+\left(\frac{1-2\upsilon}{1-\upsilon}\right)\frac{1}{R^2}\int_o^R R\int_o^R PdRdR - \frac{1}{b^2}\int_o^b R\int_o^R PdRdR$$

$$-\frac{\alpha E}{1-\upsilon}T + \frac{\upsilon}{1-\upsilon}\int_o^R PdR$$

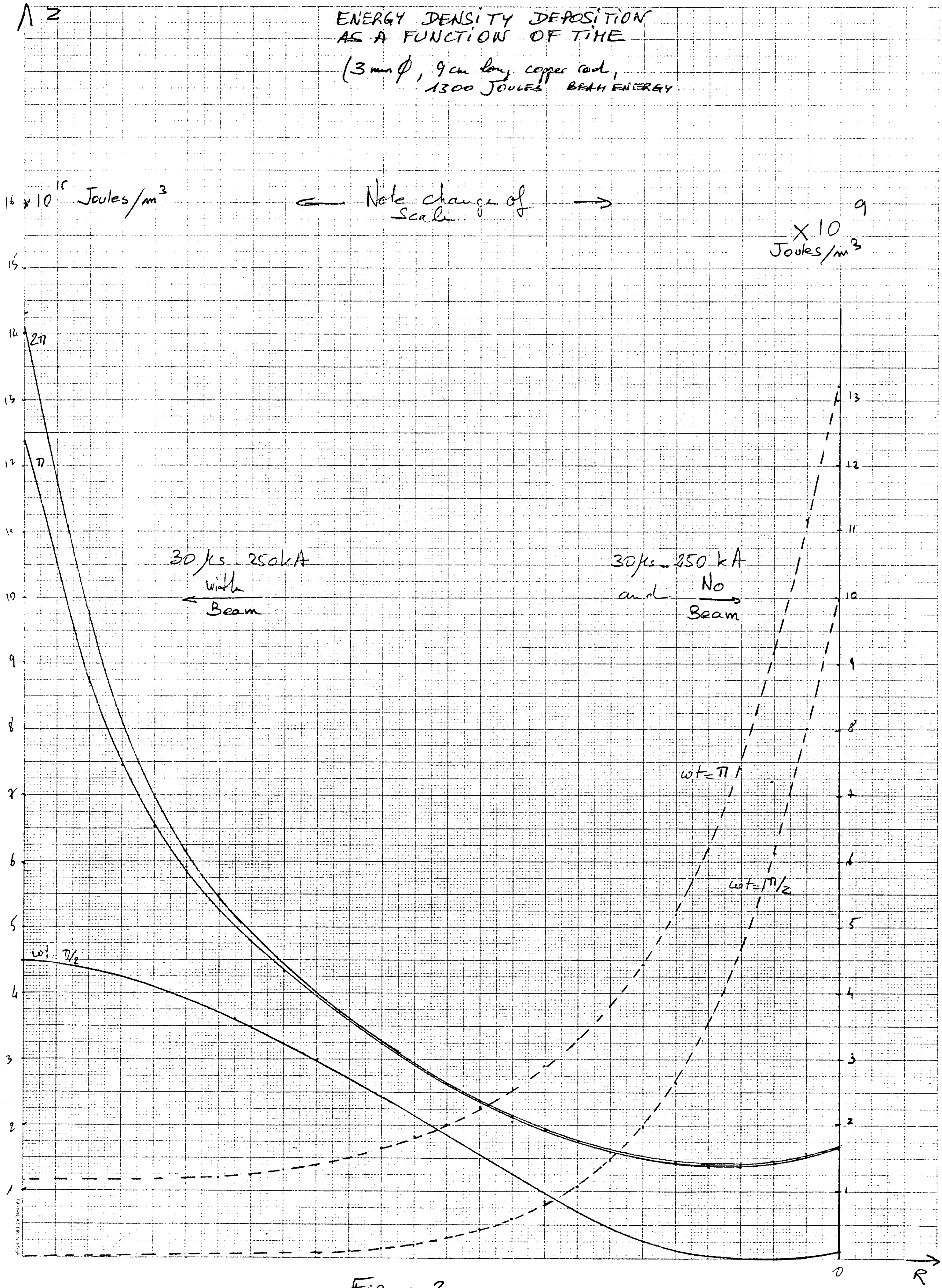
$$\sigma_z = \upsilon\,(\sigma_R + \sigma_\theta) - \sigma E T$$

Incorporation of these two sets of equations ((10) and (11)) in DOT poses no problem, this allowing direct step by step calculation of the quasi static stresses, as the magnetic field and the current penetrate the target.

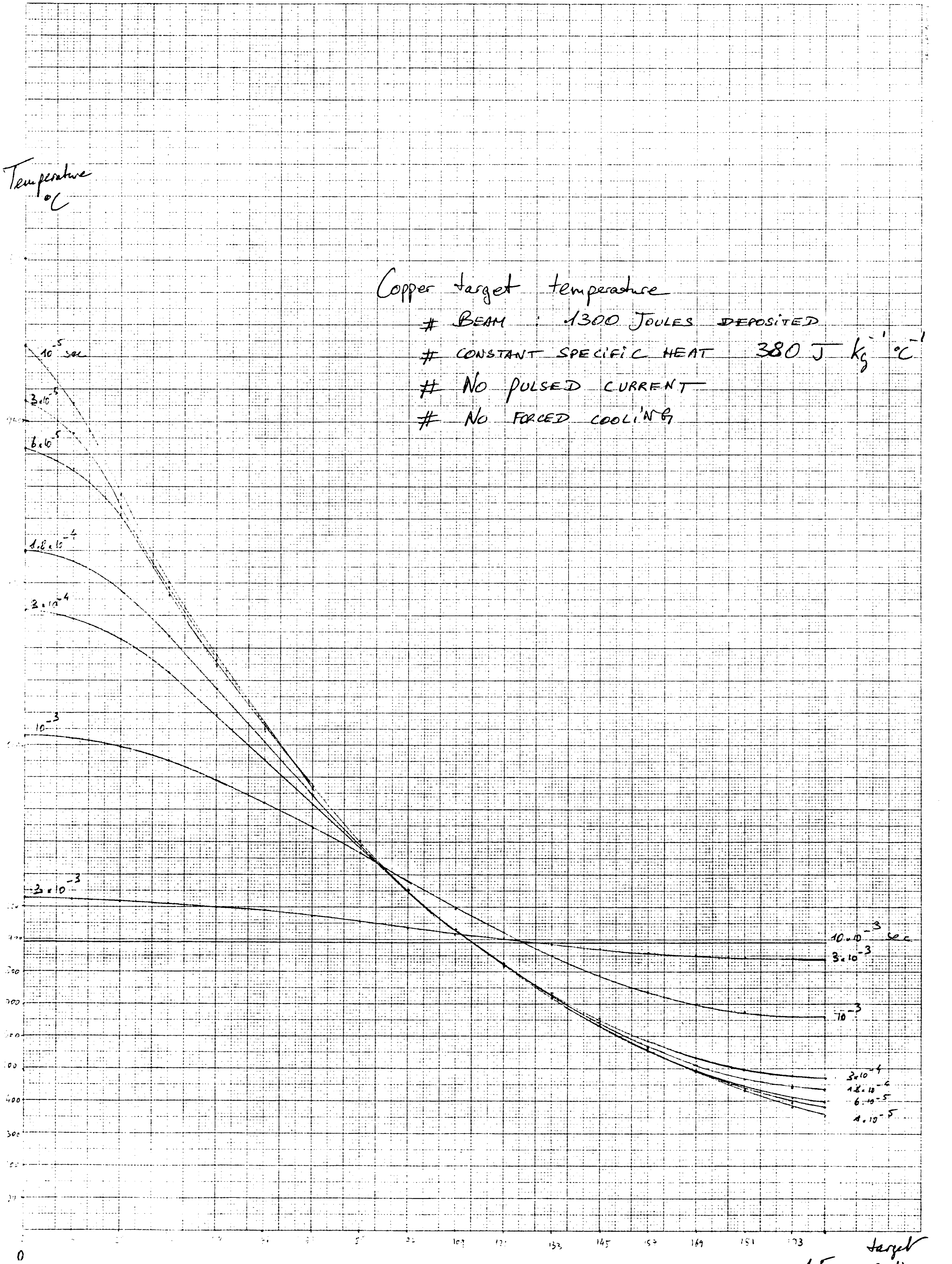

Z Axis of symetry - Axisymetric - 101 radial nodes
CURRENT DENSITY
Amps /m²
6×10¹⁰
ωt = π/2
π with Beam
π
π
-6 ×10¹⁰
LEGEND :
LINEAR CASE (CONSTANT ELECTRICAL CONDUCTIVITY)
ELEC. CONDUCTIVITY VARIABLE WITH TEMPERATURE
VARIABLE CONDUCTIVITY + BEAM
MAGNETIC FIELD
H0 = 33.1 TESLA AT 250kA
H/H0
ωt = π/2
π
0.1π
π with Beam
3π/2
TARGET TEMPERATURE (NO BEAM)
T°C
ωt = π
3π/2
π/2
300
200
100
50
1.5 MM
R
TARGET RADIUS

- Figure 1 -

ENERGY DENSITY DEPOSITION AS A FUNCTION OF TIME
(3 mm ϕ, 9 cm long copper rod, 1300 JOULES BEAM ENERGY



– Figure 2 –



Temperature °C
Copper target temperature
BEAM : 1300 JOULES DEPOSITED
CONSTANT SPECIFIC HEAT 380 J kg-1 °C-1
No PULSED CURRENT
No FORCED COOLING
10-5 sec
3.10-5
6.10-5
1.8.10-4
3.10-4
10-3
3.10-3
10.10-3 sec
3.10-3
10-3
3.10-4
1.8.10-4
6.10-5
1.10-5
0
target 1.5mm radius.

Figure 3

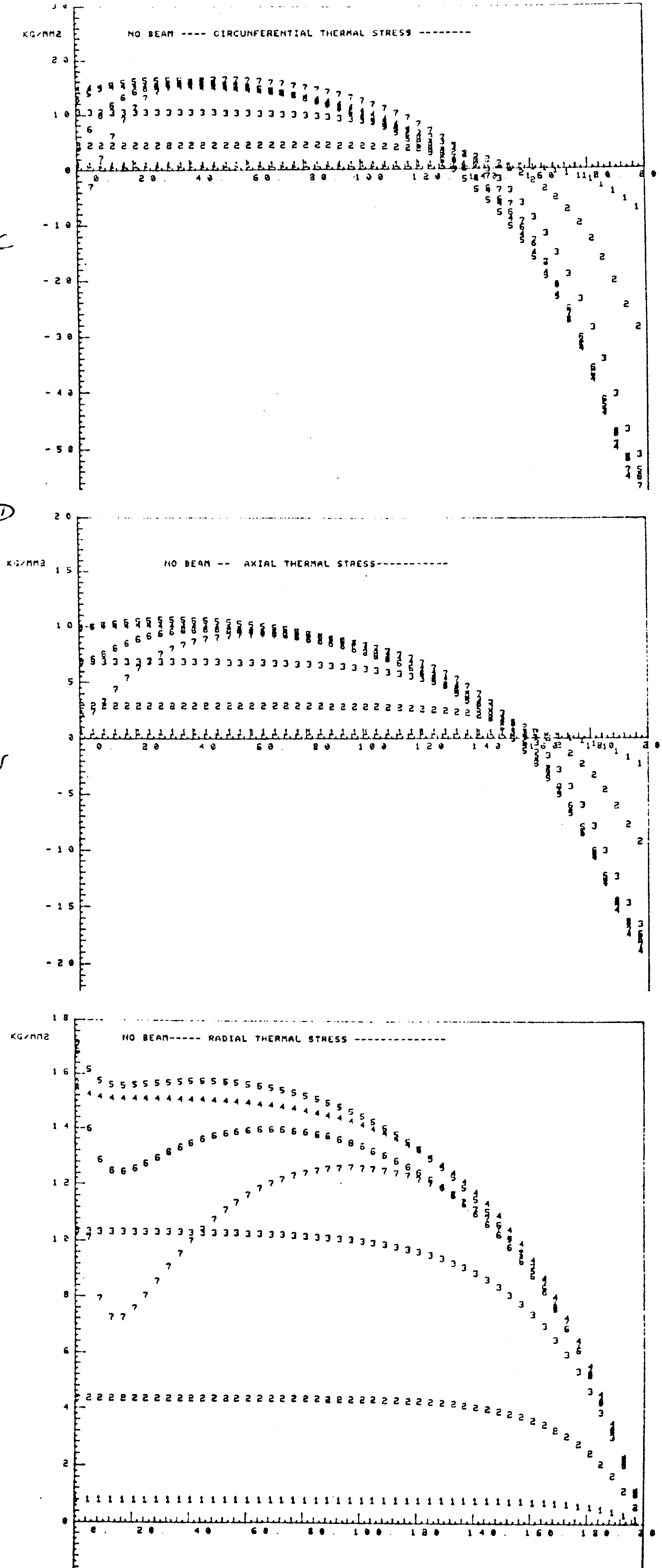
PURE THERMAL STRESSES
(NO BEAM -
NO MAGNETIC PINCH)

FOR

TARGET
AXIALLY
CONSTRAINED
RADIALLY
FREE

+ : TRACTION
− : COMPRESSION

1 : t = 5 μs
2 : t = 10 μs
3 : — 15 μs
4 : — 20 μs
5 : — 25 μs
6 : — 30 μs
7 : — 35 μs



— FIGURE 4 —

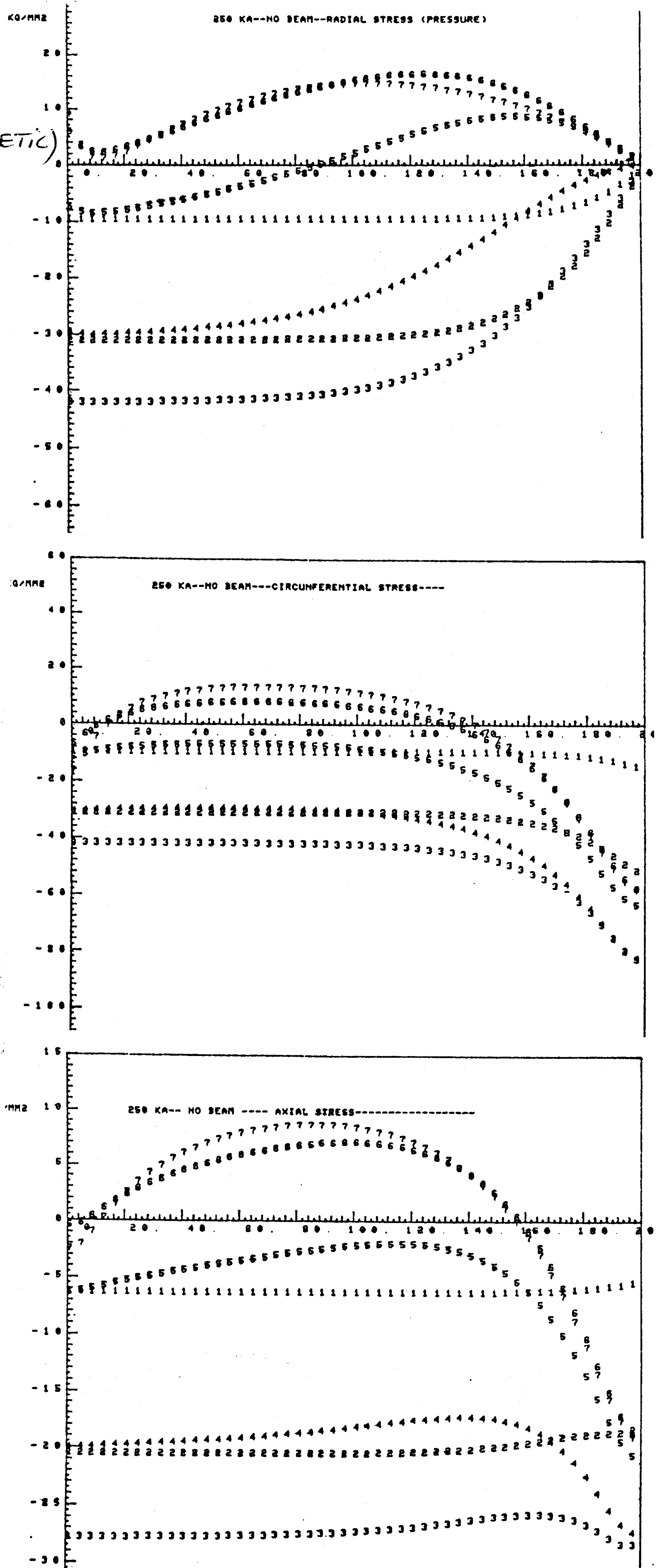
STRESSES
(THERMAL & MAGNETIC)
WITHOUT BEAM

TARGET AXIALLY
CONSTRAINED
RADIALLY
FREE

+ : TRACTION

– : COMPRESSION

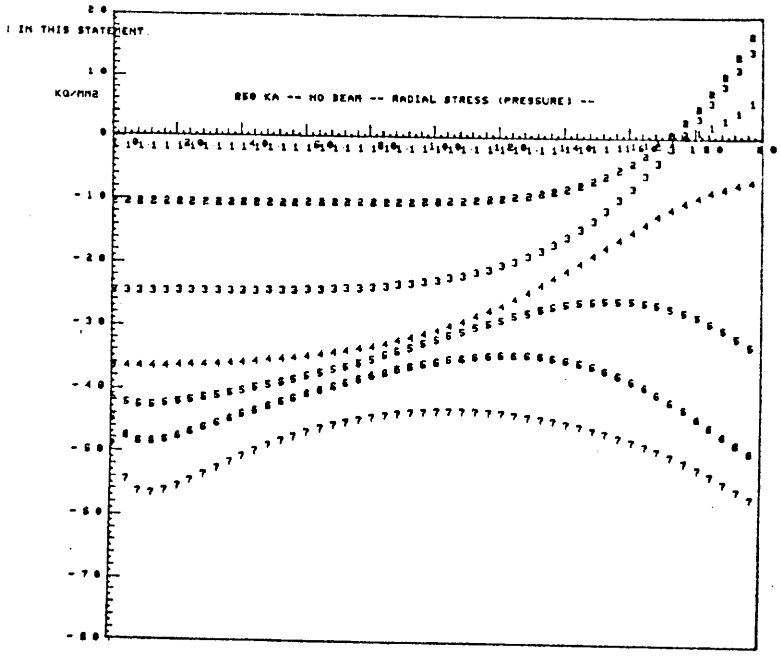
1 : t = 5 µs
2 : —— 10 —
3 : —— 15 —
4 : —— 20 —
5 : —— 25 —
6 : —— 30 —
7 : —— 35 —



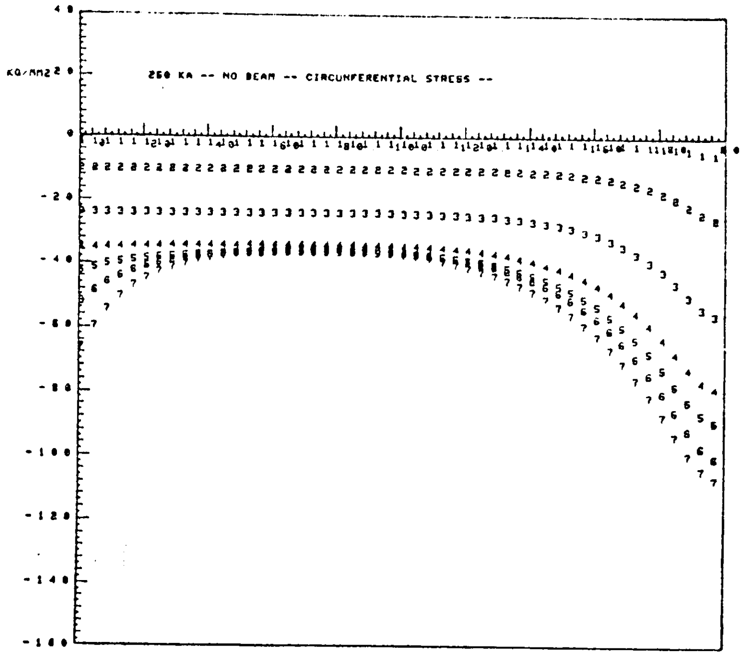
— FIGURE 5 —

STRESSES
(THERMAL & MAGNETIC)
WITHOUT BEAM

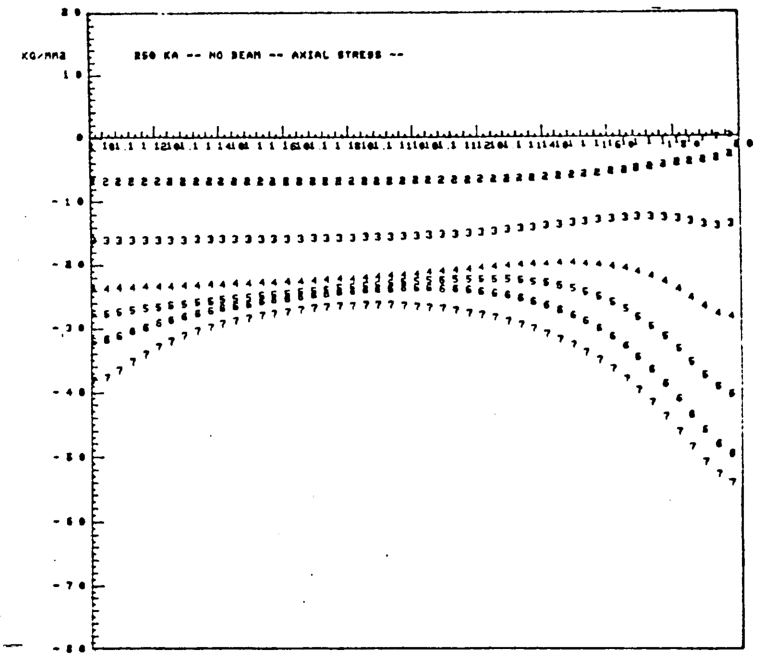
TARGET AXIALLY
& RADIALLY
<u>CONSTRAINED</u>



+ : TRACTION
— : COMPRESSION



1. t = 5 μs
2: — 10 —
3: — 15 —
4: — 20 —
5: — 25 —
6: — 30 —
7: — 35 —



– FIGURE 6 –

250 kA . 30 μs - COPPER - VARIABLE CONDUCTIVITIES - NO BEAM

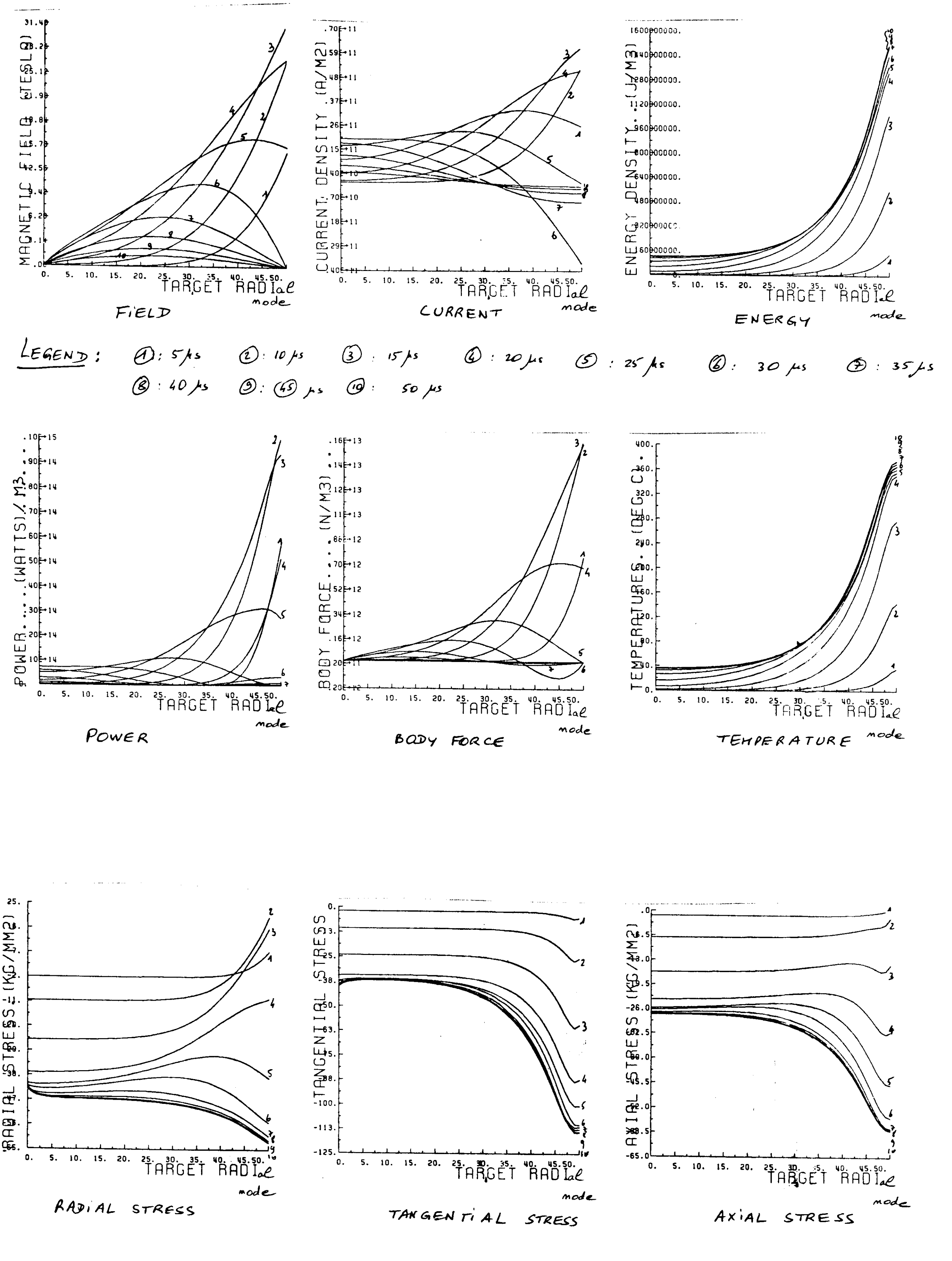
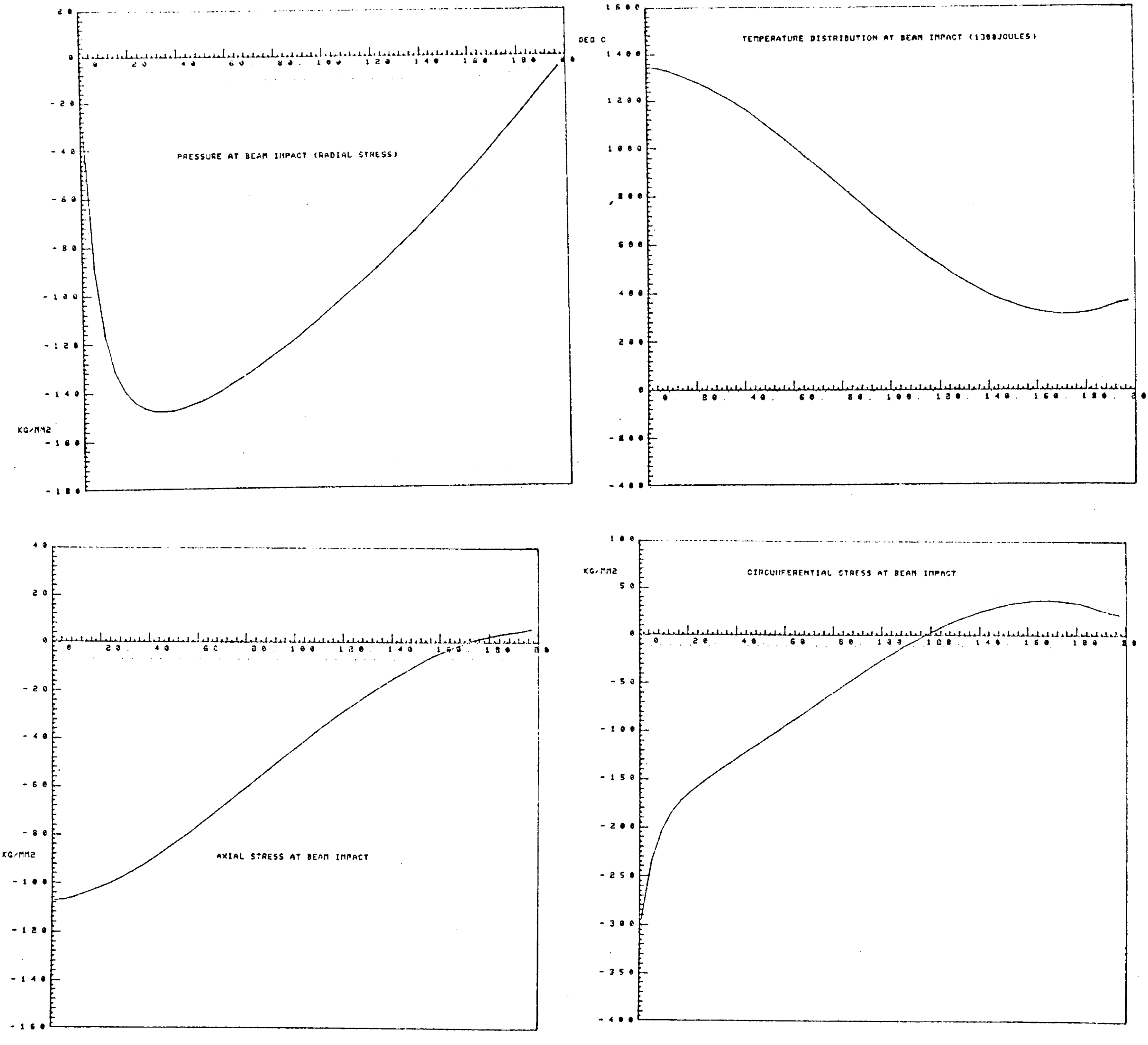


FIGURE 7 : TOTALLY CONSTRAINED TARGET . TIME EVOLUTION OF VARIOUS FIELDS .



TEMPERATURE AND STRESSES OF AN AXIALLY CONSTRAINED, RADIALLY FREE TARGET AT BEAM IMPACT, WITH LATENT HEAT OF FUSION INCORPORATED, inertia forces ignored

— FIGURE 8 —

EJNW/Draft 1

RESULTS OF A SURVEY OF POSSIBLE SCIENTIFIC COLLABORATIONS FOR THE CONSTRUCTION OF ACOL AND A PROPOSED AGREEMENT ON SUCH A COLLABORATION WITH THE RUTHERFORD APPLETON LABORATORY

INTRODUCTION

1. The ACOL Project can only be realised within the timescale given in the Design Report if the resources of manpower within CERN, and particularly in the PS Division, can be supplemented by help from institutions in Member States.

2. The existence of a collaboration with LAL at Orsay on the construction of the LEP pre-injector prompted the suggestion that there might be other laboratories able to construct parts of the ACOL machine.

3. During 1983 many laboratories and universities in Europe were asked if they were prepared to set up a scientific collaboration to assist in the design and project supervision of component systems of ACOL.

4. A number of small collaborations were set up to assist CERN in the preparation of the design. The subjects were matched to the available expertise in the collaborating institution.

RESPONSE TO ENQUIRY

5. While the High Energy Physics community at CERN is experienced in the kind of scientific collaboration suited to its needs, there are few precedents for scientific collaboration on the construction of accelerators. In the absence of a standard model, CERN proceeded with caution, first enquiring if help could be provided as part of the normal exchange between scientists, then agreeing to contracts of limited duration when it became clear that the financial rules of the collaborator demanded some form of remuneration.

6. Apart from two laboratories, DESY and KFA Julich, who generously offered the services of a theoretical consultant for a limited time, all the favourable replies contained a request for reimbursenent of salaries and some of the overheads.

7. The list of topics and collaborating institutes is as follows:

(i) Construction of a prototype injection septum magnet for ACOL - NIKHEF,Amsterdam.

(ii) Filling a series of capsules with lithium for the focusing system for the antiproton production target - KFZ,Karlsruhe.

(iii)Computer study of the mixing of magnet fringe fields. - University of Graz,Austria

(iv) Theoretical study of intensity limits of the improved AA - University of Genova, Italy

(v) Development of a plasma lens focusing technique for the ACOL production beam. - University of Naples,Italy

(vi) Provision of pulsed high-current power supplies for the ACOL focusing elements - Culham Laboratory, United Kingdom.

(vii)Calculation of particle trajectories in ACOL - DESY, Germany (no financial provisions other than travel)

(viii)Optics calculations of non-linear effects - KFA Julich, Germany (no financial provisions other than travel)

(ix) Study of ceramic microwave waveguides - University of Naples,Italy

(x) Design and production supervision for the quadrupole magnets of the ACOL ring - RAL, United Kingdom

(xi) Design and production supervisiono of mechanical components of the modified AA stochastic cooling system - (collaborators still being sought)

(xii)Development of broad band amplifier systems for stochastic cooling in ACOL - (collaborators still being sought)

8. The response to the enquiry suggests that while the present climate of financial severity persists the standard model for such a collaboration should include the reimbursment of staff costs and an allowance for overheads. In no case did two institutes offer the same kind of expertise

9. Now that the construction of ACOL is starting, CERN is anxious to prolong and enlarge some of these collaborations. The need to do so is particularly urgent in order to make an early start on the components on the critical path .One of the collaborations, (x), would involve a sum of money worthy of the attention of the Finance Committee. Details of the agreement which is proposed follow.

PROPOSED AGREEMENT ON THE COLLABORATION WITH RAL

10. The RAL assisted CERN in the design of the ends of the wide quadrupole magnets during the construction of the AA. The same team has just completed the construction of the magnets of the SNS . Their services were offered to design and supervise the construction of the quadrupole magnets for ACOL which are rather similar to those of the AA. The agreement would include three dimensional field calculations using the unique facilities for such computations at RAL.

11. The agreement is contained in a letter from the head of the SNS Division at RAL to the PS Division Leader .

12. The estimates of man-years of effort and design costs are:

	1984	1985	1986	
RAL manpower	1.8	2.8	1.4	MY
Design costs	22	4	-	£K

13. The estimated cost of the work comprise:

6 man-years of RAL staff	£150,000
Design costs (external)	£ 26,000
	£176,000

14. The work includes design,consultancy on technical matters, liason with manufacturers, once the contractual formalities have been completed by CERN, and supervision of delivery.

15. The RAL confirm in their letter that their staff costs are those which would be cahrged to SERC projects on the basis that ACOL is of scientific interest to the RAL programme.

RECOMMENDATION

16. The Finance Committee is invited to take note of the results of the enquiry into possible forms of scientific collaboration between CERN and Member State institutions. The Finance Committee is also invited to agree that, without a call for tenders, a contract be negotiated with RAL for the Design and Project Supervision of the Quadrupole Magnets for ACOL for a total price of £176,000.

Science and Engineering Research Council
Rutherford Appleton Laboratory

Mr R Billinge
Head, PS Division
CERN
1211 Geneva 23
Switzerland

Chilton, Didcot,
Oxfordshire OX11 0QX
Telegrams: Ruthlab Abingdon
Telex: 83159
Tel: Abingdon (0235) 21900
Extension:

20 February 1984

Dear Roy

MAGNETS FOR ACOL

I can confirm that RAL is willing to undertake the work for ACOL as described on the attached list on a consultancy basis beginning 1 April 1984. The estimated cost of the work is as follows:

	£
6 Man-years of RAL staff	150,000
Design costs external to RAL	26,000
	176,000

I suggest that we send you a record of the monthly usage of staff and external commitment and spend (approximately 1 month in arrears). We would bill you quarterly for expenditure incurred.

We would undertake to consult with your Project Leader if the rate of usage shows signs of being greater than expected. The expected usage is as follows:

	1.4.84-31.12.84	1985	1986
RAL manpower (MY)	1.8	2.8	1.4
Design costs £K	22	4	

Travel costs would be dealt with on the basis of a request for visits by CERN, the cost of which would be reimbursed on an individual basis.

I should add that the staff costs are those which would be charged to SERC projects on the basis that ACOL is of scientific interest to the RAL programme.

I look forward to a fruitful project.

Best wishes.

Yours sincerely

David.

David A Gray
Head, SNS Division

LIST OF WORK FOR CERN ON ACOL

1. Design of narrow and wide quadrupoles, including vacuum vessels and magnet supports.

2. Liaison with tenderers and CERN during the tender process. All formal communication with the firms to be through CERN.

3. Acting as consultants and liaison with CERN and the firms during the manufacturing phase, all formal communication with the firms to be through CERN.

4. To be in attendance at CERN for liaison after delivery of magnets to CERN.

DAG/pg
20.2.84