A FEM APPROACH OF THERMOSET MATERIALS INJECTION MOULDING MODELING

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1. ABSTRACT

This paper reports basic results obtained in the application of a new CAE model based on F.E.M. approach, and its aim is to analyze and simulate the moulding process of a thermoset component.
The software has been developed within the frame of an international consortium involving CRF, SW developer company and other international partners.

Basically the code solutor works by evaluating and resolving the energy equation and the flow equation; at the same time; for every time step and for every control volume, energy and flow balances are requested.

This code is based on two modules

- Filling module
- Curing module

The first one is able to simulate the filling phase of a mould injection and can give the values and the time histories of variables which are involved in this type of process, for example fields of pressure, temperature, viscosity.
A mould designer can also have as a result the position of weld lines, air traps and the orientation of fibers inside his mould cavity in order to optimize the position of injection points and the moulding parameters.

The filling module can also give the designer a precise idea of the curing phase, especially about curing time and the highest peaks of temperature through the thickness of the analyzed mould.

The second one is used for a better evaluation of the curing phase, in order to give a designer much more precise results about this phase with special emphasis on curing time prediction.

The developed model can give the designer very important information about curing time, grade of cure vs thickness, field of temperature during the whole curing phase.
The input set of data is obtained from characterization of thermoset materials and setting the injection parameters.

In order to give readers a more precise idea of this methodology, we are reporting an example of this kind of analysis using an automotive component simulation.
This component is a headlamp, a typical automotive component made by Magneti Marelli (Lighting Division of FIAT GROUP); particular attention will be devoted to evaluation of surface quality to optimize reflector optical performances.

1. INTRODUCTION

Fiat Research Center (CRF) is a partner of an international consortium in order to develop a code for numerical simulation of thermoset material injection moulding.

The code, named MF/TSET, has been developed with the collaboration of Moldflow Limited Company.

This consortium will end at the beginning of May and the "output" of this activity will be the first commercial version of this code.

The aim of CRF methodology, by using this code, is to simulate the injection moulding of thermoset materials in order to optimize both the runner and cavity lay-outs, the process parameters and to point out design problems if any.

This numerical tool might be a very useful one for mould designers in order to reduce the time between the initial CAD design and the construction of the final mould.

This code has been used in CRF in collaboration with Magneti Marelli Lighting Group in order to optimize their moulds and to check new ideas and new potential solutions without the high cost and time usually wasted by traditional experimental evaluations.

2. INTRODUCTION TO THE CODE

The code uses a FEM (Finite Element Model) approach in order to simulate the injection process. Commonly the first step of this kind of analysis is to "translate" CAD-3D surfaces design in a FEM modeler by using a CAD-FEM translator (usually an IGES interface), the second step is to obtain a mesh by using this FEM modeler.

The meshes used by MF/TSET are based on linear triangular shell elements to simulate the 3D geometry and the thickness of analyzed component.
Runners can be simulated as well by using a particular sort of two node beam named "runner" element.

Plenty of shapes of runner sections can be defined in order to get a realistic simulation of the runner lay-out behaviour (Figure 1).

During the calculations, the mould and the cavities are divided into layers throughout the thickness in order to use a finite difference/finite element algorithm to analyze the cavity filling and curing phases of the moulding cycle (Figure 2).
A default number of layers is given, but this number can be changed by the operator. As a default, eleven layers are considered on half a mould cavity and fifteen layers on the mould metal.

The basic idea of the code solver is to solve, for each control volume and for each time step, an Energy equation and a Flow equation at the same time.

The Energy equation is based on an energy balance between the material heat absorption during time and the heat propagation for conductivity, viscous heating of material, heat due to material compression and the esothermal curing reaction heat.

The Flow equation is based on a momentum equation which gives rise to a plane pressure field in the mould (pressure through thickness is considered to be constant, Hele-Shaw hypothesis).

The calculations are run only on half a thickness and then mirrored on the other side of the mould; mould temperature is considered to be constant on the whole mould surfaces.

THE COMPONENT

The component shown as an example of this simulation methodology is a double parabolic surface headlamp reflector made by Magneti Marelli Lighting. The first reflecting surface is the highbeam one, the second surface is the lowerbeam one.

The FEM model (Figure 3) is based on a 3100 shell element mesh and the thermoset material used is of the BMC type (based on an insatured polyester resin filled with a mineral filler and reinforced with short glass fibers); the mould temperature is 155 ºC and the injection temperature is 30 ºC. The injection time is 2.3 second, which corresponds to a material flow rate of 156.27 cm³/s.

ANALYSIS OF RESULTS

Filling Module Results

Now what you can read below is an example of a typical numerical simulation of injection moulding for thermoset materials; this set of results is given by the filling module, which is the first one of the MF/TSET code (the second one is the curing module). At the end of the filling calculation you can have a restart file in order to run a curing calculation if you consider your previous filling run to be a pretty good one.

WELD LINES - AIR TRAPS (Figure 4)

Using this kind of codes you can predict the position of weld lines. This capability is very important because you could have weld lines on a reflecting surface of the reflector: in this situation you will usually have a bad optical quality of the component.

So, this kind of information is very useful to designers in order to decide where to put the injection point and the runner geometry.

Position of air traps is very important as well; if you know where air traps are you can know where to put flow vents: if flow vents are not in the correct position material could be burnt up by high temperature of air which is compressed against mould surfaces by material flow.

FILL TIME (Figure 5)

You can analyze the time history of filling in order to decide if the injection point is in a good position or not to make the flow well balanced and to check if there are points in the mould which are difficult to be filled.

In this example you can see that the mould filling is well balanced. There could be some little warp effect on the highlight bezel where the two front meet each other, but in that position this phenomenon is not dangerous.

Without simulations designers and moulders are compelled to use short shots in order to understand if their filling is balanced and which are the critical areas of their mould cavity.

TEMPERATURE (Temperature during Filling Phase; Figure 6)

The field of Temperature is quite costant (about 30 °C, like the injection temperature), except where the flow stops at the end of the filling phase.

TMPG (Grid Temperature at the End of Filling; Figure 7)

At the end of filling you can also check the temperature through the thickness (layered temperature) and control if you have too high peaks of temperature in some layers and if all temperature values are below a dangerous level for the injected thermoset material. In this example all the temperature values are below this so called "red level" (about 180 °C).

Without this sort of codes moulders can understand if there are temperature problems only by analyzing moulded prototypes: this means that much more time must be wasted in tuning the injection and the mould temperatures.

PRESSURE (Figure 8)

The pressure distribution all over the component is quite good and well balanced except at the end of filling of the highlight parabolic surface, where pressure value is low, and the packing effect is not very good.

This fact is not so dangerous because from an optical point of view, the highbeam reflecting parabolic surface is not so important as the lowerbeam one is.

SHEAR RATE and SHEAR STRESS (Figure 9)

Values of shear rate and shear stress are below a dangerous level for the injected resin, so you can see that there should not be any problem due to thermal degradation of material.

To obtain the same set of data by adopting experimental methods is very difficult, expensive and not so fast. For this reason usually designers have never used this kind of information.

GCUR (Grid Percentage of Curing at the End of Filling; Figure 10)

At the end of the filling phase you can check through the thickness for the percentage of the cured material in order to point out if there are problems due to cavity thickness reduction caused by too much material which has started the curing process during mould filling instead of at the end of it (this problem is pointed out by too high values of GCUR in the upper layers).

If the percentage of the cured material during mould filling is too high you can have aesthetic damages in the component due to cured material which has been wrinkled by other material which is still flowing in the mould cavity. This kind of damage is not optically acceptable.

In this case there are no problems except in two, localized zones, but these areas are very thick (8 mm) so there should not be any flow problem.

This is another sort of information that generally cannot be used because it is very difficult and expensive to be derived from experimental methods.

CURT (Time of curing; Figure 11)

The filling module of this code gives you a quite good value of predicted curing time in order to allow you to have a quite good idea of cycle time and modify the injection parameters if you are not satisfied with results.

In the example examinated the average curing time is about 25 seconds, except in the thickest parts of the component (expected curing time is longer than 100 seconds).
This kind of information is very useful because it tells you that process time is extended very much in those parts: the possibility of reducing thickness can be analyzed.

Curing Module Results

After a filling module calculation you can run a curing calculation in order to have more precise information about the curing phase, especially about cured material percentage and grid temperature values.

ACUR (Average Percentage of Cured Material; Figures 12, 13)

In Figure 12 you can see that after 17 seconds from the beginning of injection the average percentage of cured material through thickness is higher than 70% and that this value is evenly distributed all over the component. After 25 seconds this average value raises to 80%. In Figure 13 plots of cured material percentage and curing rate time histories are shown: as you can see after 25 seconds cured material percentage is over 80%.

If you compare Figure 12 and Figure 13 you can see that after 25 seconds you can extract the component out of the mould paying attention to the extractor positioning.

Using this kind of information you can design an extractor lay-out by avoiding not enough cured areas which are pointed out very well (usually the thickest and the coldest areas) by output.

CTMP (Grid Temperature during Curing Phase; Figure 14)

For each curing time-step you can also have information about layere temperature in order to check if the curing process can damage your thermos material (in fact, the curing process is an esothermal one).

It is very interesting to point out the distribution of temperature: if you compar Figure 14 with Figure 7 you can see that at the end of filling the hottest layers ar the external ones, during the curing phase the hottest ones are the internal one this is due to the thermal shield due to the external layers (which cured durin filling phase cfr. GCUR) towards the internal ones (which begin curing som seconds later, after the end of the filling phase). It is like a hot water pipe with thermal insulation outside (cured thermoset materials have a very low therm conducibility coefficient).

CONCLUSIONS

- Using a FEM approach of thermoset injection moulding modeling it is possibl to optimize process parameters and mould lay-out; plenty of solutions can b tested without any experimental cost, connected to materials, lay-out mould an injection parameters. In Figure 15 a diagramm can be seen in order to evaluat the percentual saving of time.
- Hidden design problems can be pointed out and alternative solutions can b tested before the mould is built.
- Wall thicknesses can be reduced and optimized in order to reduce cycle tim and shot weight.
- Optimization of runners lay-out can be obtained in order to minimize material i the feed system so that materials costs can be reduced.
- Optimization and reduction of wasted material has a very good falling dow effect on environment: it is cheaper to reduce wasted thermoset resins at th beginning than to be compelled to recycle them.
- Balanced filling can be obtained, curing and temperature levels can b monitored and optimized in order to reduce material damaging, residu stresses and part warpage.
- Lots of information can be obtained without any experimental cost.

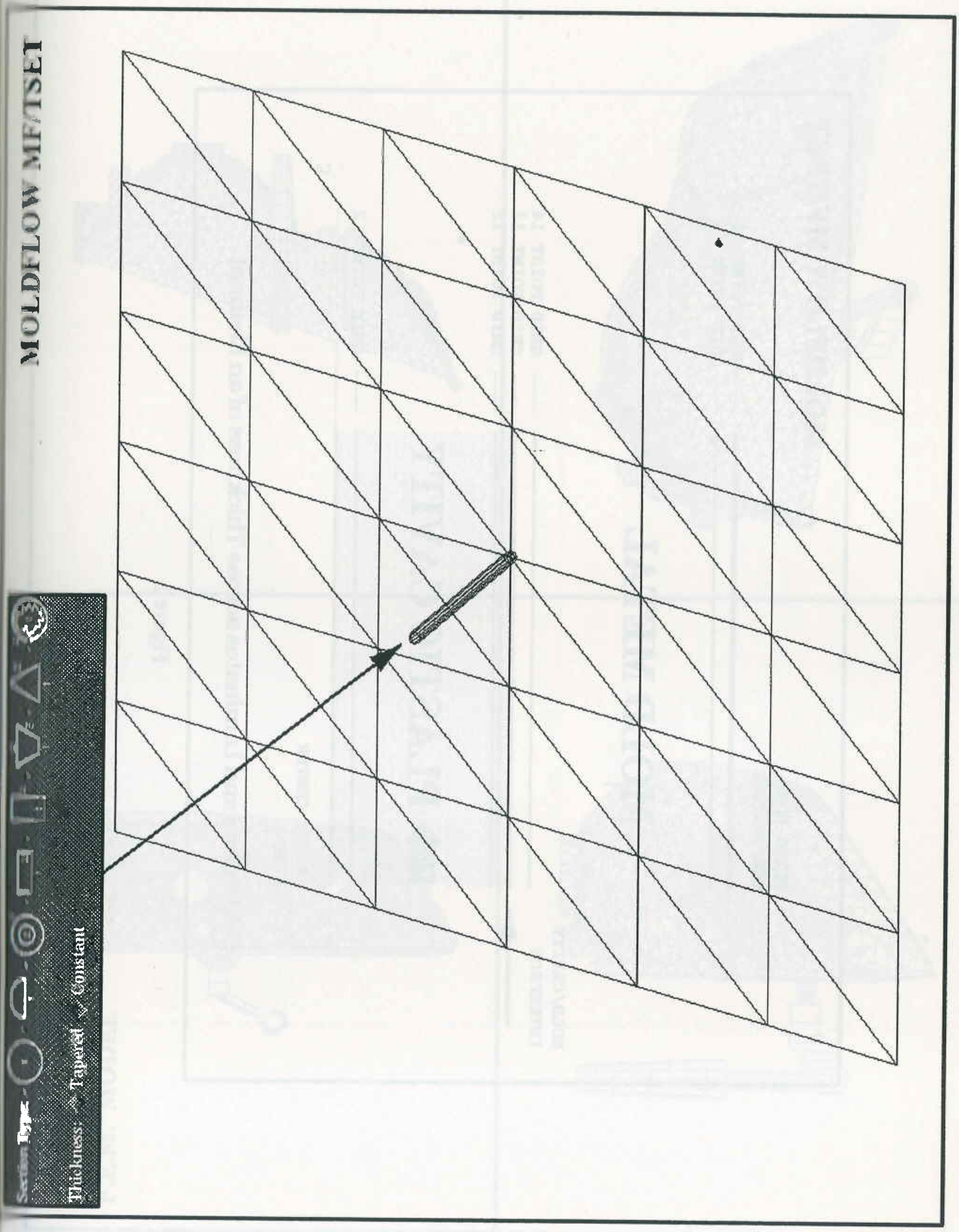
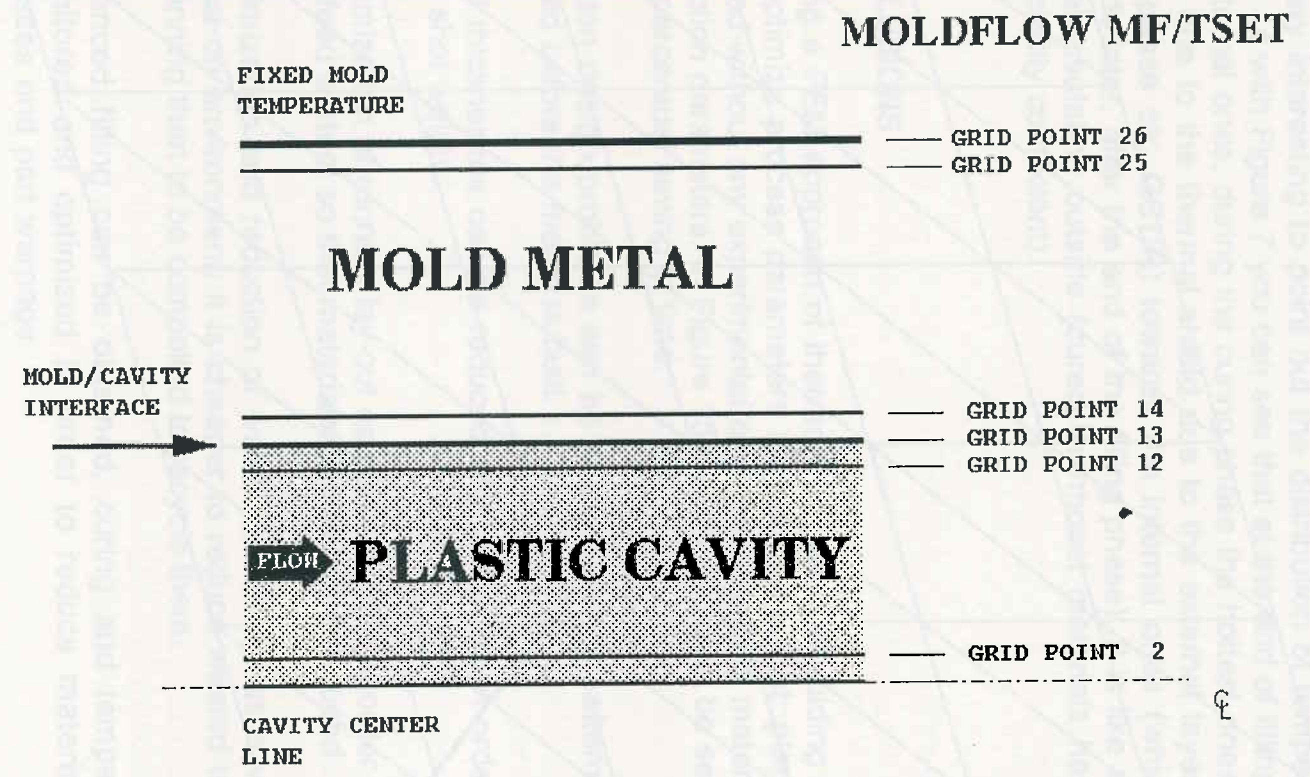


Figure 1



Grid Points and Laminates across Thickness of an Element

Figure 2

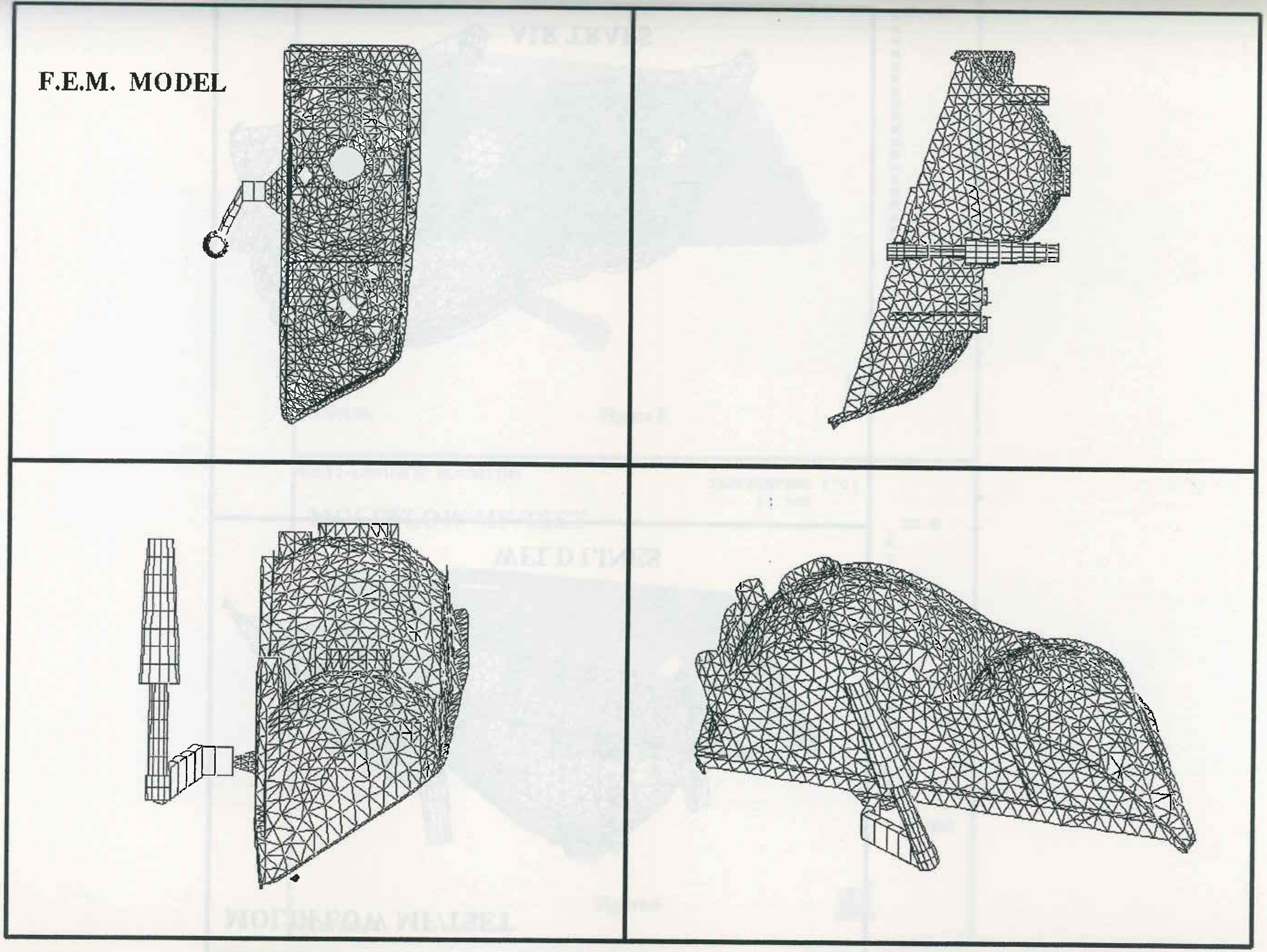
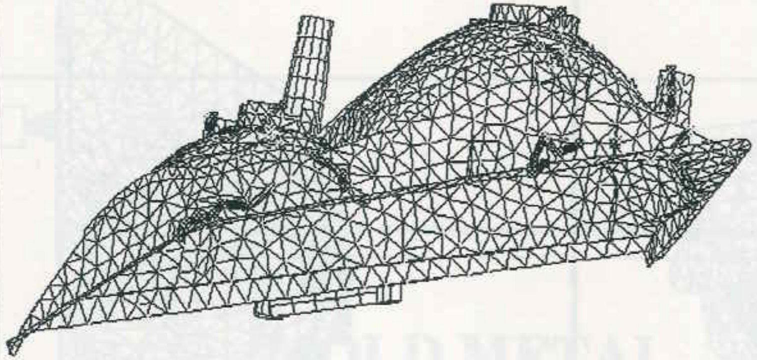
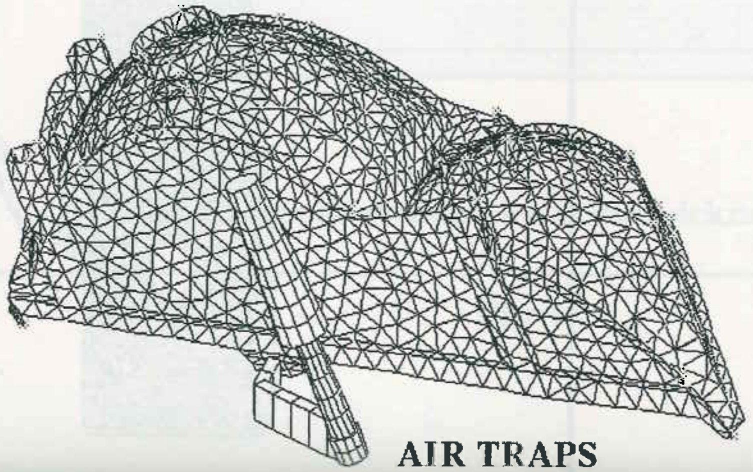


Figure 3

MOLDFLOW MF/TSET



WELD LINES



AIR TRAPS

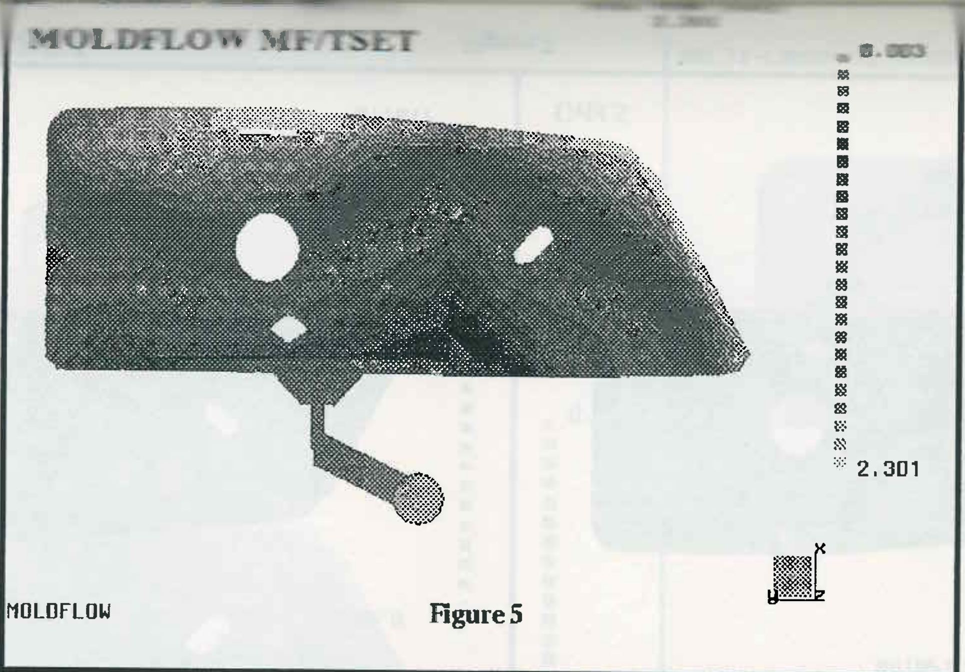


Figure 5

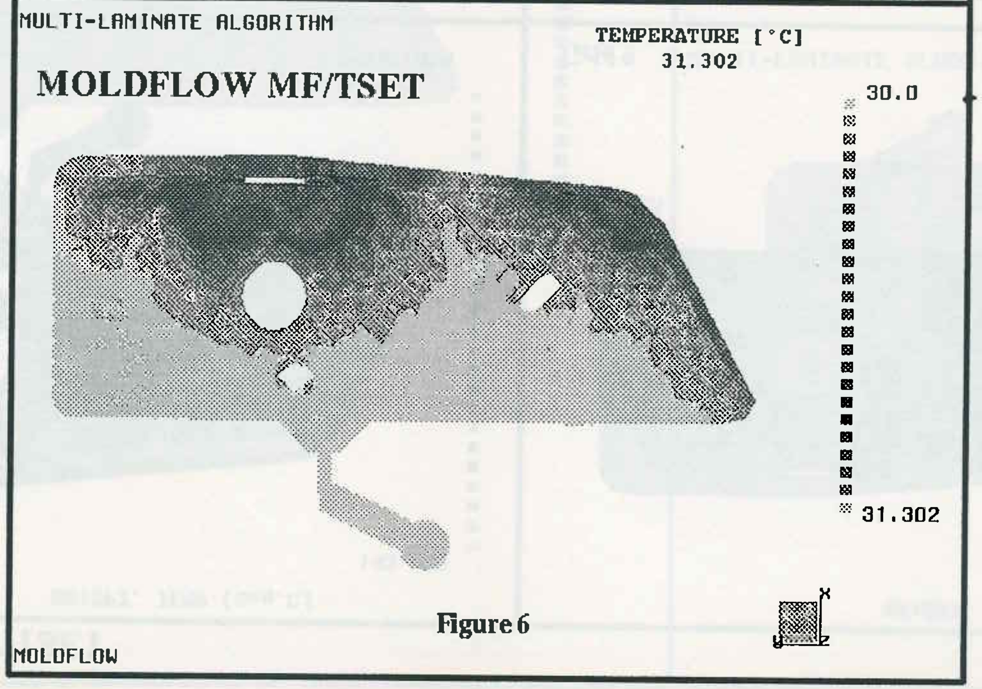


Figure 6

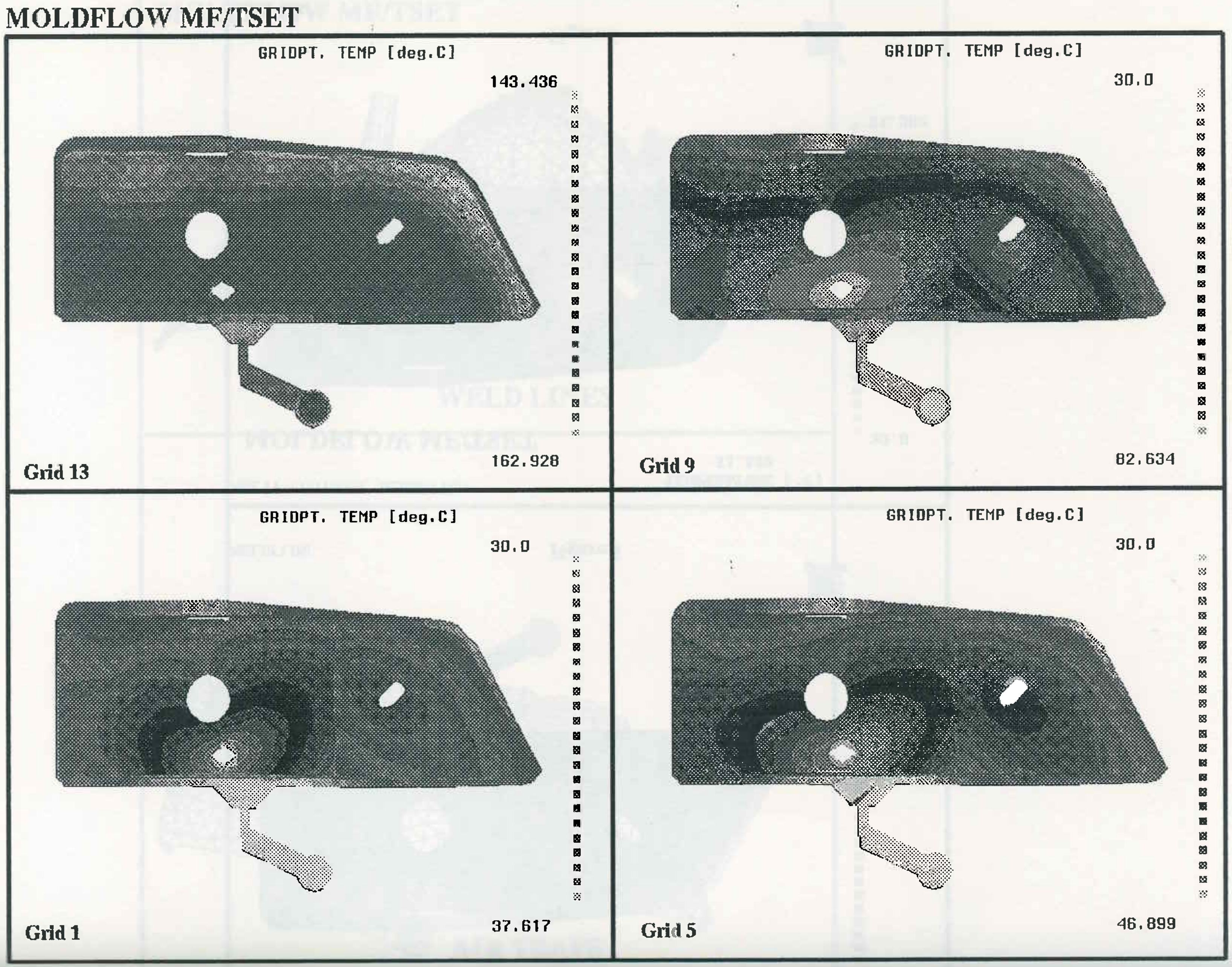

MOLDFLOW MF/TSET
GRIDPT. TEMP [deg.C]
143.436
162.928
Grid 13
GRIDPT. TEMP [deg.C]
30.0
82.634
Grid 9
GRIDPT. TEMP [deg.C]
30.0
37.617
Grid 1
GRIDPT. TEMP [deg.C]
30.0
46.899
Grid 5

Figure 7

Grid 1	37.617	Grid 5	46.899

Figure 7

MOLDFLOW MF/TSET

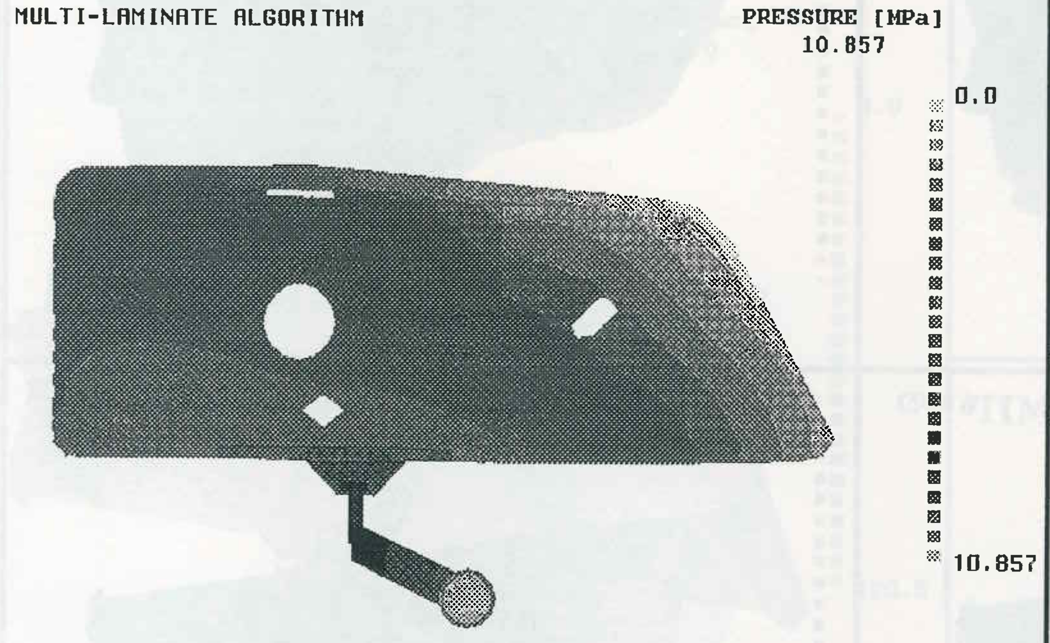


Figure 8

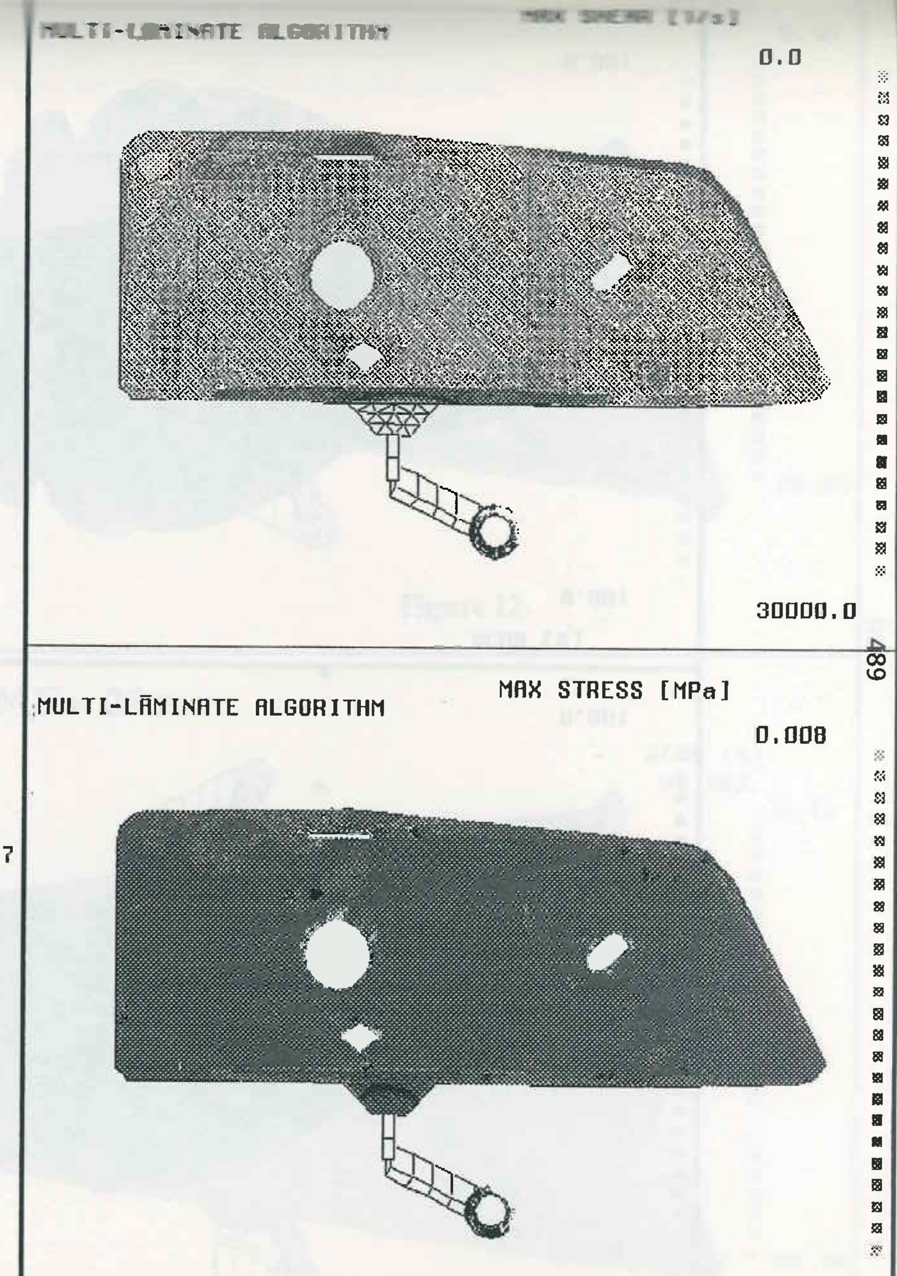
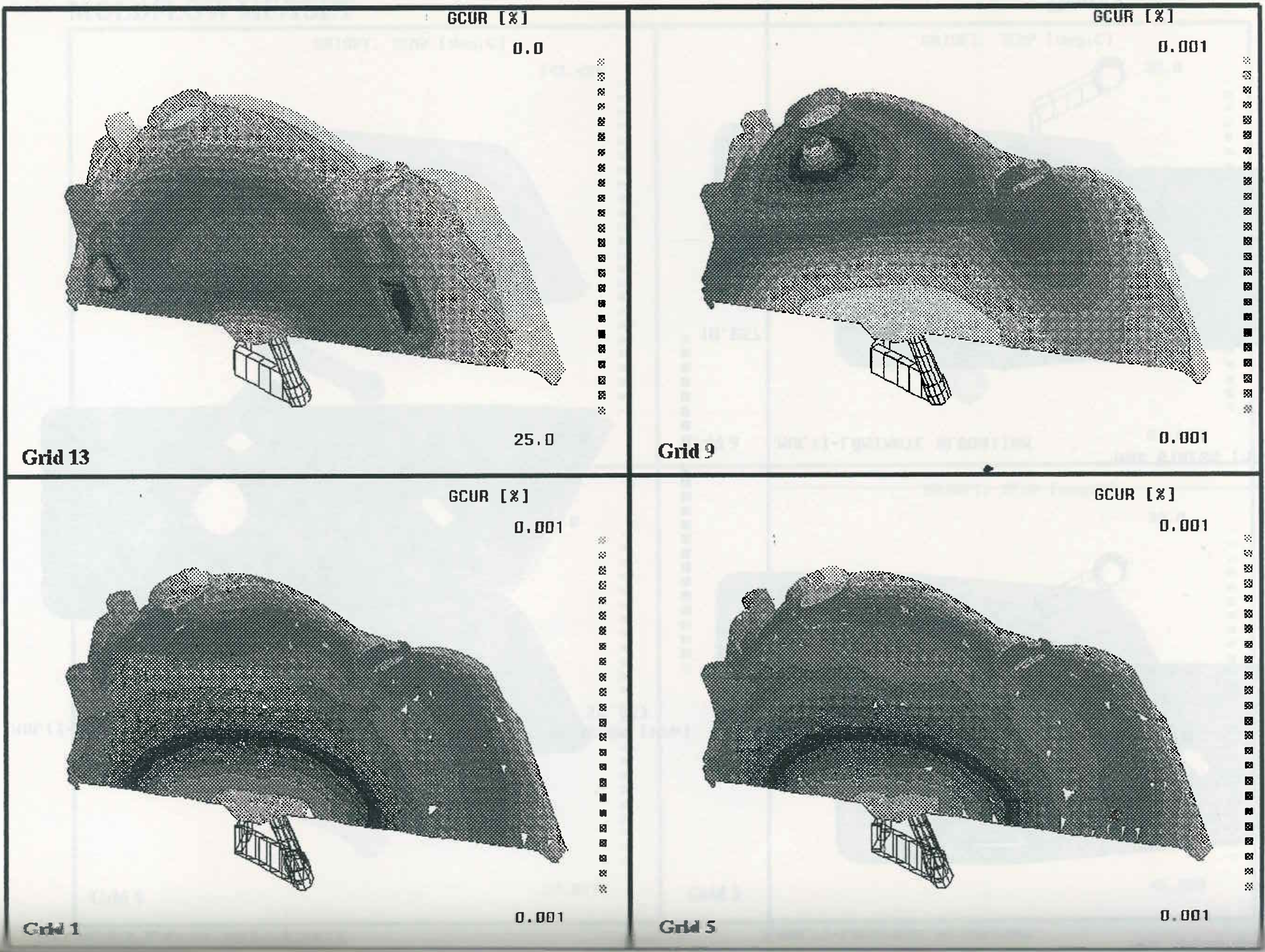


Figure 9

MOLDFLOW MF/TSET



Grid 1

Grid 5

MOLDFLOW MF/TSET

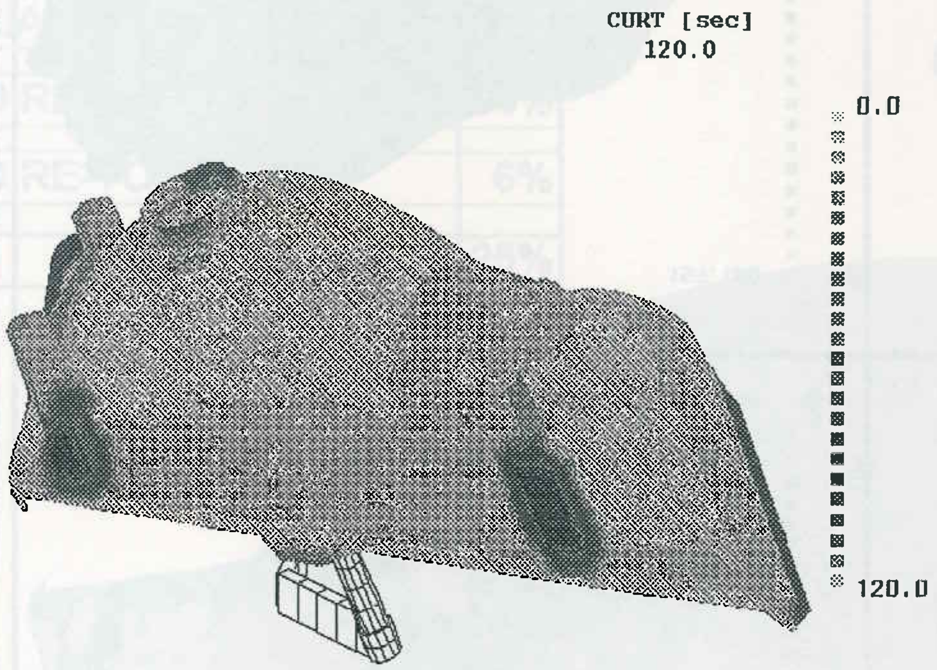


Figure 11

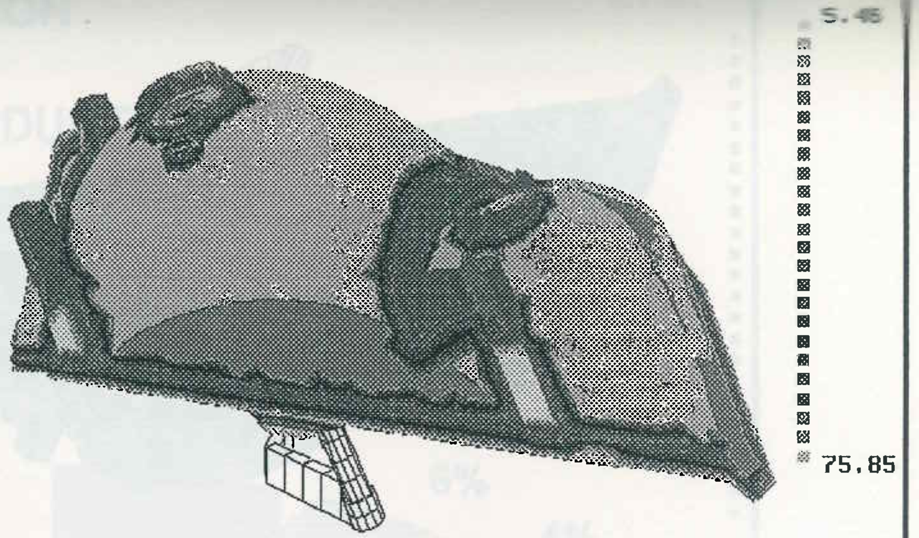


Figure 12

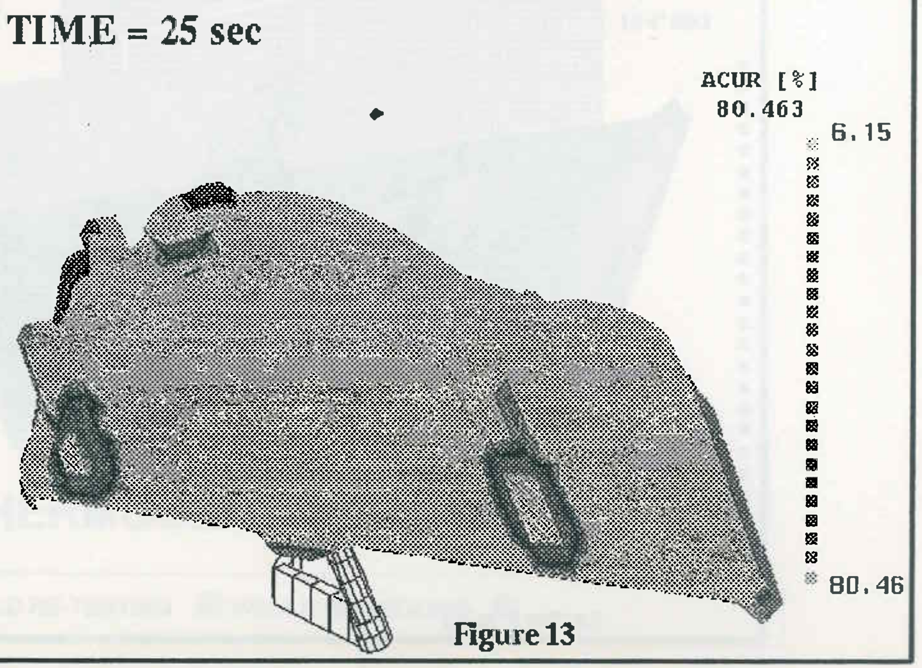
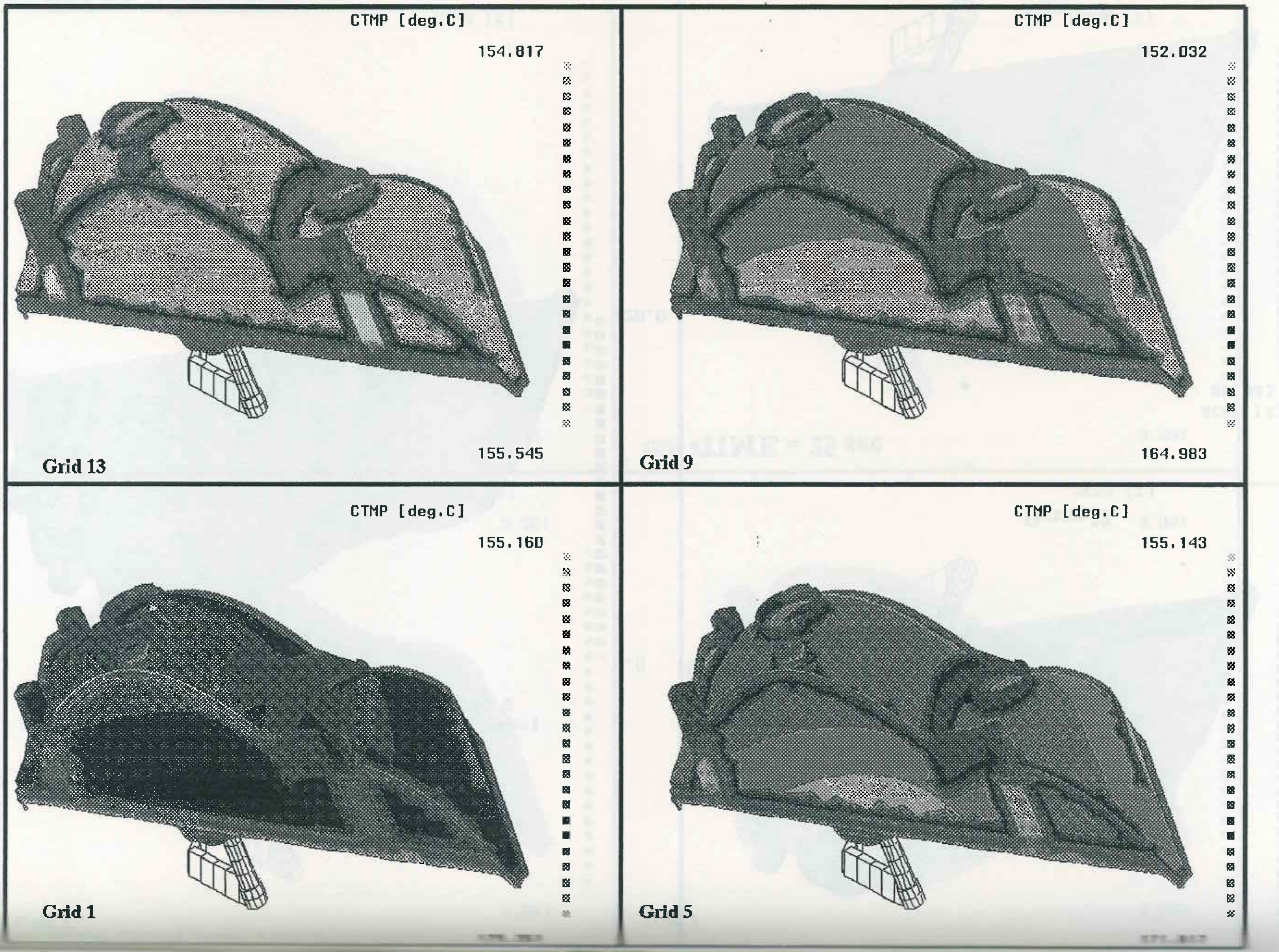


Figure 13

MOLDFLOW MF/TSET



NUMERICAL SIMULATION

AVERAGE SAVINGS ON PRODUCTION

NUMERICAL SIMULATION

AVERAGE SAVINGS ON PRODUCTION

CYCLE TIME	9%
MATERIAL	6%
MOULD RE-TESTING	4%
MOULD RE-TOOLING	6%
TOTAL	25%

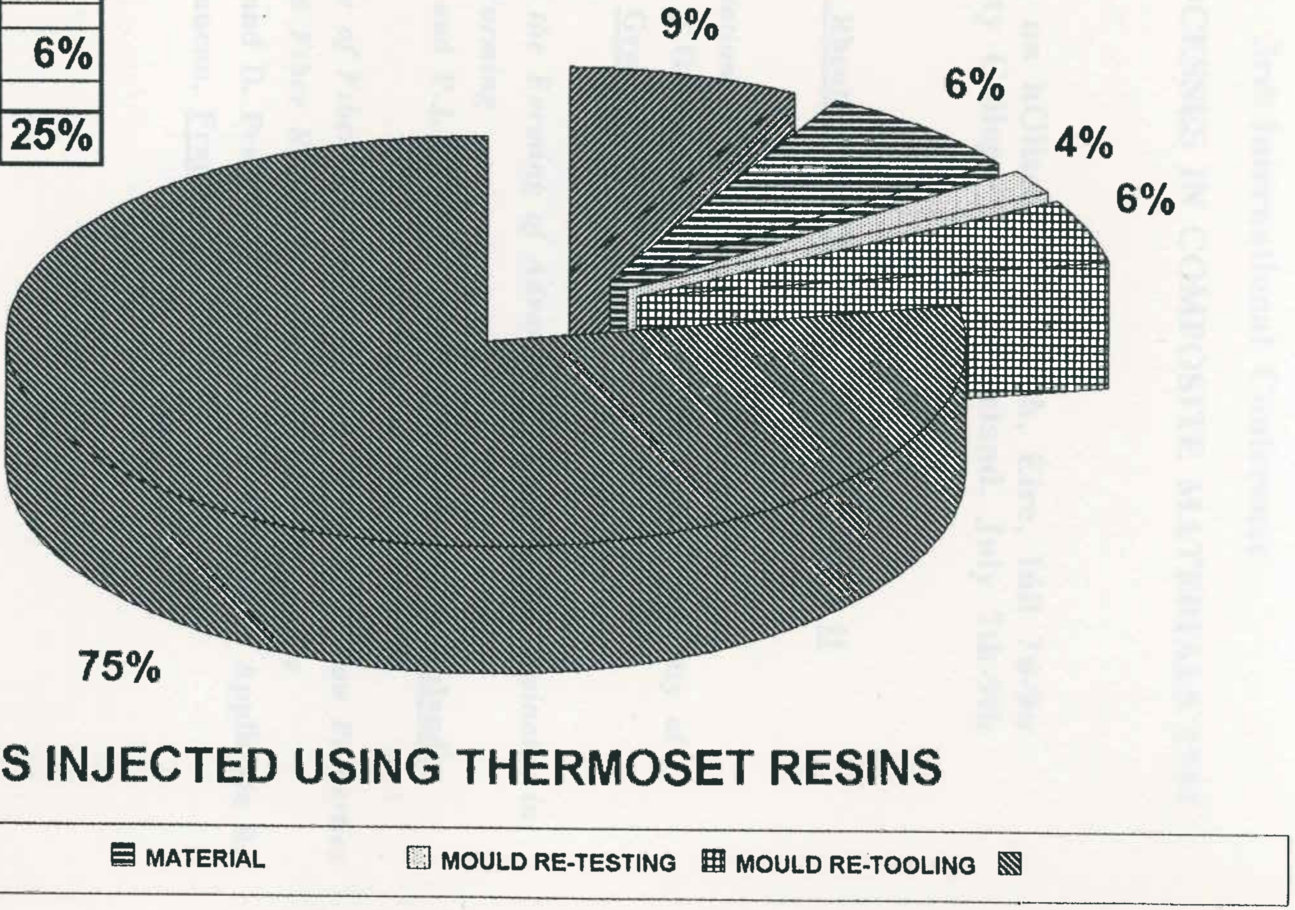


Figure 15