

SPECIFICATION OF PRESSURE-VOLUME-TEMPERATURE (PVT) MEASUREMENTS RELEVANT TO INDUSTRIAL POLYMER PROCESSING

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ABSTRACT

The critical parameters which control shrinkage and warpage in moulded parts have been identified from a series of systematic studies which involved a literature search, consultation meetings, industrial visits and a process simulation analysis on injection moulded parts using Moldflow software. These investigations were aimed to enable NPL to specify the ranges of all key parameters and to assess how industrially relevant PVT data could help to make commercial software more reliable, thereby benefiting the polymer processing industry. The potential of the currently available PVT measurement techniques to meet this challenge has been reviewed.

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
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1. INTRODUCTION

Shrinkage, warpage and sink marks are important problems of plastic injection moulded products. Thermally induced volume shrinkage of the part during cooling, residual flow, thermal stresses produced during filling and packing phases have been related to these defects (1,2). For an injection moulder to take on premium work requiring tight tolerances with increased confidence and reduced scrap rates, an improved understanding of the shrinkage and warpage behaviour in plastic components may be required. The ability to predict behaviour accurately can be expected to provide the moulder with the benefits of reduced cycle times, reduced time to market and reduced scrap rates with consequent commercial benefits.

Commercial software packages, such as Moldflow, C-Mold etc. are available which have the capability of predicting the shrinkage and warpage behaviour in plastic components to a large extent. However, accurate prediction is only possible when good quality credible data relevant to industrial processing conditions are available. This is particularly important for a moulder launching new products to ensure mould design is right first time. In addition, he should also be able to select correct processing conditions and modify the choice of polymer with ease each time his requirement changes. As injection moulding is a rapid, high pressure process, there is a requirement for accurate data for the software packages which evaluate the relationship between pressure, volume and temperature (i.e. PVT) behaviour of polymers at high pressures and at high cooling rates. Until recently most of the experimental PVT data in the literature are reported either in equilibrium state (3-6) or at very slow (maximum 10°C/min) cooling rates (7, 8). The National Physical Laboratory (NPL) in the UK have recently developed (jointly with SWO Polymertechnic) PVT equipment which is capable of providing PVT data at high cooling rates (up to 250°C/min) and at high pressure (up to 250 MPa) on thin samples bringing the measurement close to industrial processing conditions (9). A recent report from C-Mold has described a new methodology in their computer simulation software by which shrinkage and warpage predictions are claimed to within 10% of measured values using data obtained indirectly from Differential Scanning Calorimetry (DSC) (10) and slow cooling PVT work.

The purpose of this report is to identify those critical parameters which control shrinkage and warpage in moulded parts from a series of systematic studies which involved a literature search, a number of consultation meetings and visits to moulders, material suppliers and software companies and a short process simulation analysis on injection moulded parts using a commercial software package (Moldflow). It was anticipated that these investigations would enable NPL to specify the ranges of all key parameters and to assess how industrially relevant PVT data could help to make commercial software more reliable, thereby benefiting the polymer processing industry. The potential of the currently available PVT measurement techniques to meet this challenge has been reviewed.

2. PVT MEASUREMENT

The degree of crystallinity in polymers depends on the rate of cooling, molecular structure, shear and pressure history, presence of nucleating agents etc. Properties of semi-crystalline polymers are particularly sensitive to the rate of cooling. Under fast cooling rates, the transition to the crystalline phase occurs at lower temperatures (a downward shift of ~100°C in transition temperature due to fast cooling in PA66 has been reported in ref. 10). The degree of change from slow cooling rates to fast cooling rates depends on the molecular structure; the degree to which the material shrinks is also affected due to the change in density. Changes induced by crystallisation, in particular, have been found to significantly influence shrinkage and warpage values. Several other factors such as visco-elastic behaviour of polymers, variable mould temperature profile due to non-uniform cooling, molecular and fibre orientations etc. also contribute directly to actual shrinkage and warpage values in moulded parts (Figs. 1 and 2).

Pressure is known to induce molecular order and hence shift polymer melting points (T_m), crystallisation temperatures (T_{crys}) or glass transition temperatures (T_g) to higher temperatures (Figs. 3 and 4). It is therefore, important to understand the pressure dependence of T_m , T_{crys} and T_g from both practical (i.e. material structure and property relationships) and theoretical (i.e. free volume, compressibility effects) viewpoints (2, 11).

Cooling rate plays a critical role in polymer processing because materials experience rapid cooling when transferring from the melt to the solid state (Figs. 5-7). Like pressure, cooling rates also influence the parameters (T_{crys} and T_g) but in this case, their positions are shifted to lower temperatures (Figs. 5 and 6). Since most PVT data on polymeric materials are available under equilibrium state or low cooling rates, there is need to introduce fast cooling rate effects into both PVT measurements and modelling equations. Attempts have been made to incorporate this parameter in a modified time dependent Tait equation (1,8) which until now had been representing volumetric dependence of polymers as a function of temperature and pressure but not the cooling rate. Since the cooling rate affects the crystal nucleation and growth processes, the final properties of polymeric products are also affected beyond the forming stage (8). For example, in PEEK (Poly Ether Ether Ketone) based composites, cooling rates greater than 700°C/min can quench the polymeric matrix to the amorphous state while cooling rates in the order of 200°C/min can prevent crystallisation for PPS (Poly Phenylene Sulphide) composites (12). A macrokinetic model of crystallisation behaviour has been proposed by these workers which is capable of describing crystallisation changes in isothermal and non-isothermal conditions including cold and melt crystallisation and quenching effects. The model is applied to develop multiple entry crystallinity - time- temperature plots for isothermal (TTT) and non-isothermal (CCT) processing conditions (Fig. 7).

3. PVT EQUIPMENT

Several PVT measurement techniques have been reported in the literature (13-35). Most of the PVT data were, however, obtained under equilibrium steady-state conditions (typical plots are shown in Fig. 8). A list of all commercial PVT equipment which work on different measurement principles is given below. The pioneering work of IKV on cooling rate dependant PVT measurements (and later continued at SWO Polymertecnic) (36-43) lead to the development of the present SWO PVT100 commercial equipment. Chang and co-workers (8) have recently used this equipment to present their cooling rate dependent PVT experimental data up to 10°C/min with the predicted PVT plots for cooling rates up to 40°C/min (Fig. 5). However, the NPL/SWO developed modified PVT100 equipment (Fig. 9) is regarded to be the only one of its kind in the world that is capable of operating at high cooling rates (up to 250°C/min) and high pressures (up to 250 MPa) including the facility for testing thin samples (thickness 2mm) bringing the size close to injection moulded part thickness.

- | | | | |
|---|----------------------------------|-----------|--------------------------|
| • PVT : direct measurement | - (SWO, refs. 40-43) | - | commercially available |
| „ | - Lundin et.al (ref. 28) | | |
| • PVT : confining fluid | - (Gnomix, refs. 3, 13-17) | - | commercially available |
| „ | - Rapra Technology (refs. 25-27) | - | „ |
| • Micro- PVT : | (C.M.S Vniigaz Ltd.) | - ref. 34 | - commercially available |
| • PDT : | - University of Manchester, UK | - ref. 35 | |
| (Pressure-Density-Temperature) measurement (results are shown in Fig. 10) | | | |

The current PVT measurement capability in the UK is rather limited. Most of the literature published in the PVT area are from Japan, USA or continental Europe. Three establishments which are known to have the PVT measurement capabilities in the U.K. in addition to NPL are: Rapra Technology (PVT), UMIST (PDT) and NEL (Micro-PVT). In addition, one U.K. equipment manufacturer reported their ability in the past to incorporate the PVT measurement facility in their standard capillary rheometers (e.g. Rosand Precision Ltd). Other companies in the U.K. have shown considerable amount of interest to incorporate PVT measurement as an additional facility in their rheometers (e.g. Magna Projects and Instruments Ltd., Fleming Polymer Testing and Consultancy).

Experimental PVT data (at equilibrium state) for more than 100 polymer melts are available from the database in ref. 4. Other sources for obtaining steady state PVT data are: the CAMPUS database (website: <http://www.campusplastics.com>), the Moldflow database (website: <http://www.moldflow.com/>) and refs. 3, 5, 6 and 7. An ISO standard on the PVT measurement (direct method) at slow cooling rate is currently in the draft form.

4. INDUSTRIAL REQUIREMENTS

A survey of industrial requirements was carried out in July 1999 at the new DTI programme launch meeting at BPTA, Telford where representatives of the UK plastics industry were asked to specify the range of key parameters for improved PVT measurements for polymer processing. A sample copy of the questionnaire is shown in Annex - 1. Analysed results from this survey are given below :

<u>Key Parameters</u>	<u>Specified Range</u>
Product thickness (range) :	0.5 mm to 12mm
Shot weight (range) :	10g to 300g
Melt temperature (range) :	150°C to 300°C
Ejection temperature (range) :	40°C to 70°C
Time in mould (range) :	6s to 60s
Estimated cooling rate (range)	1°C/s to 20°C/s
Pressure (range) :	300 bar to 2000 bar

The main point that emerged from 21 returns of the questionnaire, was that nearly all (>95%) believed that the PVT data are either important or likely to be important to their companies. About 60% of the respondents either process or supply semi-crystalline materials, the rest (40%) are involved with amorphous materials. 30% of the respondents use (or have used) at least one process simulation software and an additional 20% would consider using a commercial software package in the future. Only 20% of the plastics processors currently have access to a PVT measurement facility.

5. SPECIFICATION

In order to be able to specify ranges of pressure, volume and temperature used in the industry three main tasks were undertaken :

- 1) to study published literature of the past 25 years on PVT measurement.
- 2) to consult industry, visit moulders and collect information on current industrial requirements.
- 3) to use process simulation packages such as Moldflow, a) to demonstrate the changes in shrinkage and warpage values in injection moulded components due to variations in the cooling rate, pressure and temperature during processing and b) to investigate the resultant changes in temperature and pressure distributions, cooling time and tolerance levels in moulded parts.

The completion of the first two tasks confirmed the required specification of industrially relevant PVT measurements as initially provided by the moulders (see the list above in Section 4). In the course of this process visits were made to four moulders and one software manufacturer (where a technical presentation was also made), consultation meetings were held at NPL with companies from the material supply, moulding and software sectors. Both software companies (Moldflow and C-Mold) have now offered free use of their software to NPL for this work which indicated their interest in improving currently available PVT data and the drive for upgrading major commercial prediction packages currently supporting the polymer processing sector.

The published literature contained very little information on time dependant PVT properties, cooling rate and temperature distribution in components of different sizes or on part tolerances which are specified and obtained. Yang and Ke (2) showed pressure-time traces and thermo-mechanical history in a PVT diagram (Fig. 4). They also presented experimental warpage and shrinkage data as a function of cavity pressure (Fig. 4). The results of a detailed study by Chang and Tsaur (1) on shrinkage and warpage behaviour in semi-crystalline injection moulded parts are given in Figs. 1 and 2.

An investigation by C-Mold (10) specified a maximum tolerance of $\sim 2.8\%$ in the transverse direction and $\sim 0.7\%$ in the longitudinal direction in a plaque mould. Both experimental values and the prediction values came fairly close to their specified limits.

In the present study, the effects of a number of industrial process parameters on two injection moulded components (a hub cap and a butter dish) have been studied using Moldflow software (Figs. 11-16). It was anticipated that this investigation would highlight those critical PVT parameters which control shrinkage and warpage in moulded parts. This insight should enable NPL to produce a suitable specification for PVT measurements within a range of key parameters relevant to industrial polymer processing conditions. The nominal thickness of the two selected components are shown in Fig. 11. The hubcap is generally of 5mm uniform thickness with a diameter of 410mm; the butter dish, on the other hand, varies in thickness between 1.5mm to 3mm (see Fig. 11) with an overall dimension of 220 x 90 x 90mm.

The temperature and pressure distributions at four different nodes on the hub cap and the butter dish during a typical injection moulding run are shown in Figs. 12a-e and 13a-e as a function of industrial cooling time. Maximum cooling of $220^{\circ}\text{C}/\text{min}$ is attained after the first 20s (Figs. 12b, 12c, 13b and 13c) in the cooling cycle (commencing immediately after the packing phase). A surface temperature gradient of $\sim 1^{\circ}\text{C}/\text{mm}$ (Figs. 13a and 13c) in parts of the butter dish was noticed in the first 20s. On the other hand, a pressure difference of $\sim 7\text{MPa}$ between nodes 281 and 317 (a distance of $\sim 100\text{mm}$) was noticed in the first 60s in the hub cap (Figs. 12a and 12e). These examples confirmed the ranges of industrial pressures and melt temperatures suggested by the moulders in Section 4. Maximum cooling rates were deduced to be $\sim 500^{\circ}\text{C}/\text{min}$ (average $180^{\circ}\text{C}/\text{min}$) for the butter dish and $\sim 220^{\circ}\text{C}/\text{min}$ (average $150^{\circ}\text{C}/\text{min}$) for the hub cap in the first 20s.

The investigation was continued to determine the effects of cooling rate on the volumetric shrinkage and deflection (warpage) in both components (Figs. 14a-14d). The relationship between shrinkage and warpage in the Moldflow analysis is described in Annex-2. In all cases, the changes were observed at slow and high cooling rates ($10^{\circ}\text{C}/\text{min}$ and $250^{\circ}\text{C}/\text{min}$) as compared to normal industrial cooling rates ($257^{\circ}\text{C}/\text{min}$ for the hub cap and $370^{\circ}\text{C}/\text{min}$ for the butter dish). The high cooling rate represents the condition which can be repeated in the NPL/SWO PVT apparatus. The cooling rates produced a volume shrinkage of $\sim 1.5\%$ (in slow cooling rate) and $\sim 4\%$ (in both high and industrial cooling rates) in the hubcap and an overall 2-4% (in slow cooling rate) and an overall 4-6% (in both high and industrial cooling rates) in the butter dish. The cooling rates also contributed to warpage of the components which are presented as deflection values in Figs. 14c and 14d. In the hubcap, the deflections were in the range 0.5 to 2.3mm (for slow cooling rate) and 0.5 to 4mm (for high and industrial cooling rates), whereas in the butter dish the deflections varied between 0.5 to 1.5mm (overall) and between 0.3 to 0.6mm (on a given

surface) at slow cooling rate and between 0.2 to 2.6mm (overall) and between 0.3 to 1.0mm (on a given surface) at high and industrial cooling rates. The pressure distributions in both components were also studied as a function of cooling rates (Figs. 14e-14f). In the hub cap, the pressure varied around the centre in all cooling conditions to the extent of 2-10MPa at slow cooling rate and between 2-5 MPa at high and industrial cooling rates. The butter dish, on the other hand, showed an uniform pressure of ~4MPa in all surfaces under both slow and high cooling rates (Fig.14f). It appeared that the software contains a certain thresh hold value in the cooling rate ($> 250^{\circ}\text{C}/\text{min}$) below which no change would be noticeable. A difference in the pressure of 15 MPa around the bottom centre in the butter dish became noticeable when a cooling rate value of $370^{\circ}\text{C}/\text{min}$ was used. The reason for such an observation (see Figs. 14b and 14d also) is unclear. One reason could be due to the fact that, full utilisation of the high cooling rate effects has not been made yet, in the Moldflow analysis. The effects of cooling rate on the moulded components' shrinkage, warpage, temperature and pressure distributions are nevertheless reasonably clear. The extent by which the slow and high cooling rates differ in controlling the above parameters is also significant.

The effect of pressure on volumetric shrinkage in both components are shown in Figs. 15a-15b under normal industrial cooling conditions. As expected, the high pressure (100 MPa) resulted in a lower shrinkage value of ~2% as compared to a shrinkage value of ~5% at low pressure (30 MPa) in the hub cap. The shrinkage distribution in the butter dish, on the other hand, is complex since the part thickness varies and is relatively small ($<2\text{mm}$ in most areas). At low pressure (40 MPa), the shrinkage in the butter dish (Fig. 15b) was found to vary in the range 1.5% to 4%, as compared to the value in the range 4% to 6.5% at high pressure (100 MPa).

The effects of melt temperature on cooling time distribution were studied at three temperatures: 170°C , 240°C (industrial value) and 300°C (Figs. 16a-16b). The average cooling rates for this exercise were $160^{\circ}\text{C}/\text{min}$ (the hubcap) and $370^{\circ}\text{C}/\text{min}$ (the butter dish) at 170°C and $220^{\circ}\text{C}/\text{min}$ (the hub cap) and $580^{\circ}\text{C}/\text{min}$ (the butter dish) at 300°C . As expected, the cooling time increased with rise in the melt temperature. For the hub cap (Fig. 16a), the cooling time varied steadily with temperature between 20s to 65s, while in the butter dish (Fig. 16b), because of the thickness variation, the cooling time varied differently on different surfaces in the range 4s to 24s.

6. CONCLUSIONS

The Moldflow analysis confirmed the belief, generally held by the moulders, that the cooling rate and pressure are the two critical control parameters which have the greatest effect on the shrinkage and warpage values in injection moulded parts. The two other parameters which have significant influences are the melt temperature and the part thickness. PVT data can now be obtained at industrially meaningful pressures and cooling rates.

The Moldflow analysis also indicated that such PVT data are important for predicting component shrinkage and warpage reliably. The analysis did not appear to take full account of the high cooling rate effects, as yet and hence, the results were not always conclusive. The analysis was nevertheless largely successful in differentiating between slow and fast cooling rates (shrinkage and warpage values vary by a factor of 3), between high and low pressure runs (shrinkage varies by a factor of 2) and between low and high temperature runs (~50% variation in cooling time) in two moulded parts of different volumes. The surface temperature and pressure differences with cooling time were found to be $\sim 1^{\circ}\text{C}/\text{mm}$ and $\sim 7\text{MPa}$ respectively. The levels of tolerance in the parts due to shrinkage and warpage were determined to be: shrinkage 2-3% due to cooling rate variations, 1-2% due to pressure variations; warpage 1-2% due to cooling rate variations.

It is concluded from all three studies in Section 5, that four key parameters are important for reliable prediction of shrinkage and warpage by commercial software packages. These are: cooling rate, pressure, melt temperature and the product thickness (i.e. volume of the material). PVT is a measurement method

which is now capable of providing the required materials data close to industrial ranges of cooling rate, pressure, melt temperature and thickness. Commercial software packages, however, currently do not fully utilise the high cooling rate data in their software. But since the high cooling rate PVT data are now experimentally possible, there is an industrial drive to make more use of these data in the commercial software. The NPL/SWO PVT apparatus is the only equipment of its kind which can deliver the required PVT data at conditions close to industrial processing situation (i.e. cooling rates up to 250°C/min, pressures up to 250 MPa, temperatures up to 420°C on 2mm sample thickness).

The studies made in Section 5, confirmed the industrial ranges of key parameters originally recommended by the UK injection moulders in Section 4. The specification for the PVT measurement which can meet present industrial need and can provide the required input data to the software companies is therefore :

RECOMMENDED SPECIFICATION :

<u>Key Parameters</u>	<u>Specified Range</u>	<u>NPL Capability</u>
Cooling rate :	1°C/s to 20°C/s	up to ~5°C/s
Pressure :	30 MPa to 200 MPa	30 MPa to 250 MPa
Melt temperature	150°C to 300°C	RT to 420°C
Product thickness	0.5 mm to 12mm	2mm to 7mm

7. ACKNOWLEDGEMENTS

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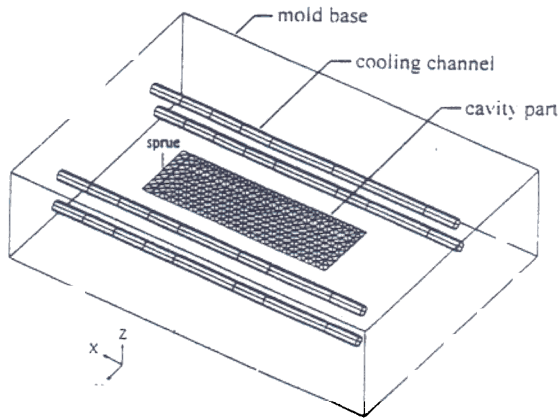
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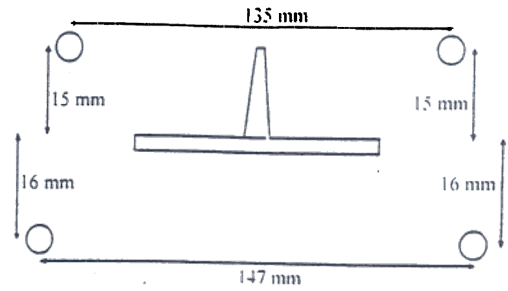
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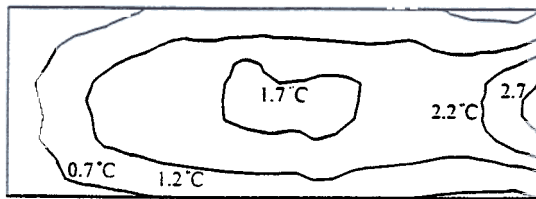
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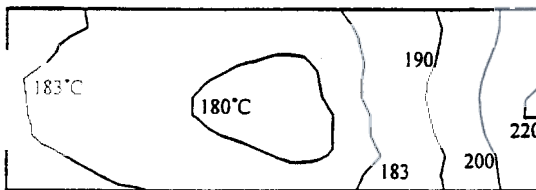
Geometrical shape of the part, mold, and cooling channel.



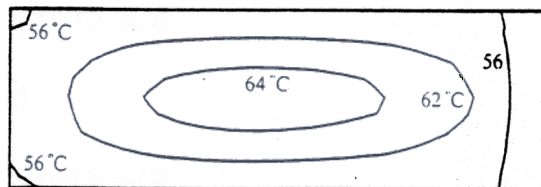
Geometrical shape of the part and cooling channel, the length of the cooling channels are all 300 mm.



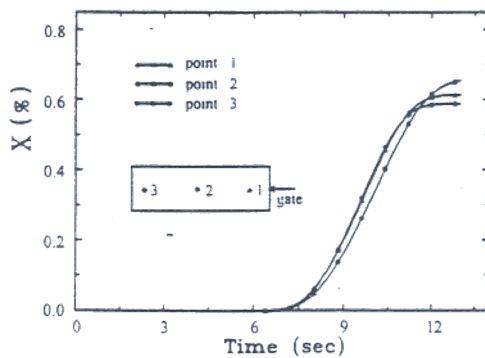
Temperature difference between the negative side mold temperature and the positive side mold temperature; the gate is at the right hand side of the part for PP.



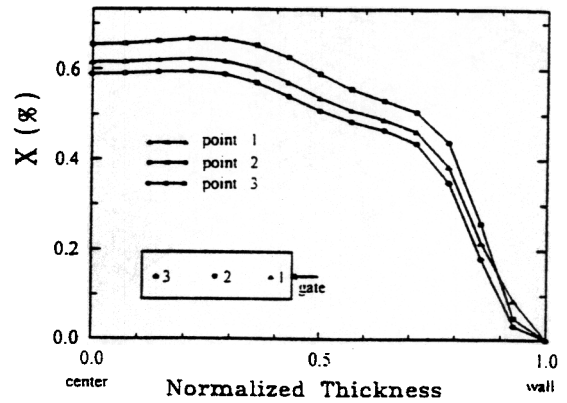
Temperature profile at the end of filling process (1 s); the gate is at the right hand side of the part for PP.



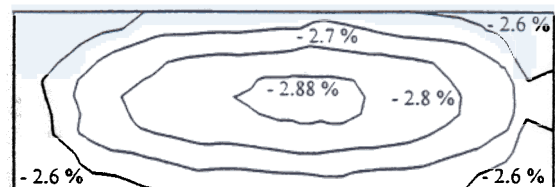
Temperature profile at the end of cooling process (14 s); the gate is at the right hand side of the part for PP.



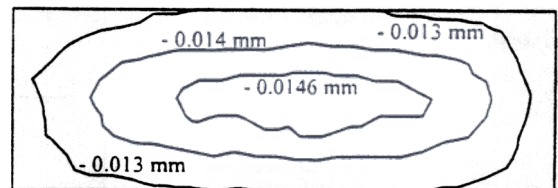
Relative crystallinity for PP of different points in the part vs. the processing time.



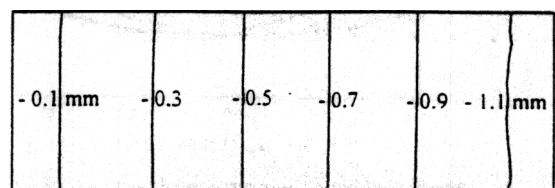
Distribution of relative crystallinity for PP in the thickness direction of different points in the part.



The diagram of the volume shrinkage distribution; the gate is at the right hand side of the part for PP.

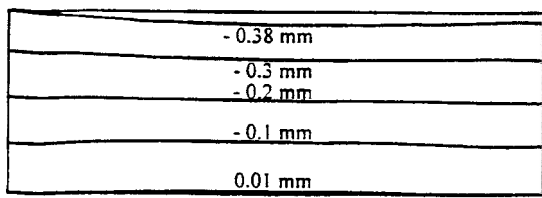


The amount of te depression profile at the part surface; the gate is at the right hand side of the part for PP.

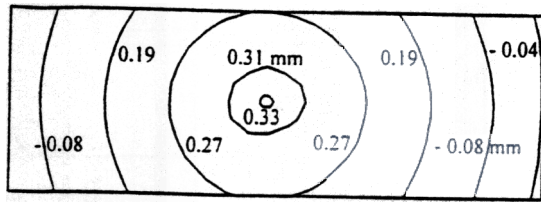


The x-displacement of the final part for PP; the gate is at the right hand side of the part.

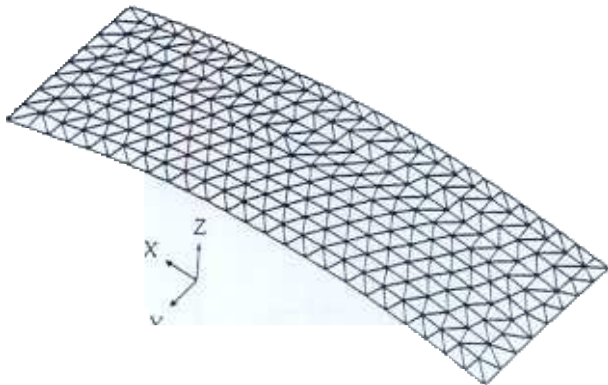
Fig. 1 (ref. 1)



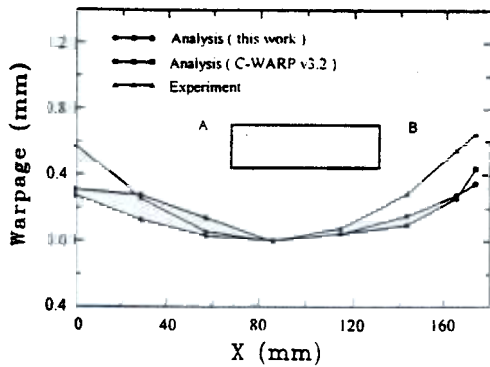
The y-displacement of the final part for PP; the gate is at the right hand side of the part.



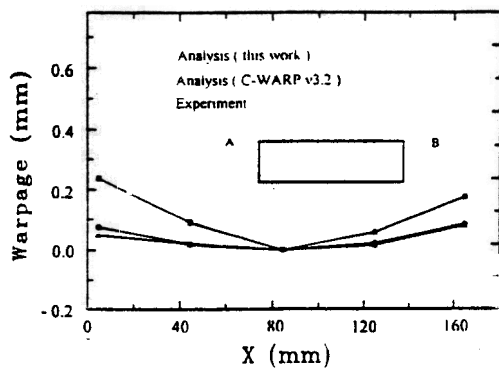
The z-displacement of the final part for PP; the gate is at the right hand side of the part.



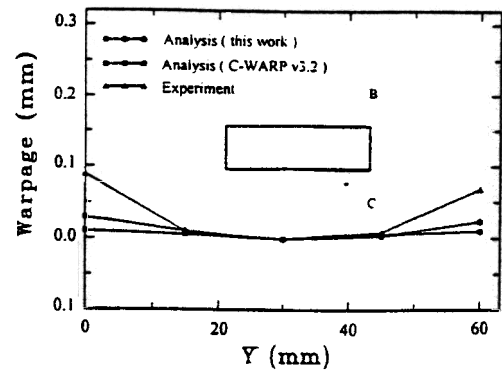
Mesh diagram of the final part for PP after deformed, exaggeration factor = 20.



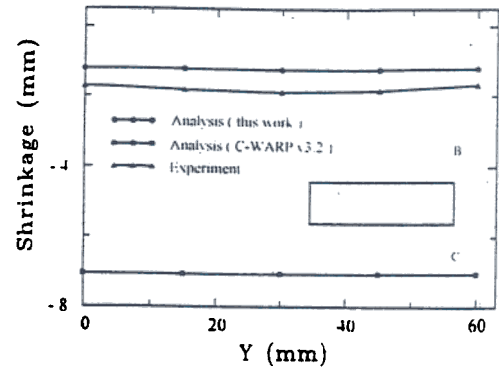
Analytical and experimental values of warpage (along AB) for PP.



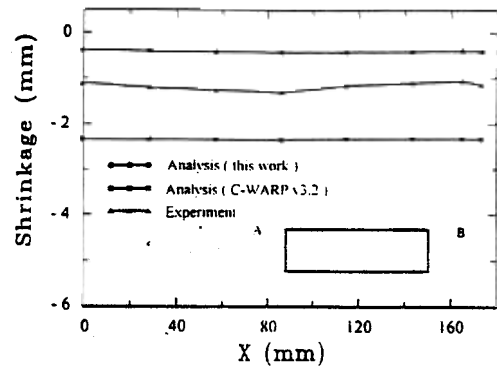
Analytical and experimental values of warpage (along AB) for ABS.



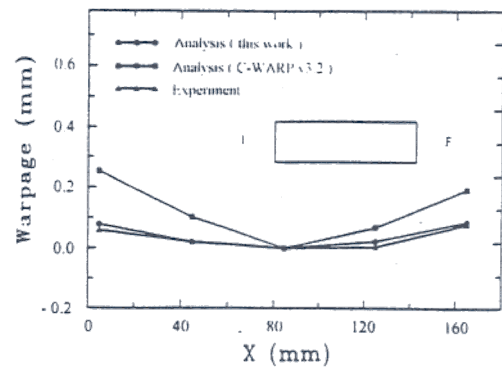
Analytical and experimental values of warpage (along BC) for PP.



Analytical and experimental values of shrinkage in length direction (along BC) for PP.

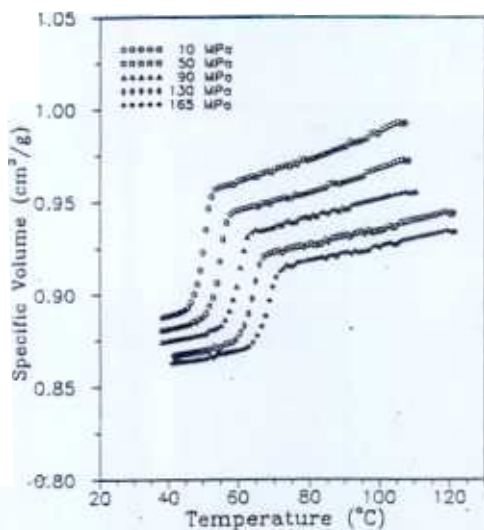


Analytical and experimental values of shrinkage in width direction (along AB) for PP.

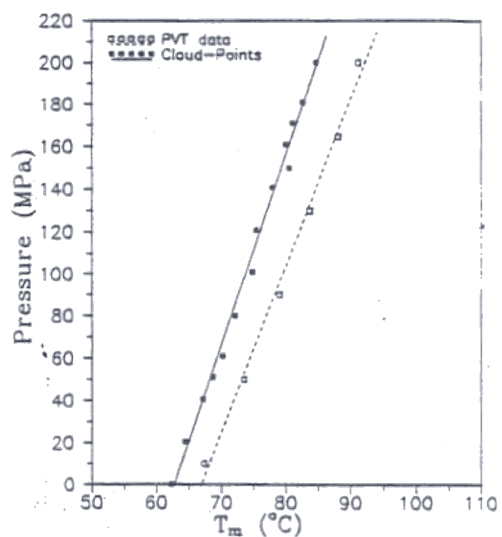


Analytical and experimental values of warpage (along EF) for ABS.

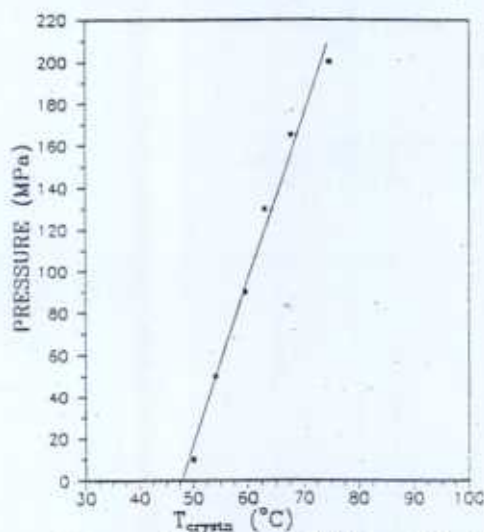
Fig. 2 (ref. 1)



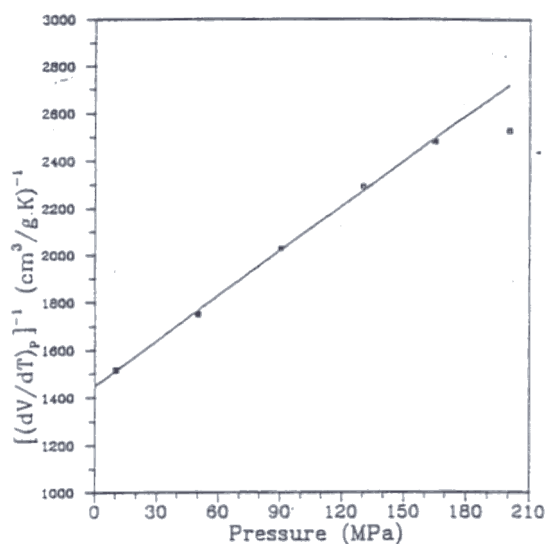
Isobaric crystallization of PEO at different pressures. Increasing pressures increase the crystallization temperatures.



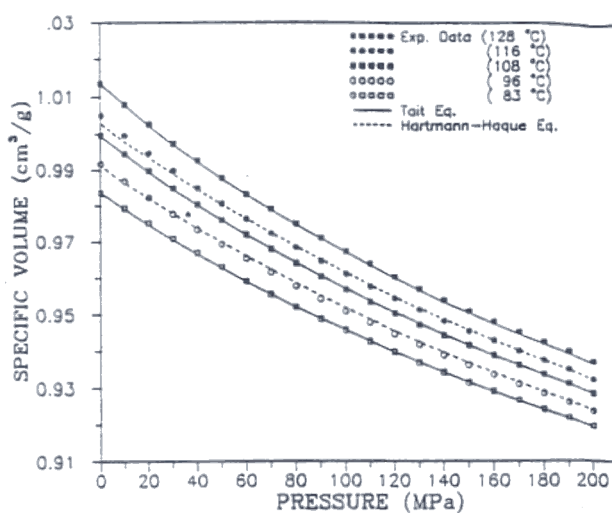
Pressure dependence of PEO melting points obtained from cloud-point and P - V - T measurements, respectively.



Pressure dependence of PEO crystallization temperature. Obtained from P - V - T measurements.

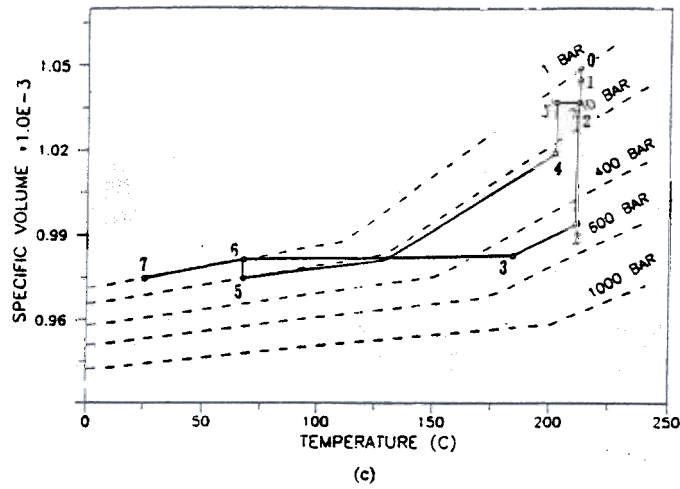
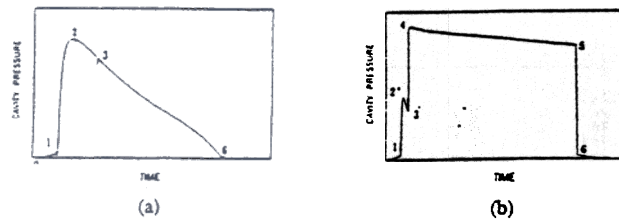


Variation of thermal expansivity with pressure.

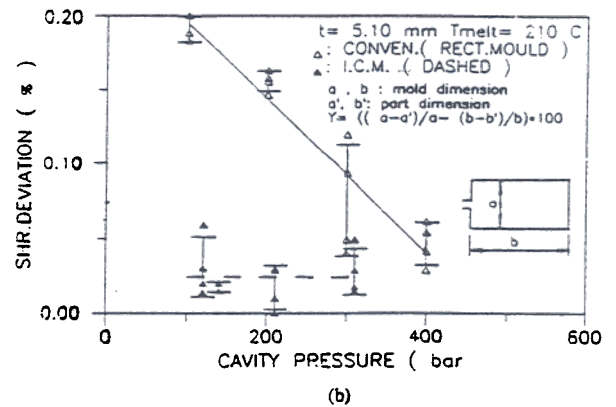
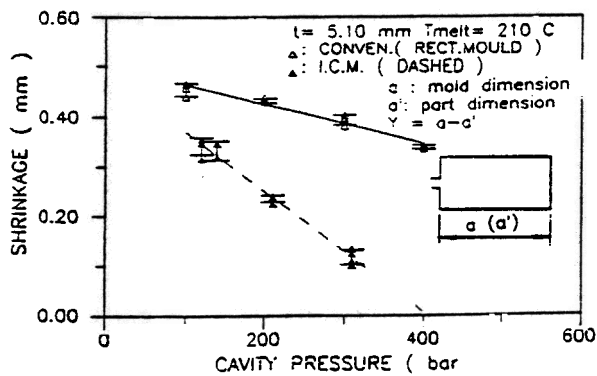
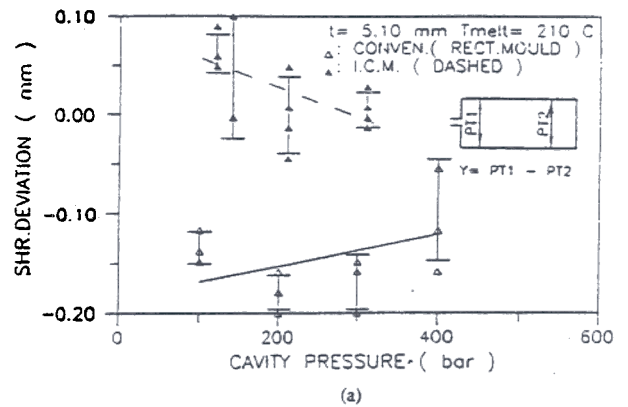
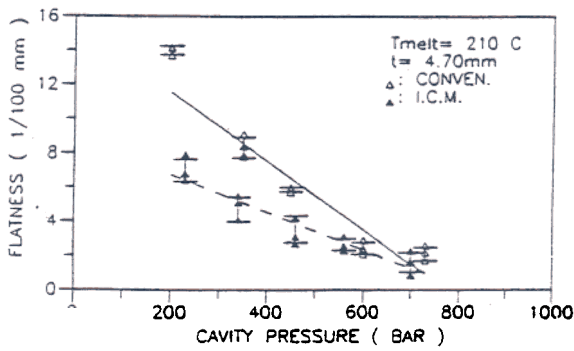


Isothermal compression of PEO melts at different temperatures (correlation with the Hartmann-Haque and Tait equations).

Fig. 3 (ref. 11)

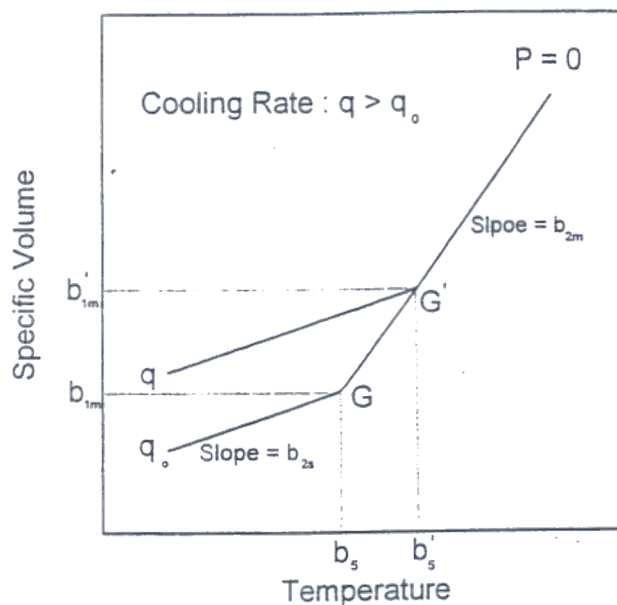


The pressure-time traces and thermalmechanical history in P-v-T diagram. (a) P-t during injection molding (b) p-t during injection compression molding (c) P-v-T history for both IM and ICM.

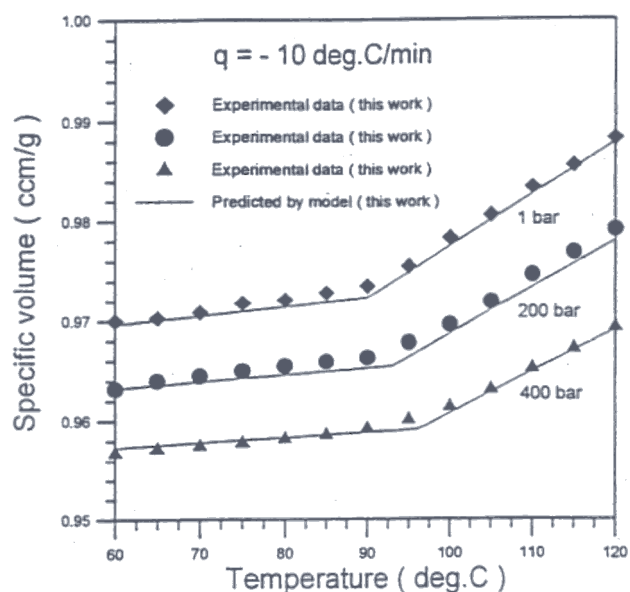


Comparison of positional and directional shrinkage variations for injection- and injection-compression-molded plaques. (a) up-stream and down-stream positions (b) along-flow and cross-flow directions

Fig. 4 (ref. 2)



Interpretation of the Tait equation parameters and the shift of the material parameters due to the cooling rate change from q_0 to q (schematically).



A comparison of the experimental data (this work) and the model-predicted results for PS (Chi-Mei PG-33) under a cooling rate of -10°C/min and three pressures of 1, 200, and 400 bars.

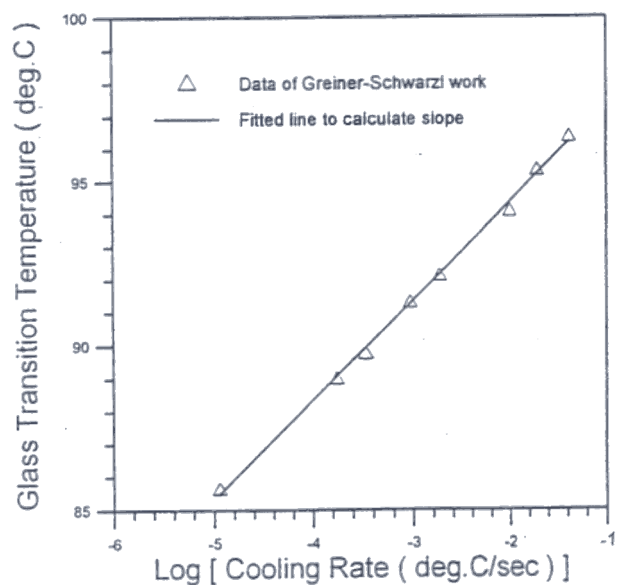
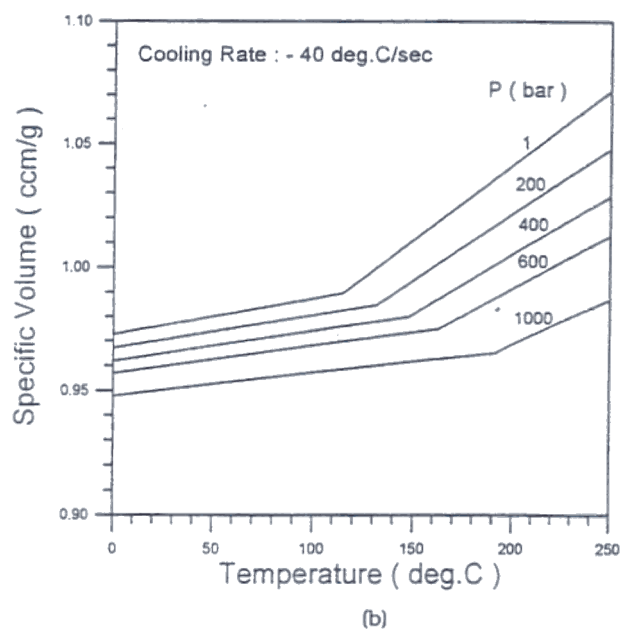
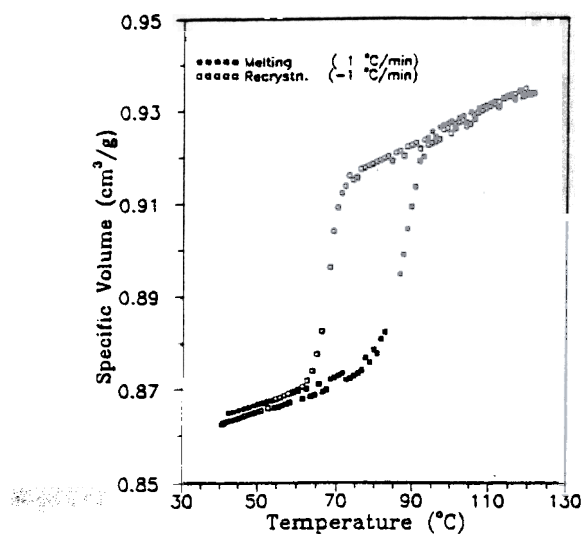


Diagram of the glass-transition temperature vs. cooling rate (log scale) for PS (Hoechst N7000) under atmospheric pressure (18).

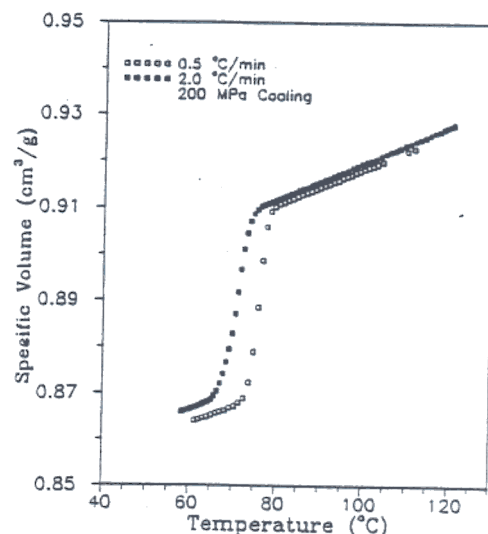


P - V - T behaviors of PS predicted by the proposed P - V - T model under a cooling rate of -40°C/s .

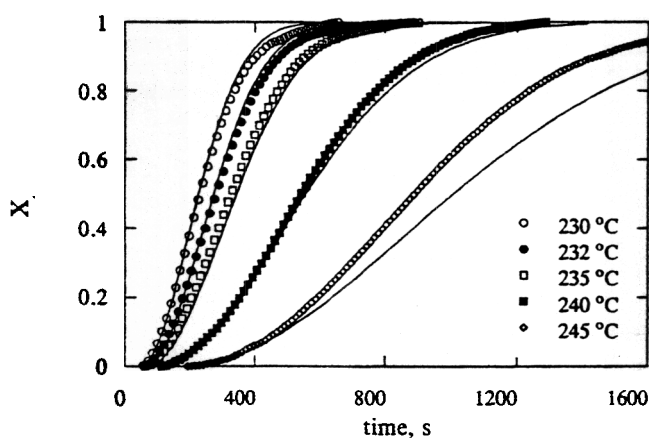
Fig. 5 (ref. 8)



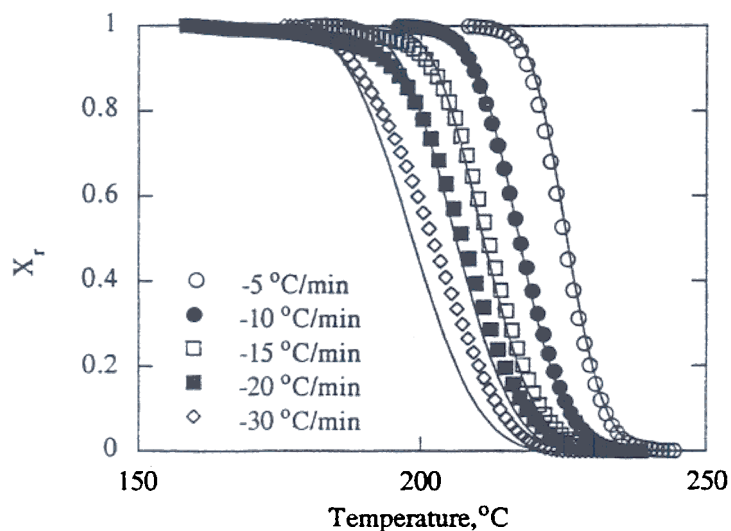
Comparison of PEO isobaric melting and crystallization at 165 MPa.



Effects of cooling rates on PEO isobaric crystallization behaviors (examples at 200 MPa).



Isothermal melt crystallization.
Experimental data (points) and theoretical predictions (line)



Crystallization at constant cooling rate.
Experimental data (points) and theoretical predictions (line)

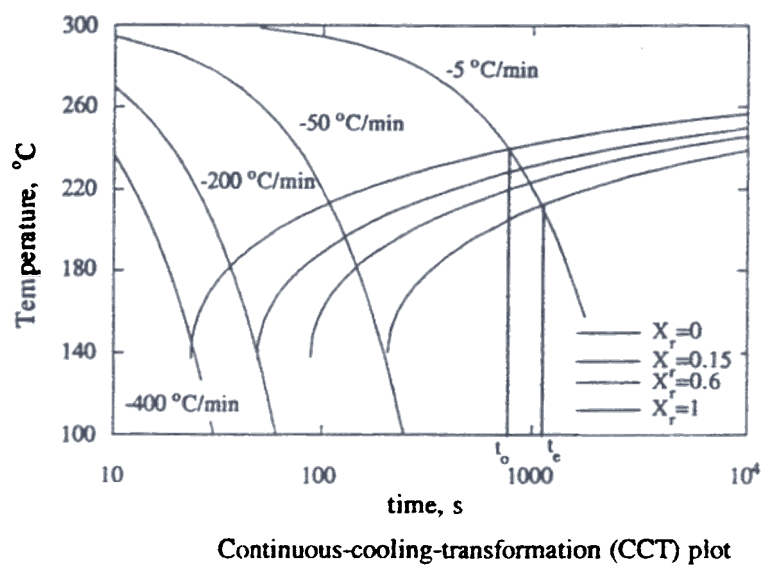
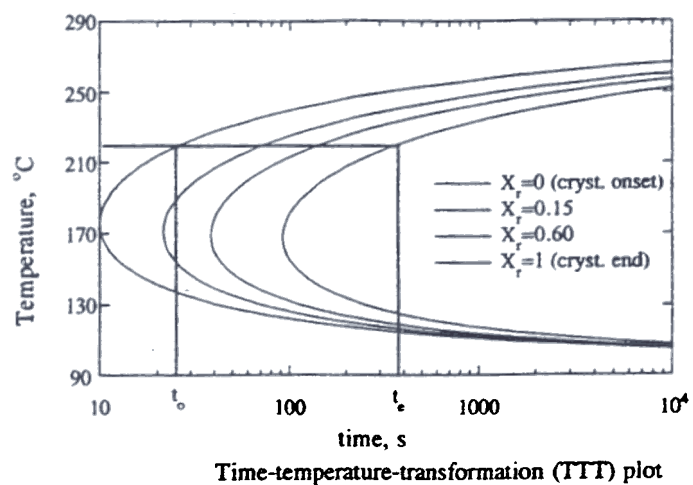
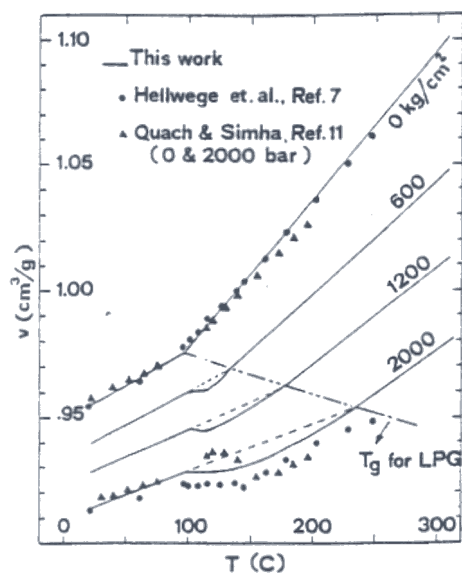
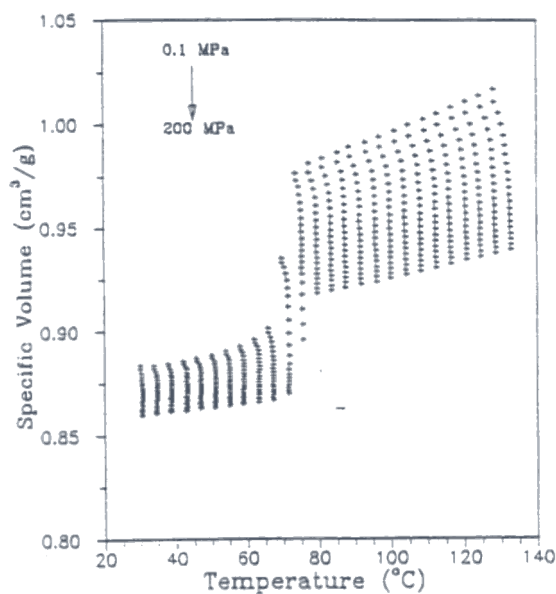


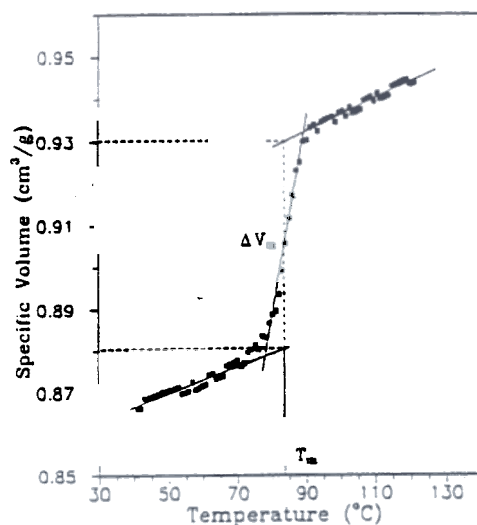
Fig. 7 (ref. 12)



pVT diagrams of three commercial polystyrenes



P-V-T data: specific volumes of poly(ethylene oxide) obtained at constant temperatures (isothermal compression experiments).



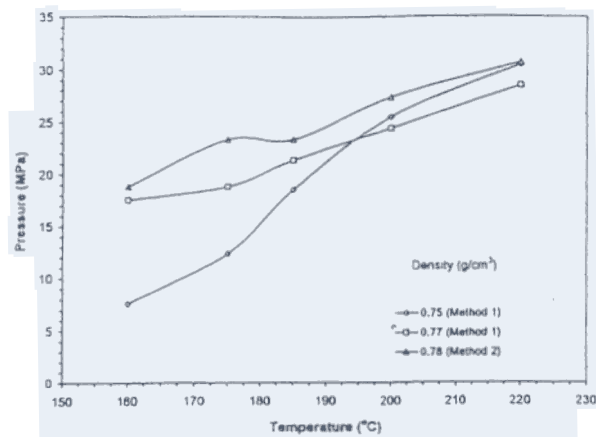
Determination of T_m and ΔV_{semi} from isobaric measurements (an example at 130 MPa).

Fig. 8

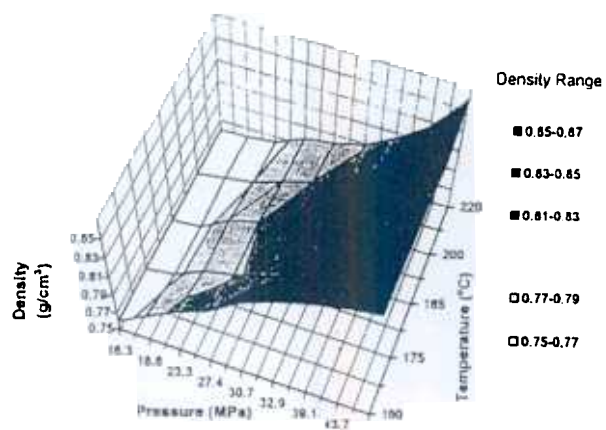
[refs. 14 (top) and 11]



Fig. 9
NPL/SWO PVT Apparatus

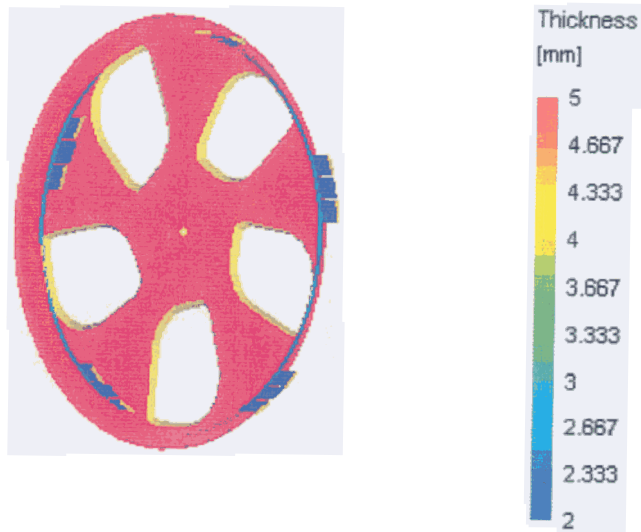


The PpT results from the novel apparatus



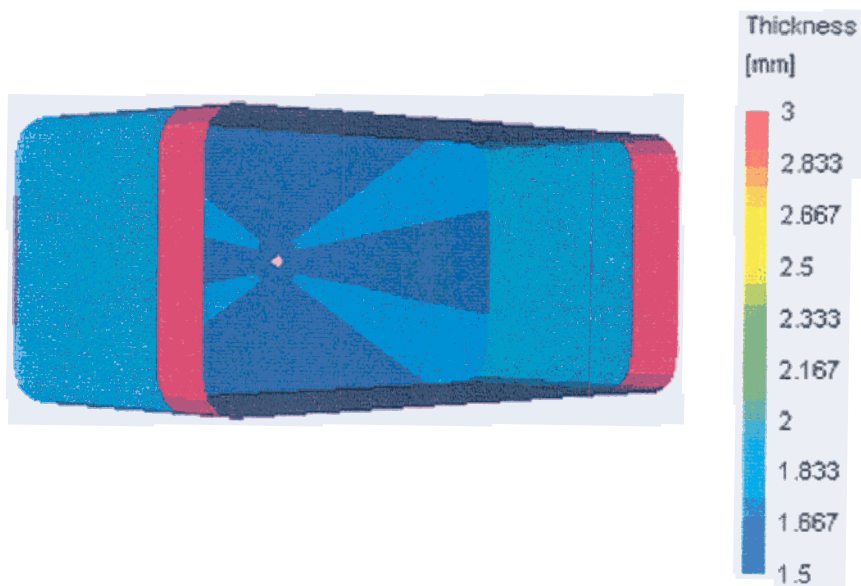
PpT curves for LDPE from an Injection moulding machine

Fig. 10 (ref. 35)



Moldflow

Ideal thickness of hubcap (diameter : 410 mm)

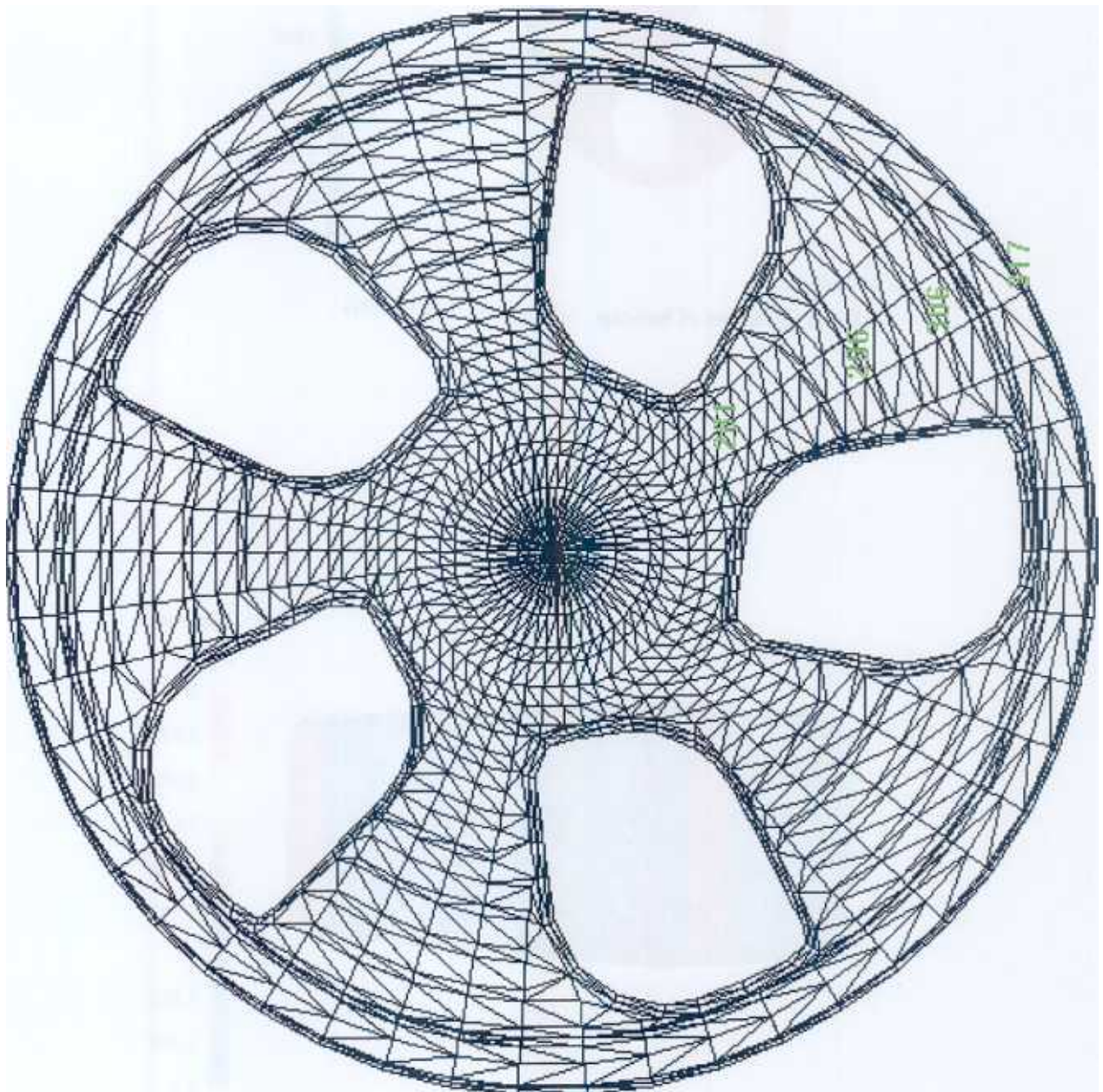


Moldflow

Ideal thickness of butter dish (dimension : 220 x 90 x 90 mm)

Fig. 11

Hubcap



MOLDFLOW

Fig. 12a

3-D mesh display of hub cap with node numbers

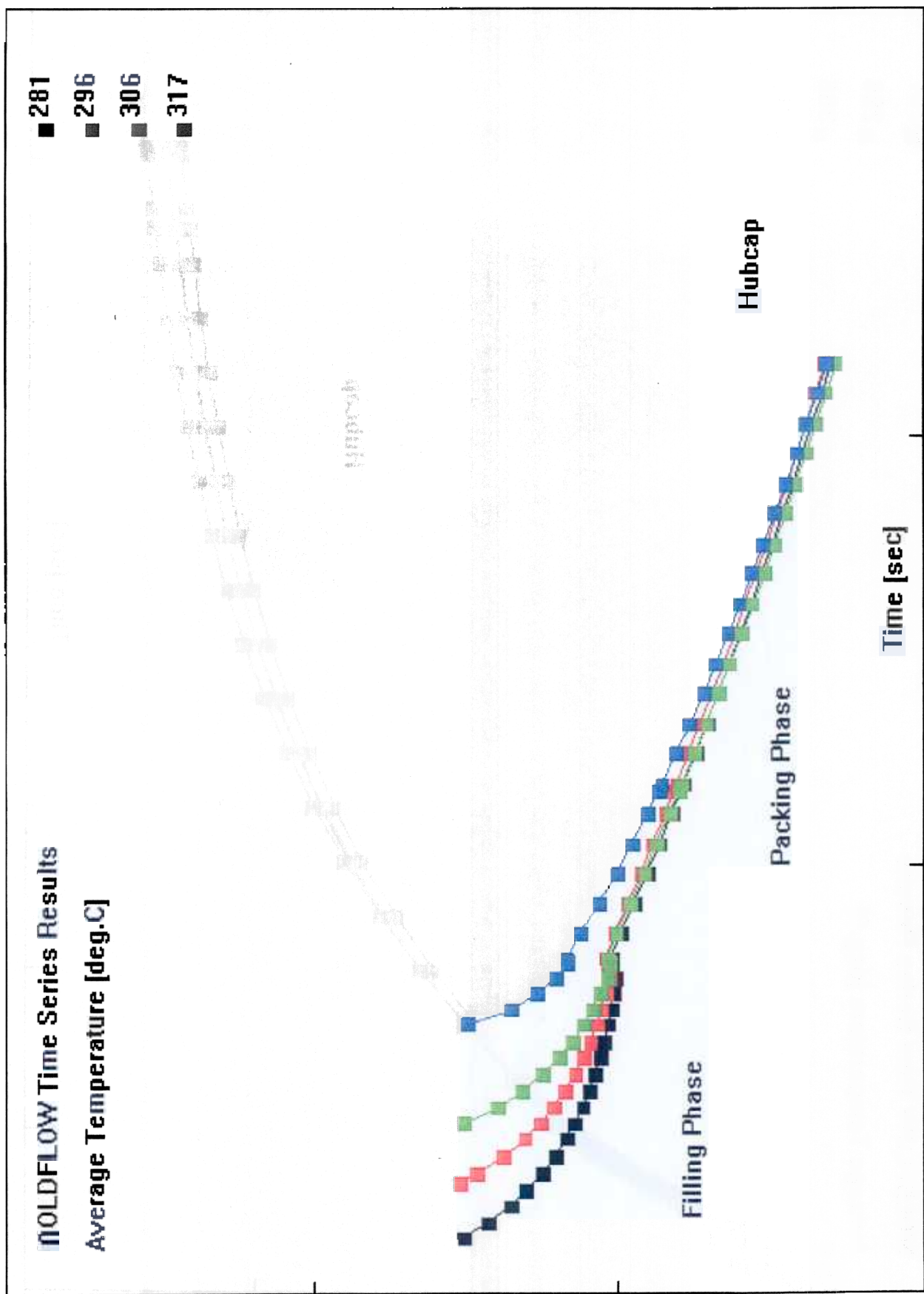


Fig. 12b (continued Fig 12c)

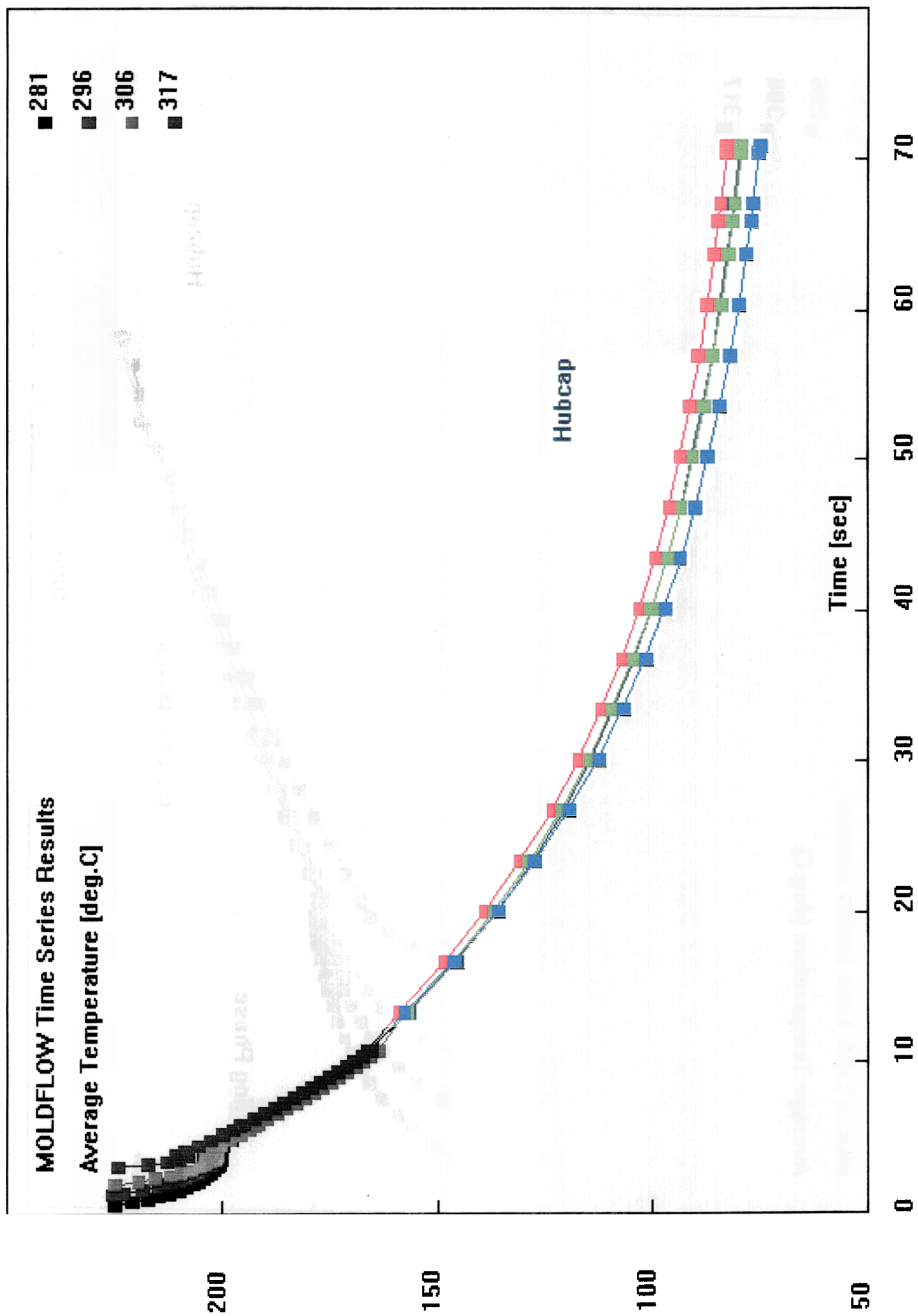


Fig. 12c

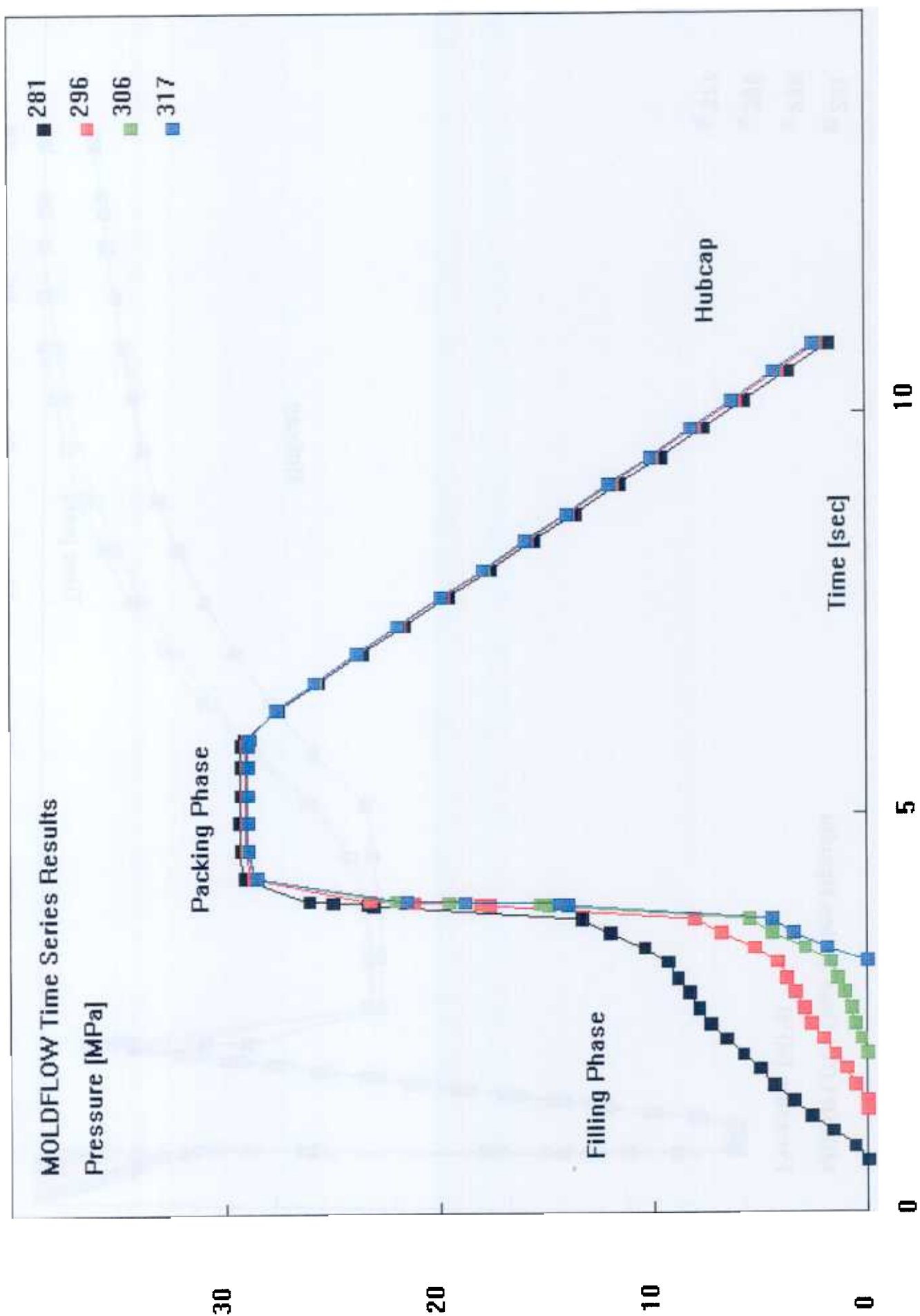


Fig. 12d (see Fig.12a for location of node numbers, continued in Fig.12e)

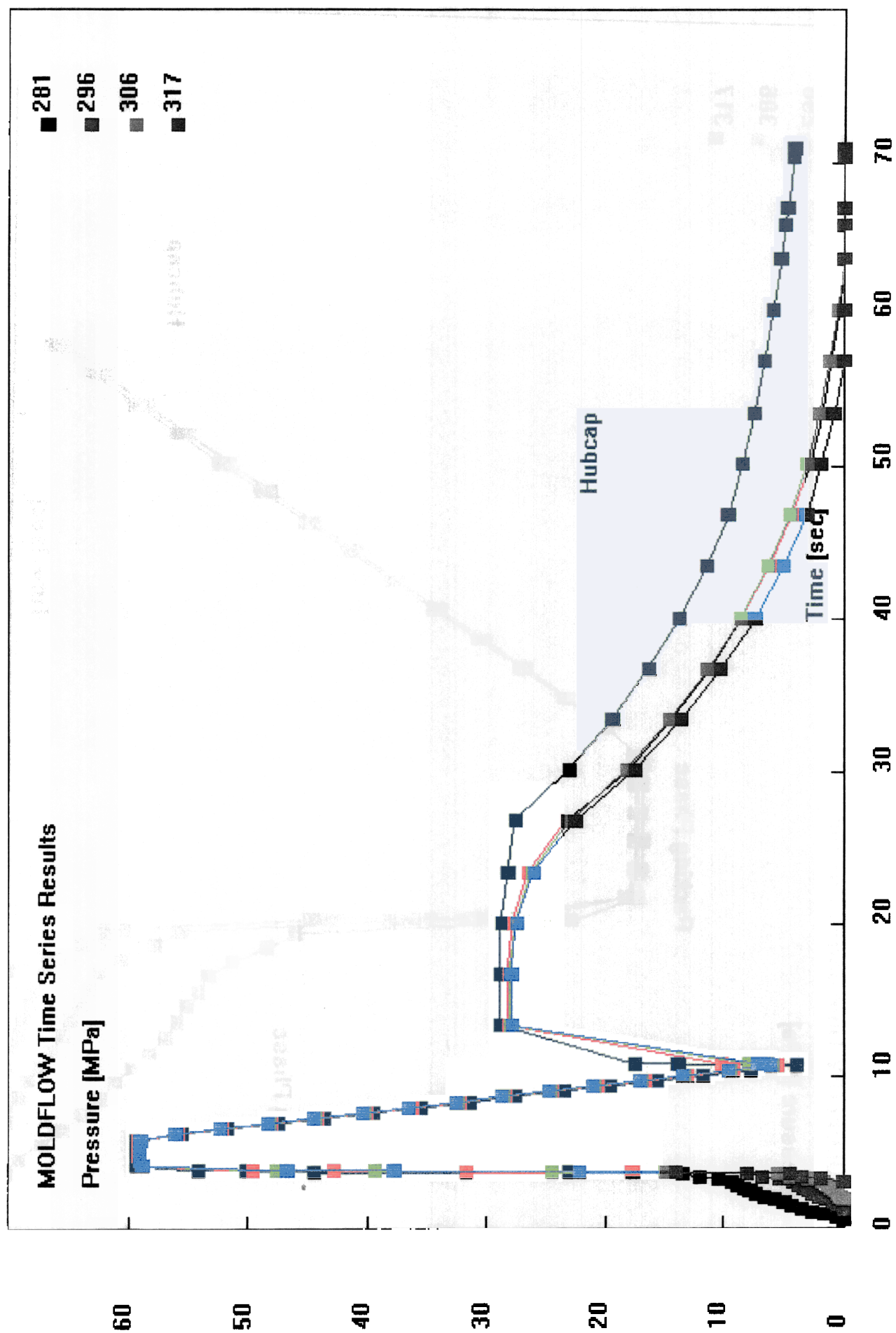
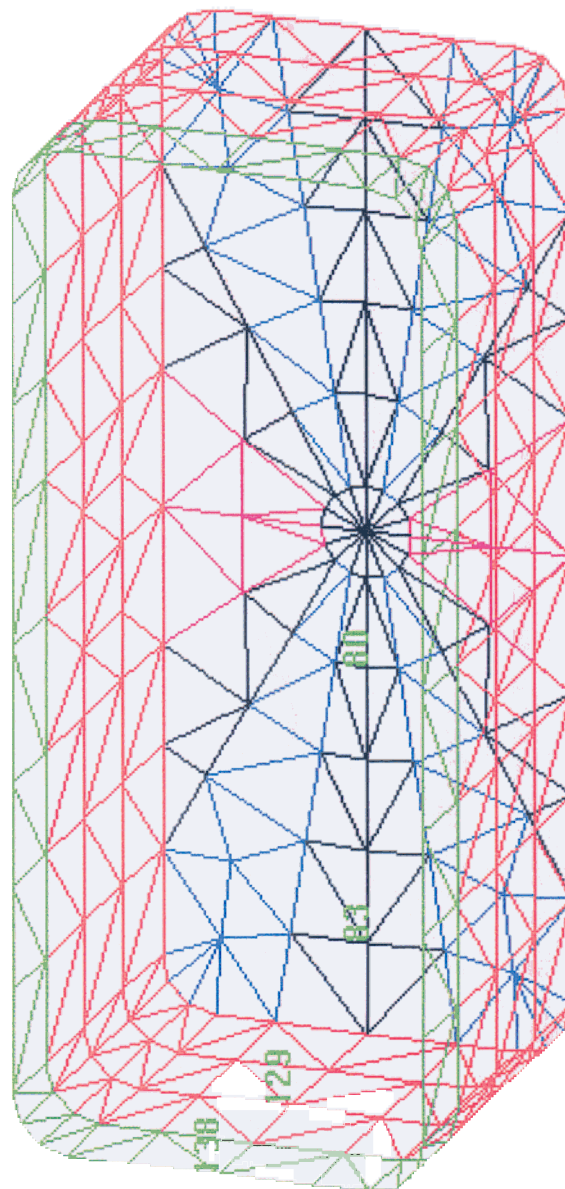


Fig. 12e



Butterdish

MOLDFLOW

Fig. 13a

3-D mesh display of butter dish with node numbers

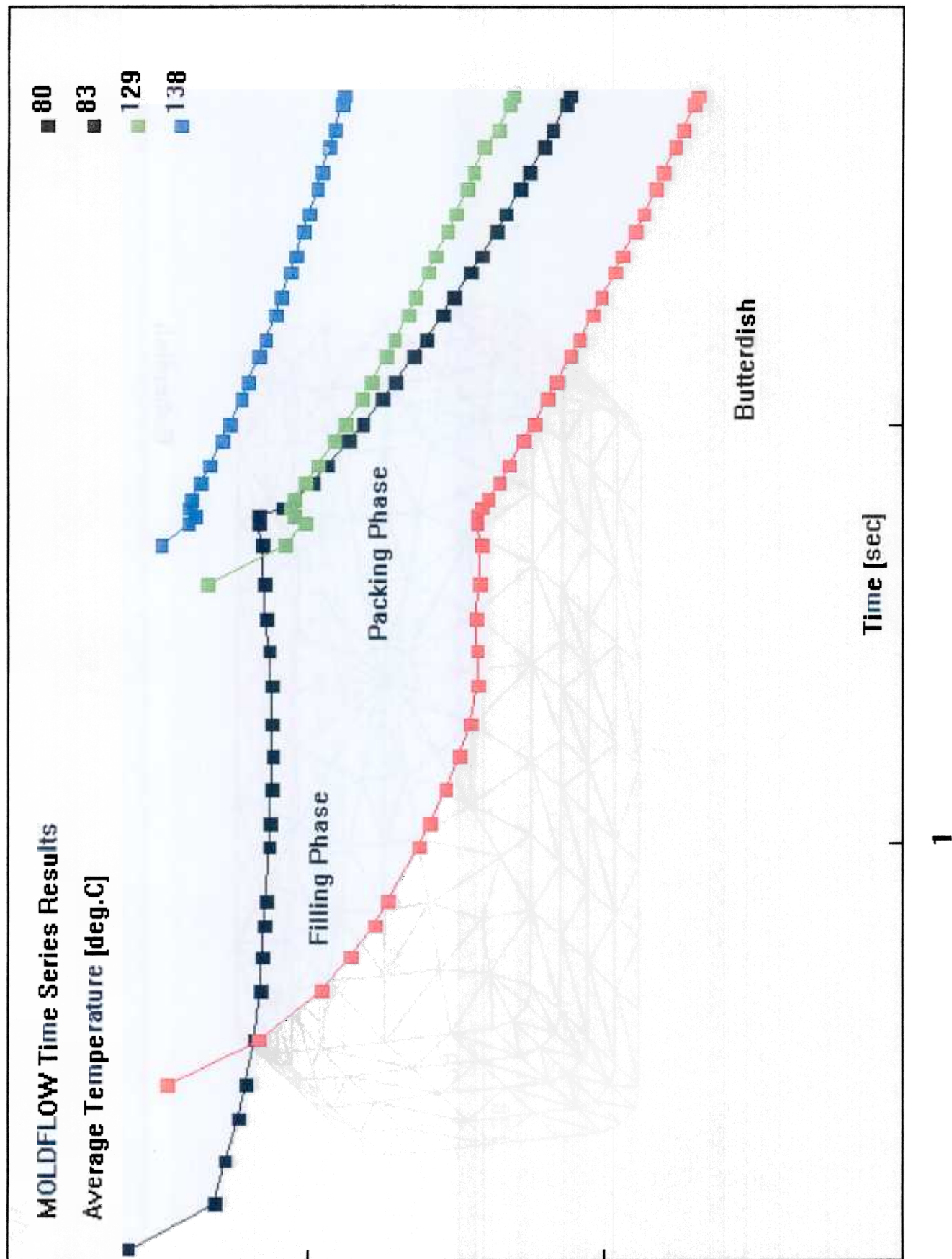


Fig 13b (continued in Fig 13c)

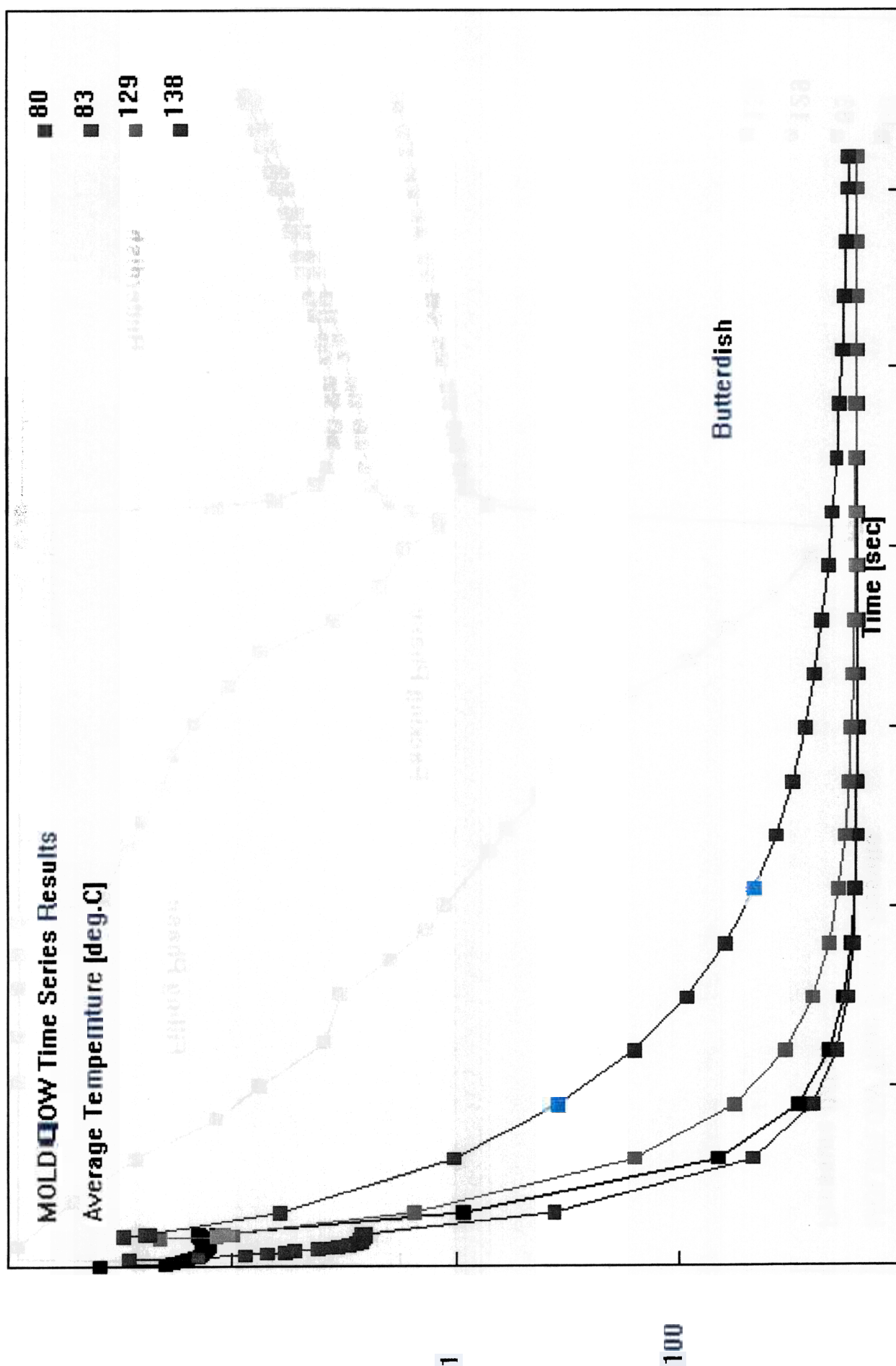


Fig.13c (see Fig 13a for location node numbers)

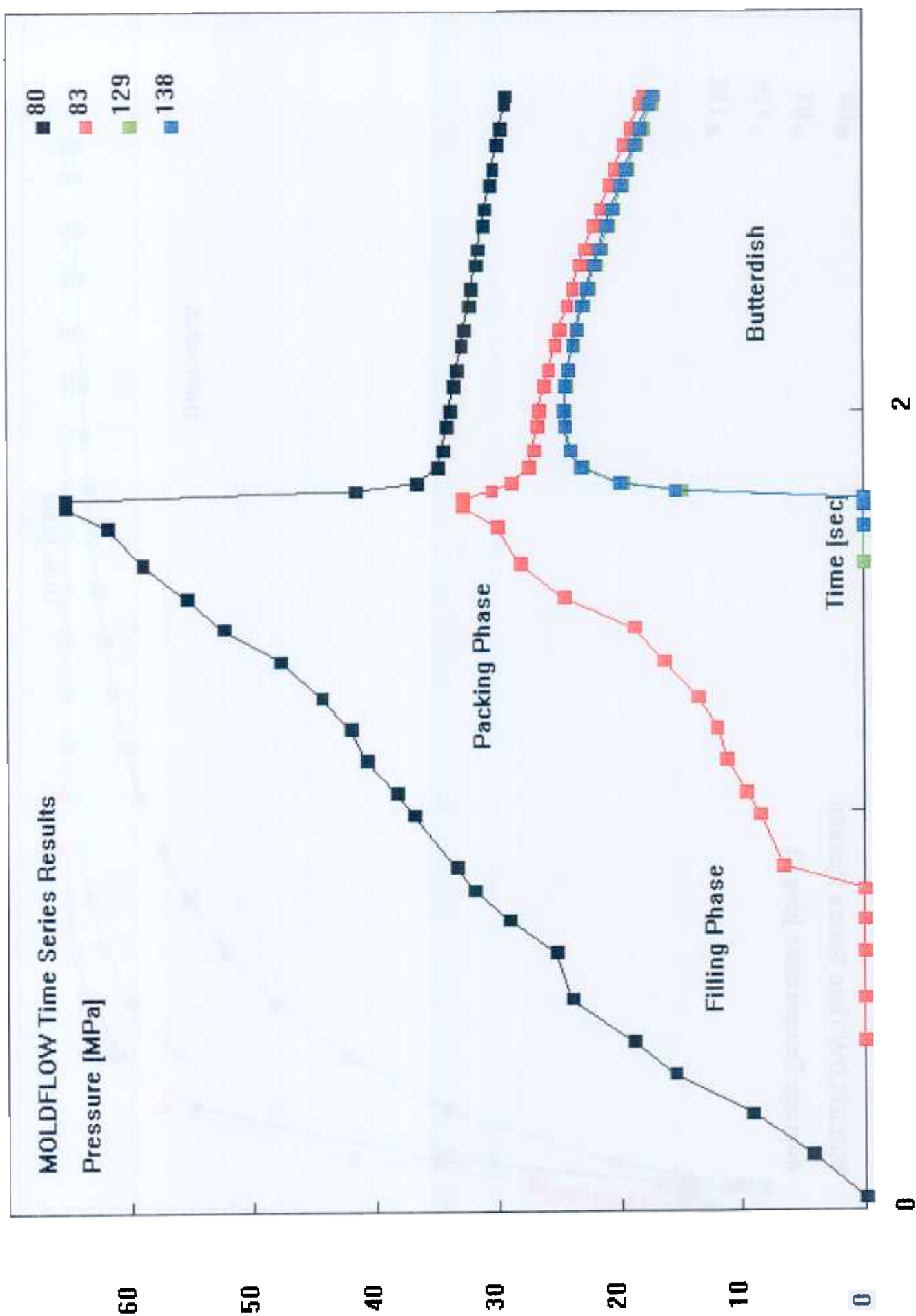


Fig. 13d (continued in Fig. 13e)

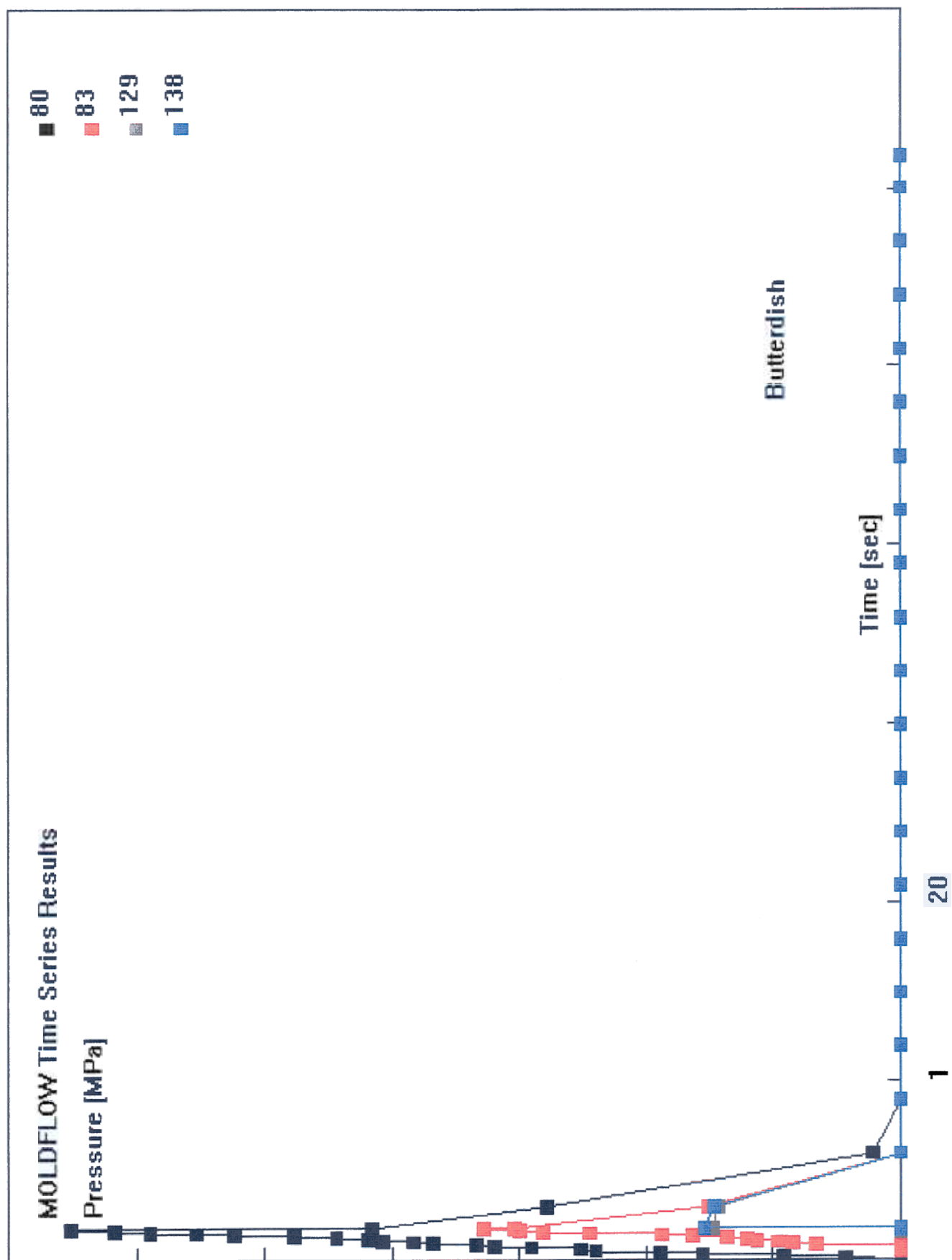


Fig. 13e (see Fig 13a for location node numbers)

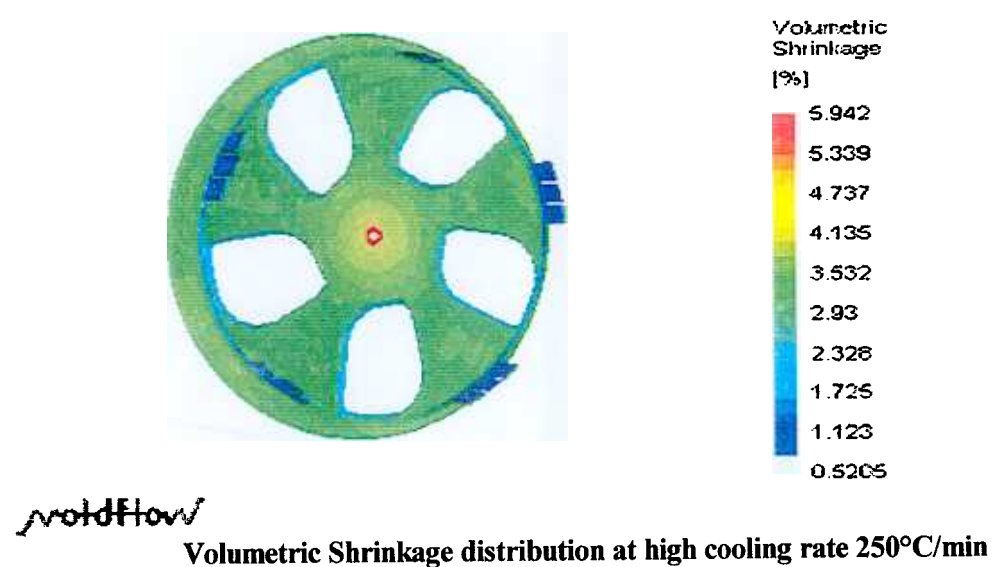
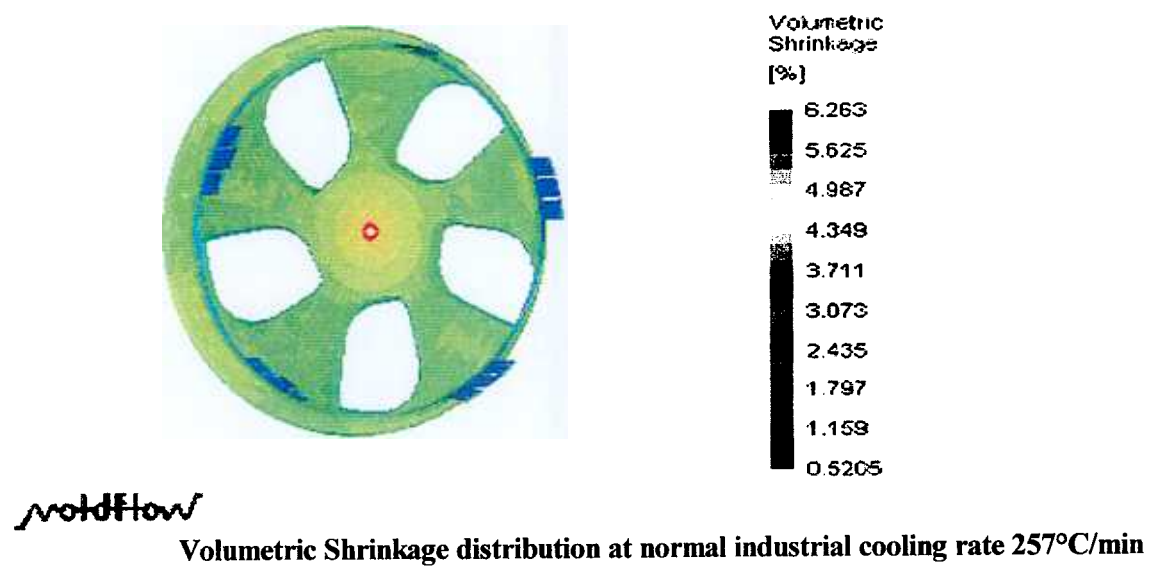
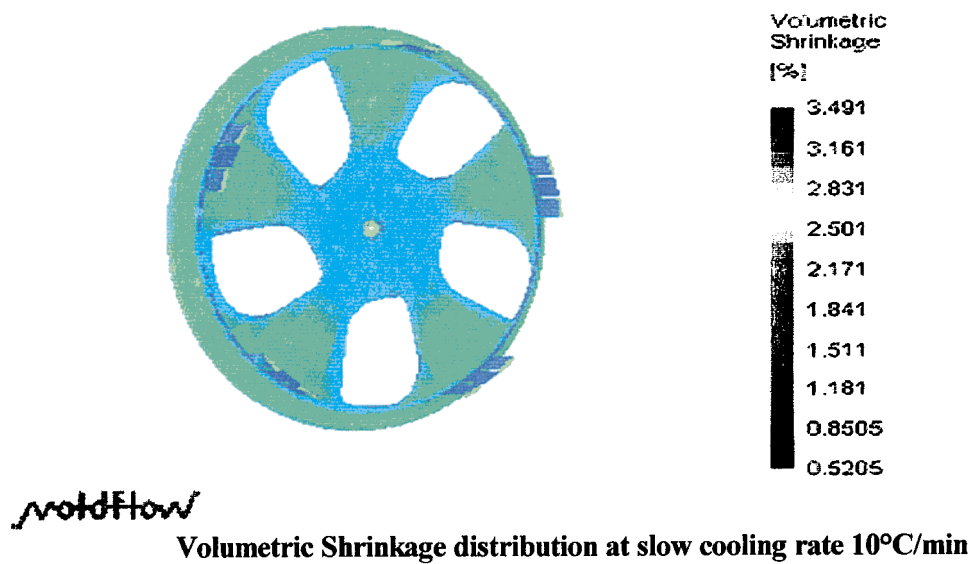
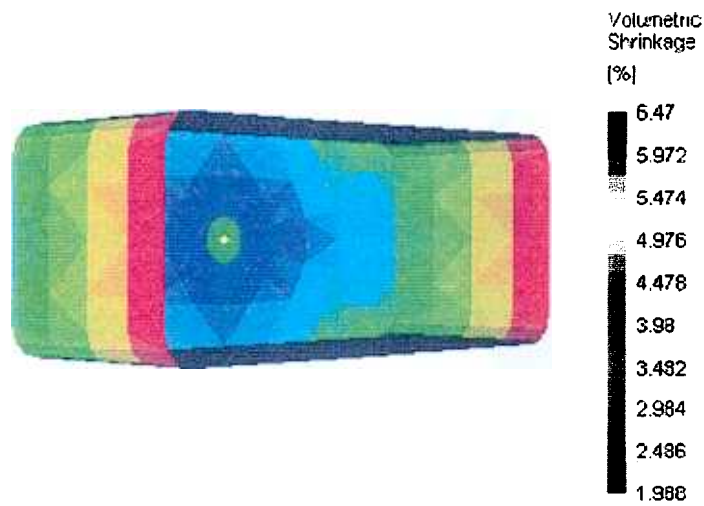


Fig. 14a



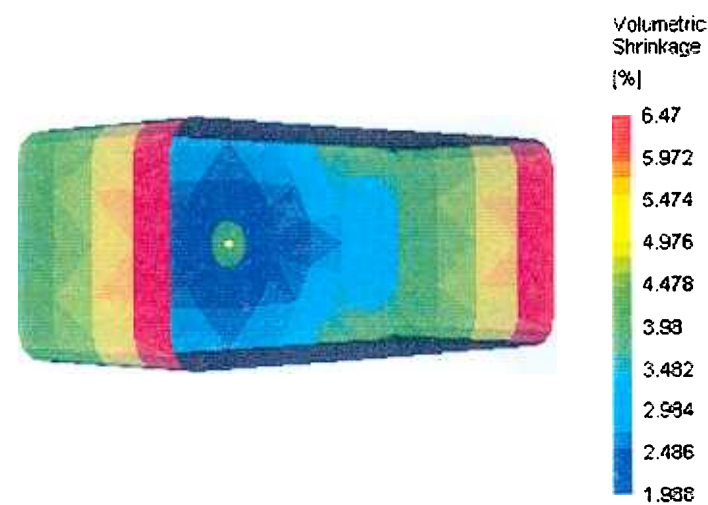
Moldflow

Volumetric Shrinkage distribution at slow cooling rate 10°C/min



Moldflow

Volumetric Shrinkage distribution at normal industrial cooling rate 370°C/min



Moldflow

Volumetric Shrinkage distribution at high cooling rate 250°C/min

Fig.14b

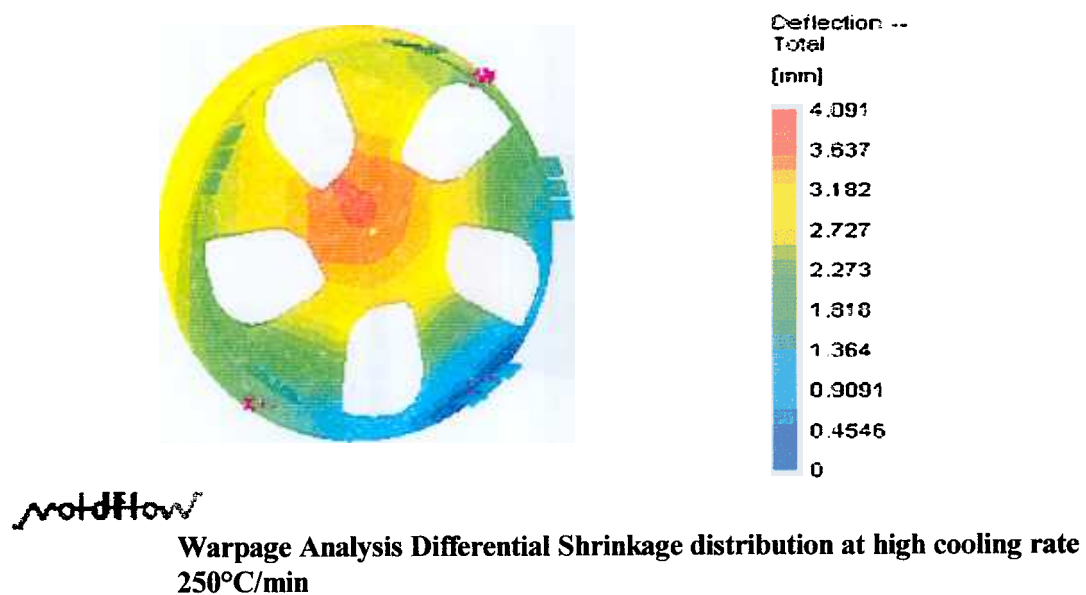
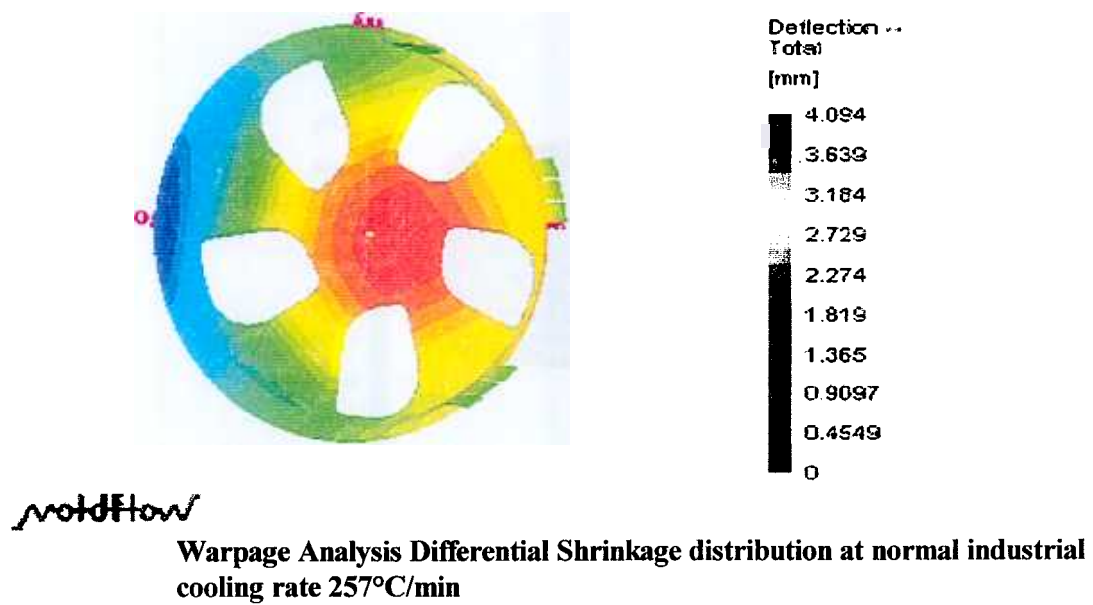
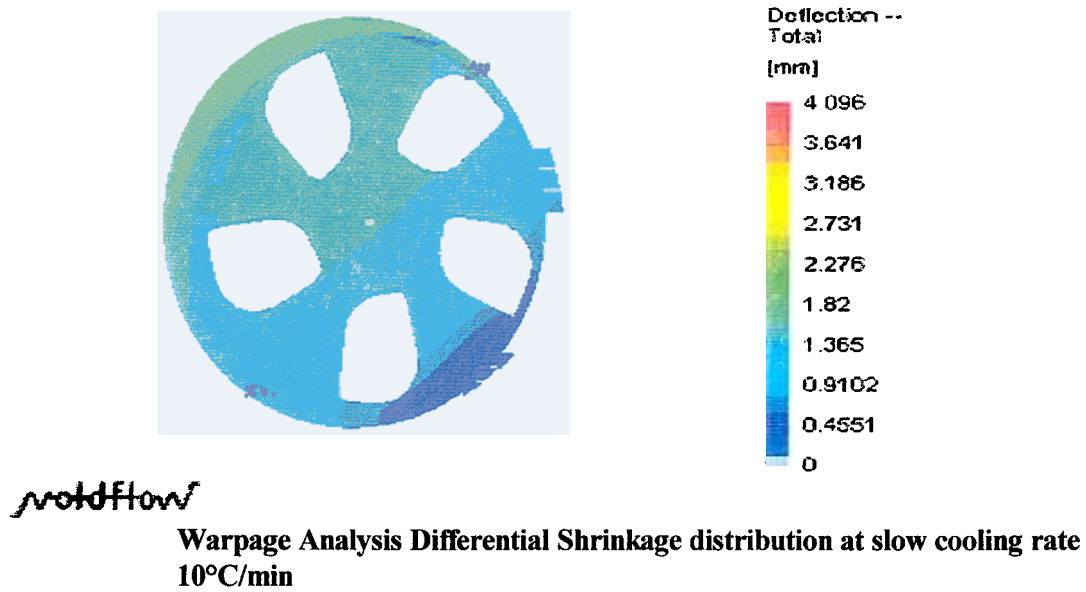
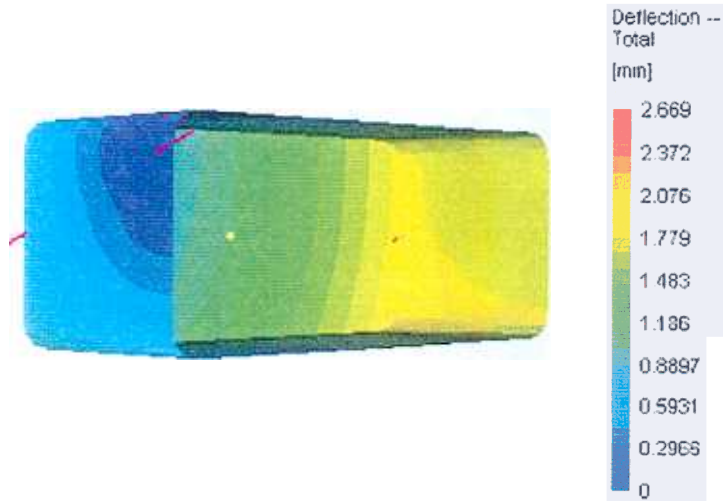
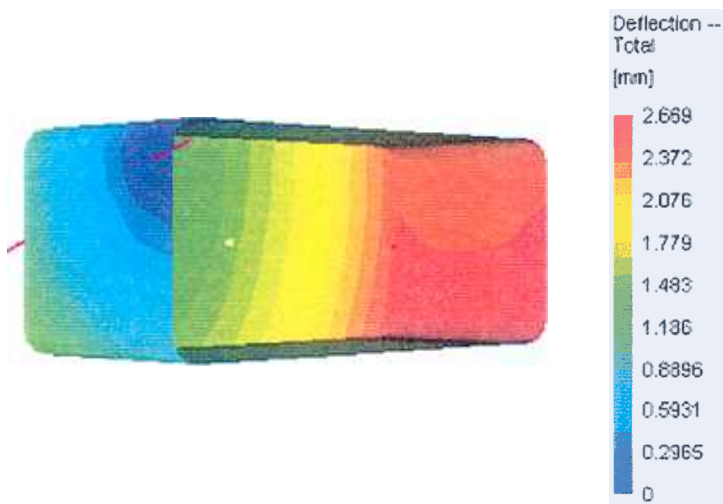


Fig. 14c



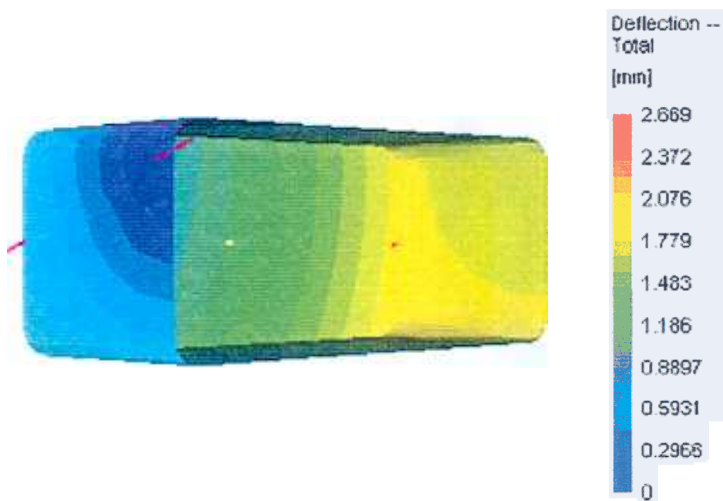
Moldflow

Warpage Analysis Differential Shrinkage distribution at slow cooling rate 10°C/min



Moldflow

Warpage Analysis Differential Shrinkage distribution at normal industrial cooling rate 370°C/min



Moldflow

Warpage Analysis Differential Shrinkage distribution at high cooling rate 250°C/min

Fig. 14d

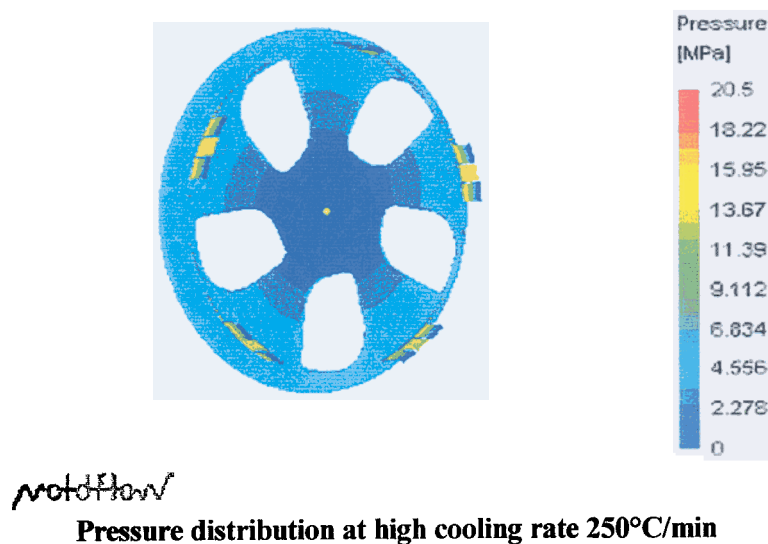
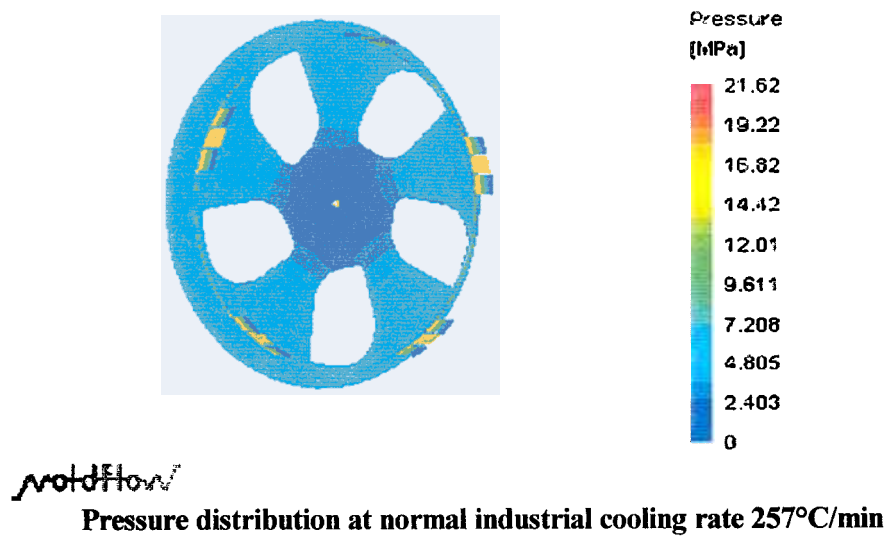
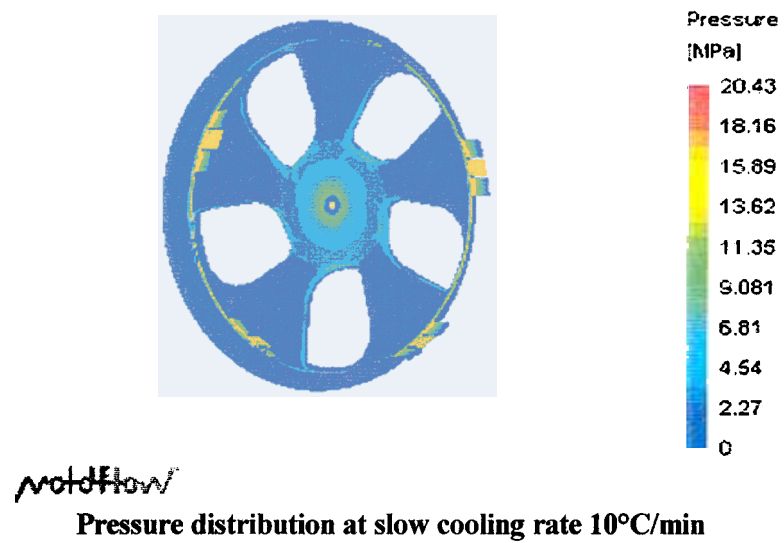
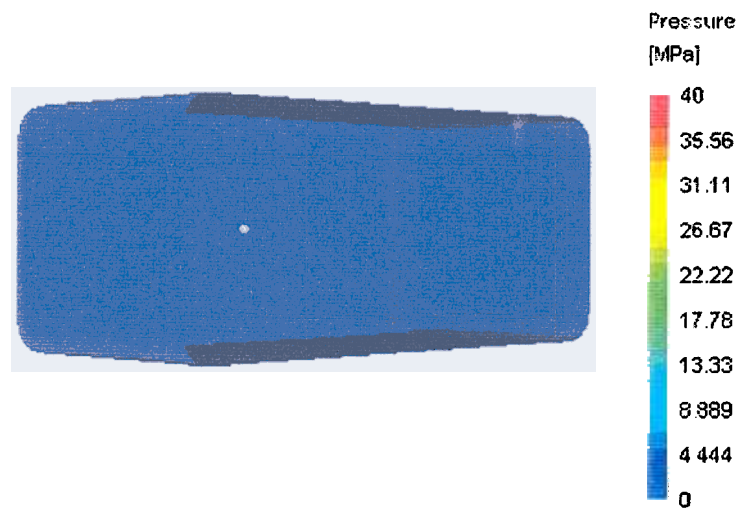
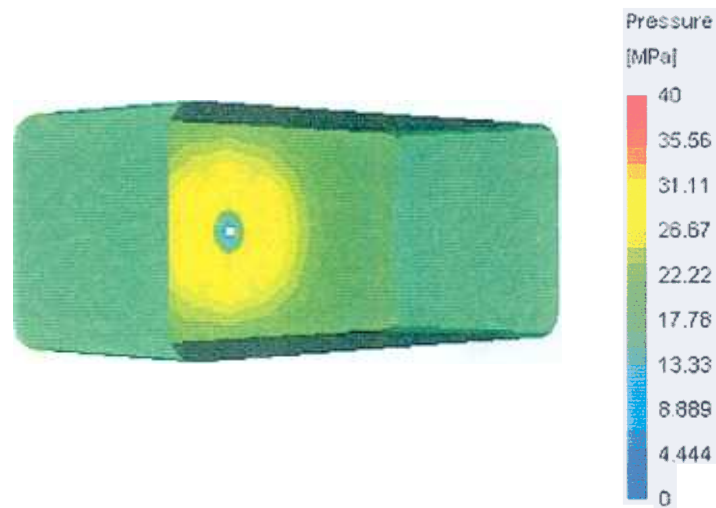


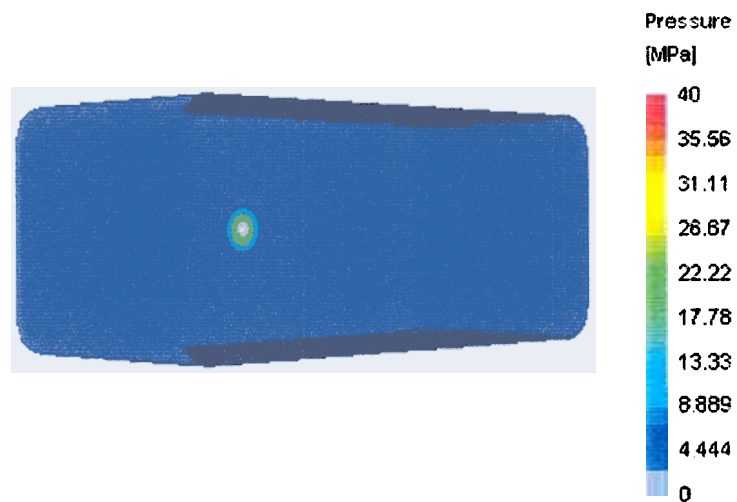
Fig. 14e



AutoFlow
Pressure distribution at slow cooling rate 10°C/min

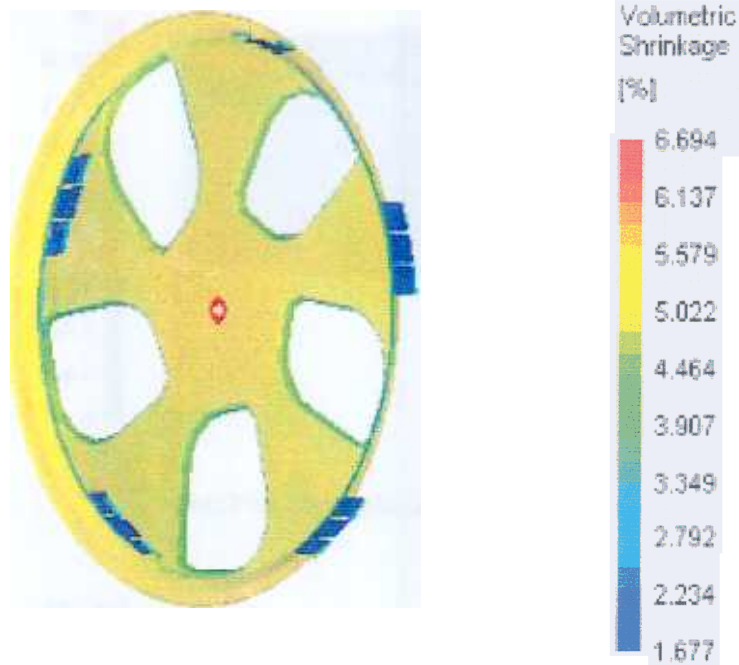


AutoFlow
Pressure distribution at normal industrial cooling rate 370°C/min



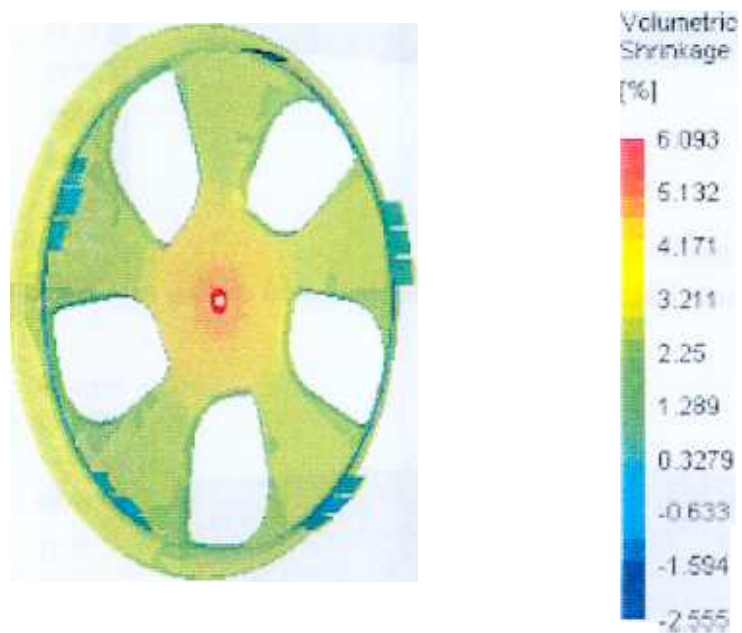
AutoFlow
Pressure distribution at high cooling rate 250°C/min

Fig. 14f



voldflow

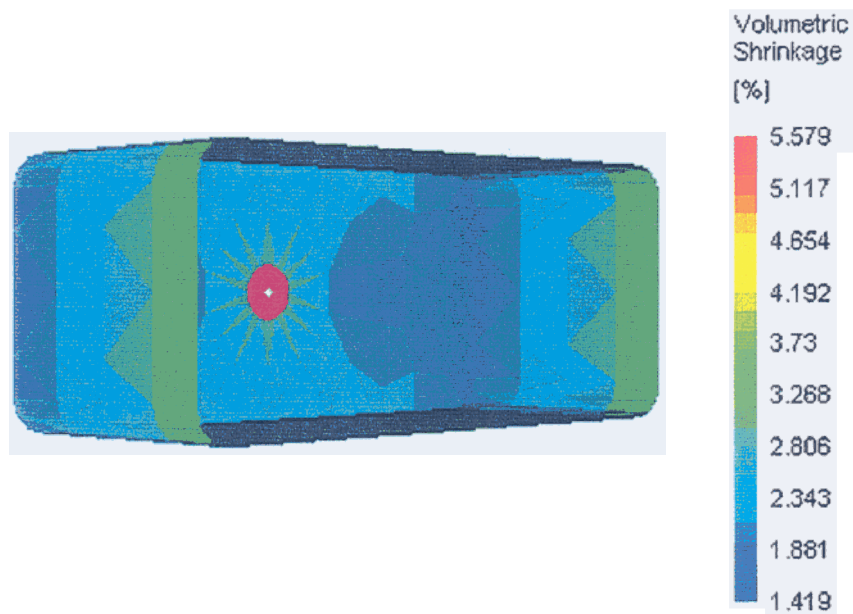
Volumetric Shrinkage distribution at low pressure, 30MPa



voldflow

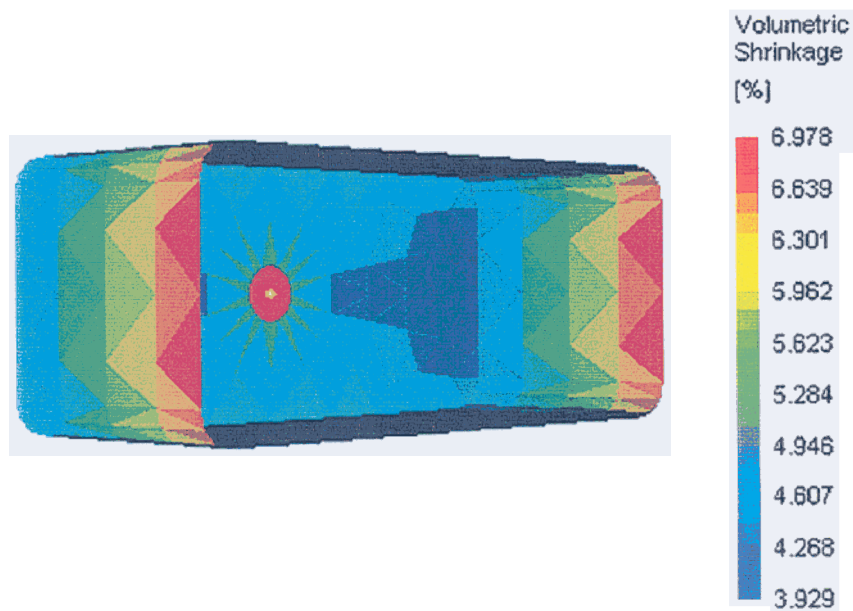
Volumetric Shrinkage distribution at high pressure, 100MPa

Fig. 15a



moldflow

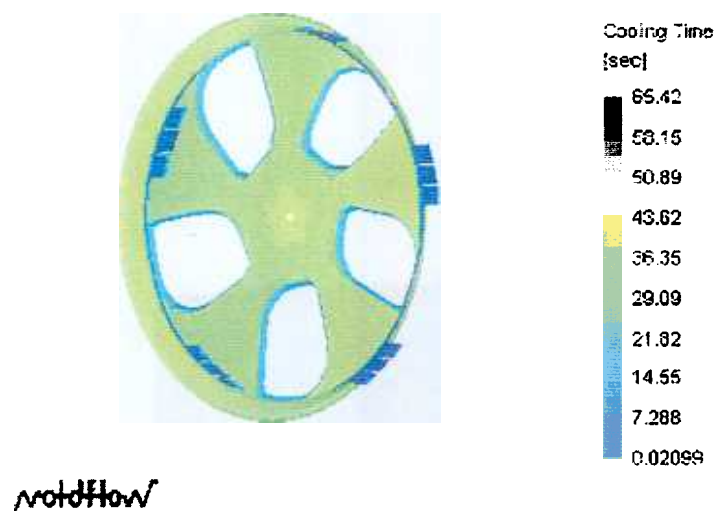
Volumetric Shrinkage distribution at normal pressure, 40MPa



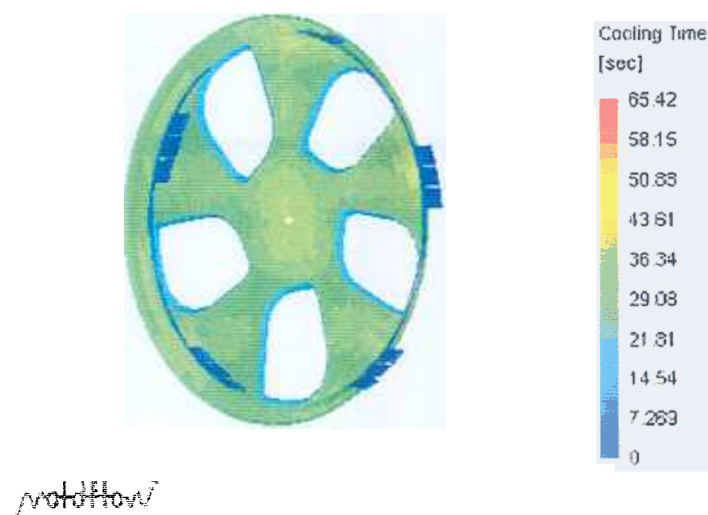
moldflow

Volumetric Shrinkage distribution at high pressure, 100MPa

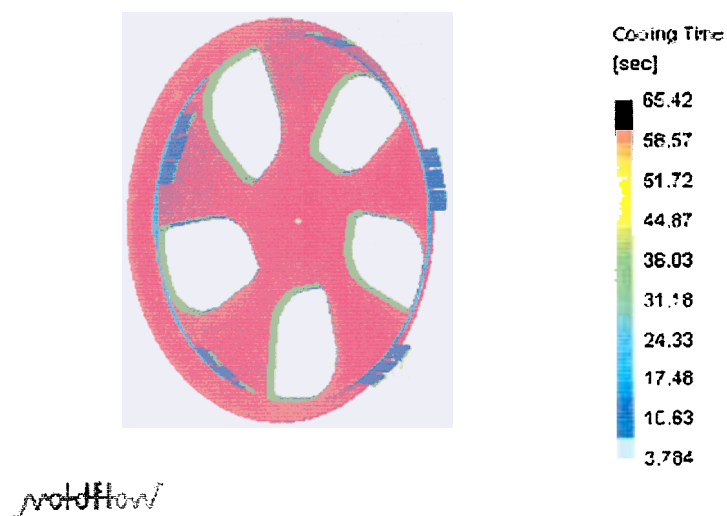
Fig. 15b



Cooling time distribution at 170°C melt temperature



Cooling time distribution at 240°C, industrial melt temperature



Cooling time distribution at 300°C melt temperature

Fig. 16a

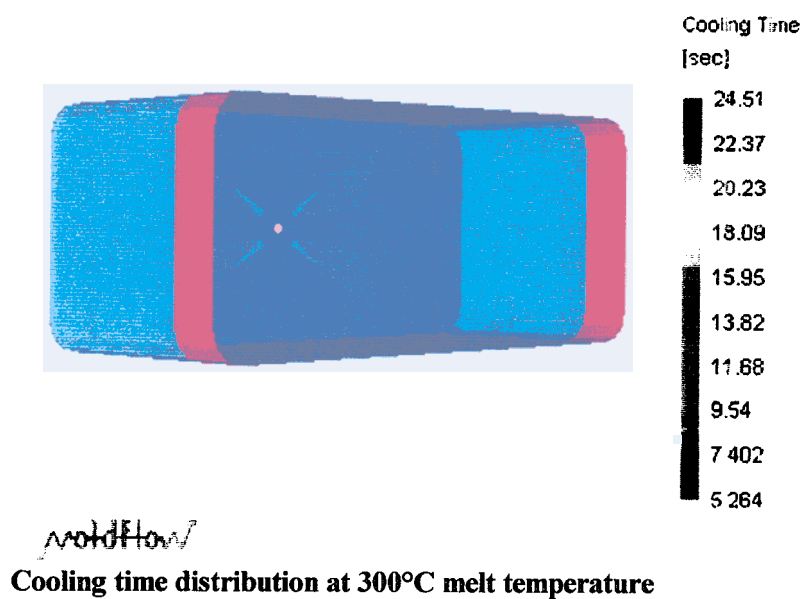
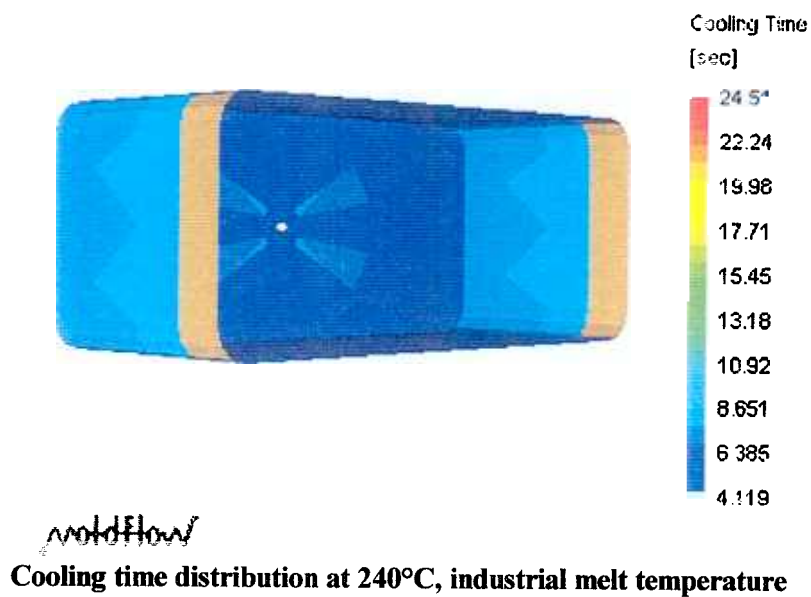
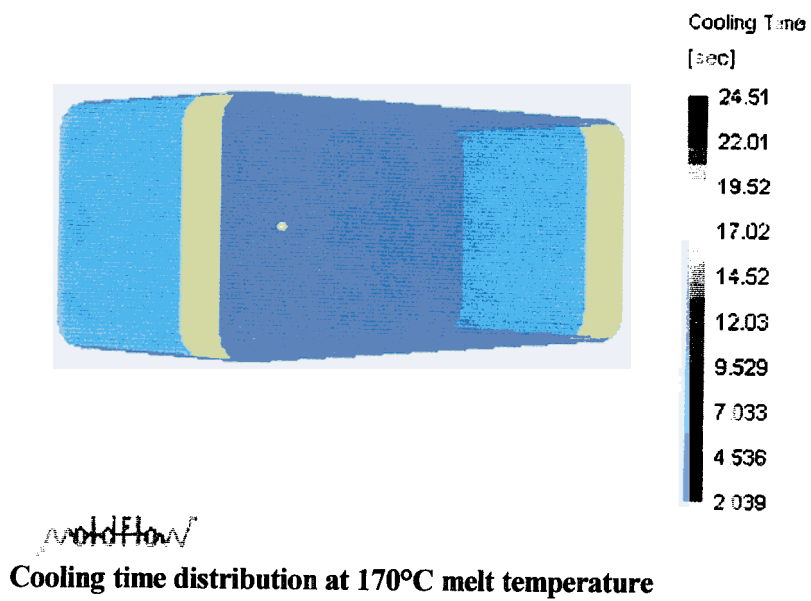


Fig. 16b

ANNEX 1

Improved PVT measurements for polymer processing: Questionnaire

*[Questions marked with an * need not be answered if already answered
in the heat transfer questionnaire]*

Name:...

Company:

Type of products produced *:

Type of processes relevant to your company (eg injection moulding, extrusion) *

.....

Do you think PVT data are important to your company ? Yes / No / Maybe

**For 80% of your company's products, please specify the range of the
following key parameters :**

Product thickness :(please give range)

Shot weight(please give range)

Melt temperature *(please give range)

Ejection temperature :.....(please give range)

Time in mould :....(please give range)

Cooling rate (if known) :..(please give range)

Pressure * :..... .(please give range)

Material types you process or supply * : semi-crystalline/amorphous/thermoset/rubber or
other.....

Polymers of most importance to your company *:

Does your company use **process simulation software** *
such as Moldflow, C-Mold or Polyflow?

Yes / No / Maybe

Do you obtain data from

a) materials suppliers data sheet*

Yes/No

b) default value in the software*

Yes/No

c) by measurement*

Yes/No

d) from the open literature*

Yes/No

e) from Campus*

Yes/No

f) other*

Yes/No

g) Are international Standards used to obtain the data * ?

Yes / No / Maybe

What equipment do you have (if any) to measure PVT parameters?

.....

Would you like to have a visit from NPL to discuss PVT or any other topic related to polymer processing?

Yes / No / Maybe

Please add any further comments or questions below:

.....

.....

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Please return to Sekhar Chakravorty, CMMT, NPL, Teddington, Middx., TW11 0LW
tel: 020 8943 6919 ; fax: 020 8943 6046
e-mail: sekhar.chakravorty@npl.co.uk

ANNEX 2

The relationship between shrinkage and warpage

Introduction

When discussing the warpage due to shrinkage, it is convenient to identify shrinkage due to:

- variation in shrinkage from region to region (differential shrinkage)
- temperature differences from one side of the mold to the other (differential cooling)
- variations in the magnitude of shrinkage in directions parallel and perpendicular to the material orientation direction (orientation shrinkage).

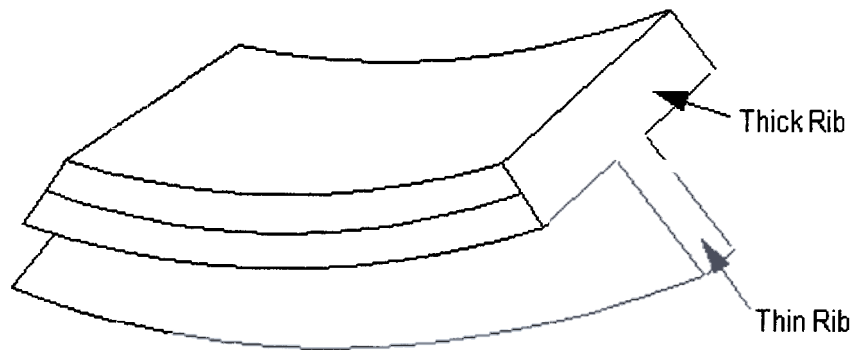
Each of these types of shrinkage will contribute to the total warpage of the product.

Differential Shrinkage

This type of shrinkage is often caused by variation in crystalline content and volumetric shrinkage.

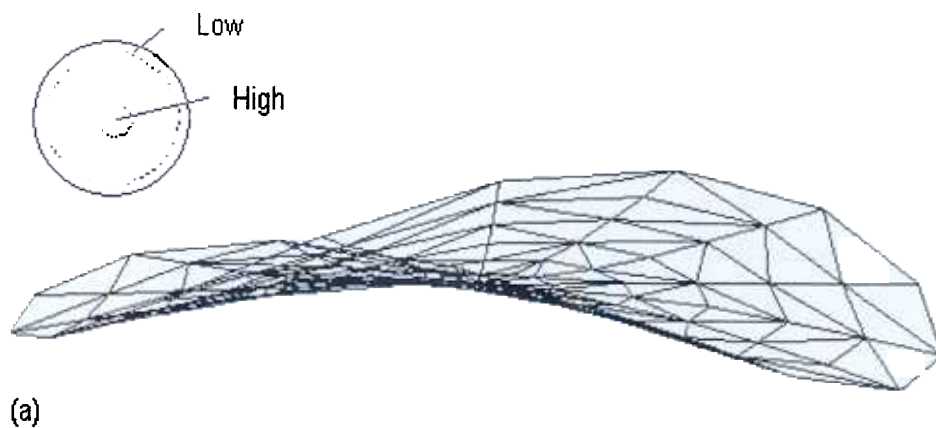
The following figure shows a thin rib attached to a thick top. In general, the cooling rate of the top will be lower than that of the thin section. The top will have increased crystalline content and so will shrink more and cause the warpage shown.

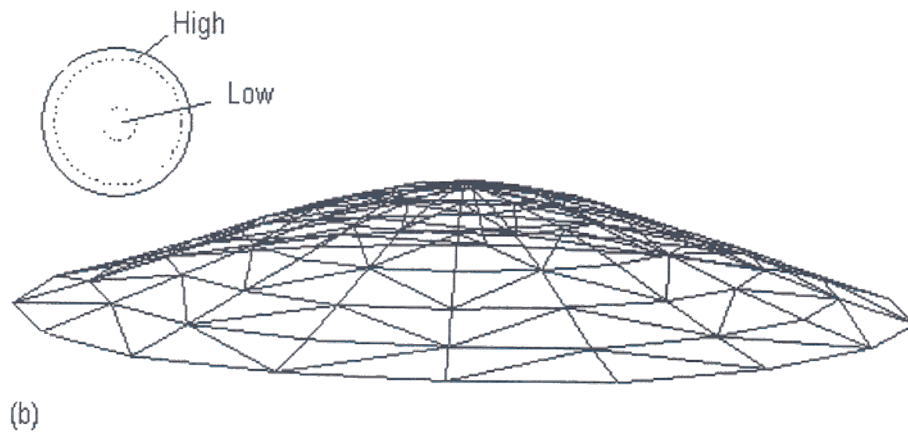
Effect of Different Section Thicknesses



The next figure (a) shows saddle warping of a centrally gated disk with high shrinkage around the gate. Conversely, if the shrinkage is higher around the outer part of the disk, the resulting warpage may cause the disk to dome, shown in (b).

Differential Shrinkage Effects

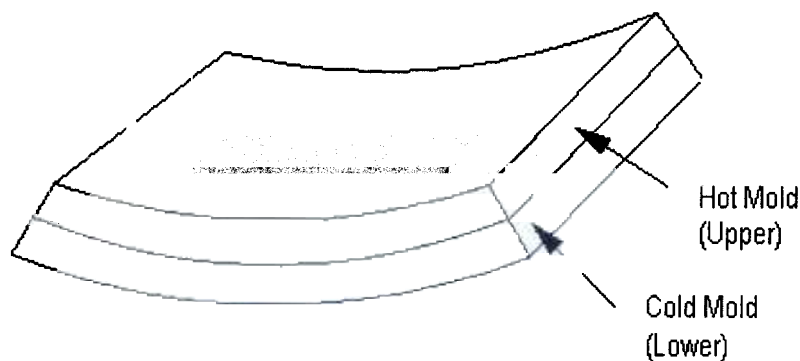




Differential Cooling

Shrinkage due to differential temperature typically results in bowing of the component, as shown in the figure below. Usually this type of shrinkage is due to poor cooling system design.

Effect of Differential Cooling



While the part is in the mold, temperature differences from one side of the mold to the other cause variations in shrinkage through the thickness of the component. In addition to this, any temperature differences at ejection will cause further warpage as both sides of the part cool to room temperature.

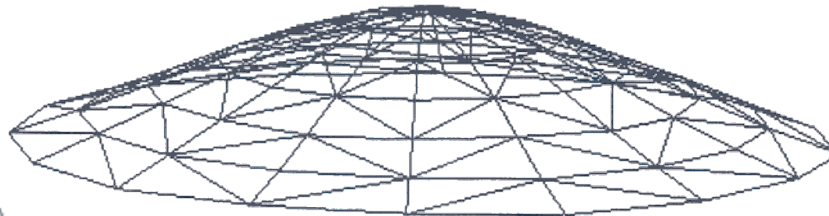
Orientation Effects

Orientation causes variation in the magnitude of shrinkage in directions parallel and perpendicular to the material orientation direction. This type of shrinkage can produce warpage similar to that from differential shrinkage. Figure (a) below shows the warpage when parallel shrinkage is greater than perpendicular shrinkage. On the other hand doming can be produced if the perpendicular shrinkage is higher than parallel shrinkage, see (b).

Effect of Orientation on Shrinkage



(a)



(b)

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