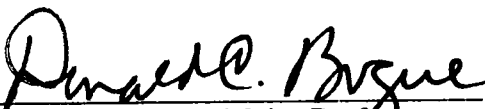
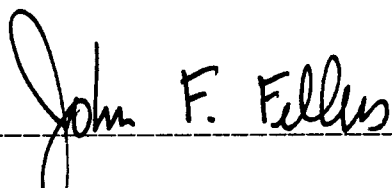


To the Graduate Council:

I am submitting herewith a thesis written by Runjun Das entitled "Evaluation of Computer Programs for Injection Molding." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Polymer Engineering.


Donald C. Bogue, Major Professor

We have read this thesis
and recommend its acceptance:




Accepted for the Council:


Associate Vice Provost
and Dean of the Graduate School

EVALUATION
OF
COMPUTER PROGRAMS
FOR
INJECTION MOLDING

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Runjun Das
December 1991

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ABSTRACT

Several computer programs for dealing with the mold filling step in injection molding are now available commercially. In the present work two such programs (C-FLOW and Mold Filling) have been run to study their accuracy in various cases and to prepare case studies for classroom use. The programs were compared with each other and with experimental data (or experimental observations) from several sources. Three geometries were studied: (1) a flat rectangular mold with internal obstructions, a geometry used by the Cornell injection molding group; (2) a simulation of a 24" TV cabinet, a practical geometry of considerable complexity (2545 nodes, 4635 elements), provided to us by the Philips Consumer Electronics Company; and (3) a simplified version of the Philips geometry (1366 node 2399 elements), which maintains the overall shape of the complete simulation but omits many small details (grooves, slots, etc.).

Both the C-FLOW and Mold Filling programs were run for the flat rectangular mold, giving results in reasonable agreement with each and with experimental data from the literature (pressure vs. time), excepting only the the pressure tap nearest the end of the mold gave predicted pressures quite a bit more than the measured ones.

The full Philips simulation of the TV cabinet and a simplified version of it were run on C-FLOW, the polymer being a high impact polystyrene for which Philips had rheological data. Predictions for

inlet pressure vs. time were in reasonable agreement between the two simulations. The final inlet pressures from the simulations were 39.MPa for the simplified model and 30 MPa for the Philips' model which are in reasonable agreement with in-plant (production) values of 30 - 40 MPa. The full simulation gives a spurious pressure "spike" at the end of the fill because of numerical problems associated with many small elements and some subjective judgement is necessary to determine the true value. The computer program predicted "short shots" at about 65% of full-fill pressure, compared with plant experience of about 80 - 85% of full-fill pressure, reasonable agreement in view of the un quantified nature of various kinds of short shots.

The character of "weld lines" (junction lines between two flowing polymer fronts) was studied qualitatively. SEM photographs showed that bad (visible) weld lines showed fibrous structure when broken apart whereas near-invisible weld lines or samples free of weld lines broke with faceted, smoothly cleaved surfaces. No large structural differences across the thin dimension of the weld line were observed, which tends to discredit a criterion (for good or bad weld lines) based on temperature as a primary variable, temperature varying significantly as one moves from wall to centerline. In accord with suggestions from the program vendor the quality of the weld line did correlate reasonably well with the angle at which the two melt fronts meet. This cannot be the only variable in practical

molding operations, however, and further studies of this kind are needed.

The geometries produced and stored in computer memory cover a variety of practical shapes and will provide a useful "bank" to draw upon in future classroom projects involving C-FLOW.

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CHAPTER 1

INTRODUCTION

Extensive computer software has recently been developed for the injection molding process. The filling portion of that process is a complex problem in non-Newtonian fluid mechanics, but one which has been made tractable for computer (finite element) simulation by certain simplifications of the governing equations.

The mathematical simulation used in the various programs largely follows that of the Injection Molding Project at Cornell University [1,2]. In the fluid mechanics portion one dimension (the thin dimension) is treated with the so-called "lubrication theory" assumption and large flat planes are dealt with by the classical Hele-Shaw method. These equations are solved simultaneously with a convected heat transfer formulation and a viscous rheological equation (a modified "power law"). These simplifications have been tested in simple geometries during the Cornell project but it is clear physically that they will work only approximately in certain more complicated geometries. Although several commercial programs based on the Cornell project are now available, there is little in the open literature as to how successful they are in actual use.

We have two programs available at the University of Tennessee, Knoxville : (1) C-FLOW, marketed by A. C. Tech Co., Ithaca, New York, and (2) Mold Filling, marketed by Structural Dynamics Research Corporation (SDRC), Milford, Ohio. C-FLOW is presently

being used by the Philips Consumer Electronics Company, Knoxville, and Mr. Ben Ferguson of that company kindly gave us a C-FLOW simulation of an injection molded part now in production (a 24" TV cabinet made from a high impact polystyrene (Huntsman/HIPS:707FR); certain plant data (final injection pressures), both for a satisfactory run and for a run that produced a "short shot"; and production samples of the TV cabinets themselves. The latter are useful in that one can sometimes see "weld lines", the lines where the material being introduced at two different gates (or coming around two sides of an obstruction) joins.

There is limited quantitative data in the literature showing, for example, pressure vs. time curves at various positions in a mold during the mold filling step. One study of this kind is available, however, from the original Cornell work in which a flat rectangular mold (with several obstructions) was equipped with three pressure transducers and injected with a commercial ABS [3]. Such data are useful evaluating the computer programs in a quantitative manner.

It was the short-range purpose of the present work to compare the results from the two computer programs (C-FLOW and Mold Filling) with each other, for several geometries; and to compare such results with experimental data as available (specifically, data for the flat rectangular mold described above, and the limited, but actual in-plant data provided by the Philips Company). In addition it was proposed to learn something about the nature of the weld lines by a study of the computer programs and by observations from a

scanning electron microscope. Finally it is proposed to make a start toward the long-range objective of developing a "bank" of geometries for use in classroom (and possibly outside) instruction having to do with the usefulness and shortcomings of the injection molding programs.

CHAPTER 2

LITERATURE BACKGROUND

Injection molding is one of the most important plastic fabrication operations. In the process a hot polymer melt or plasticized plastic material is injected into an empty cold cavity. When the filling is complete, more polymer is packed into the cavity at a higher pressure in order to pre-compensate for subsequent shrinkage by cooling. Cooling is continued until sufficient solidification is achieved such that the polymer can be removed in the solid state after taking the shape of the mold cavity. The mold may consist of a single cavity or a number of similar or dissimilar cavities, each connected by flow channels or runners that direct the flow of the melted plastic to individual cavities.

The overall process consists of three basic steps: (1) mold filling, which consists of pushing a polymer melt under pressure into the runner and the mold; (2) packing, in which polymer continues to be fed to the full mold (ie. the mold is "overfilled") causing a large build-up in pressure to allow for the shrinkage during the subsequent cooling step; and (3) cooling, in which the polymer solidifies in the mold by cooling until the pressure has dropped to some small residual pressure at which then the mold is opened and the part ejected. The three different stages are shown shown in the pressure-time curve in Figure 2.1.

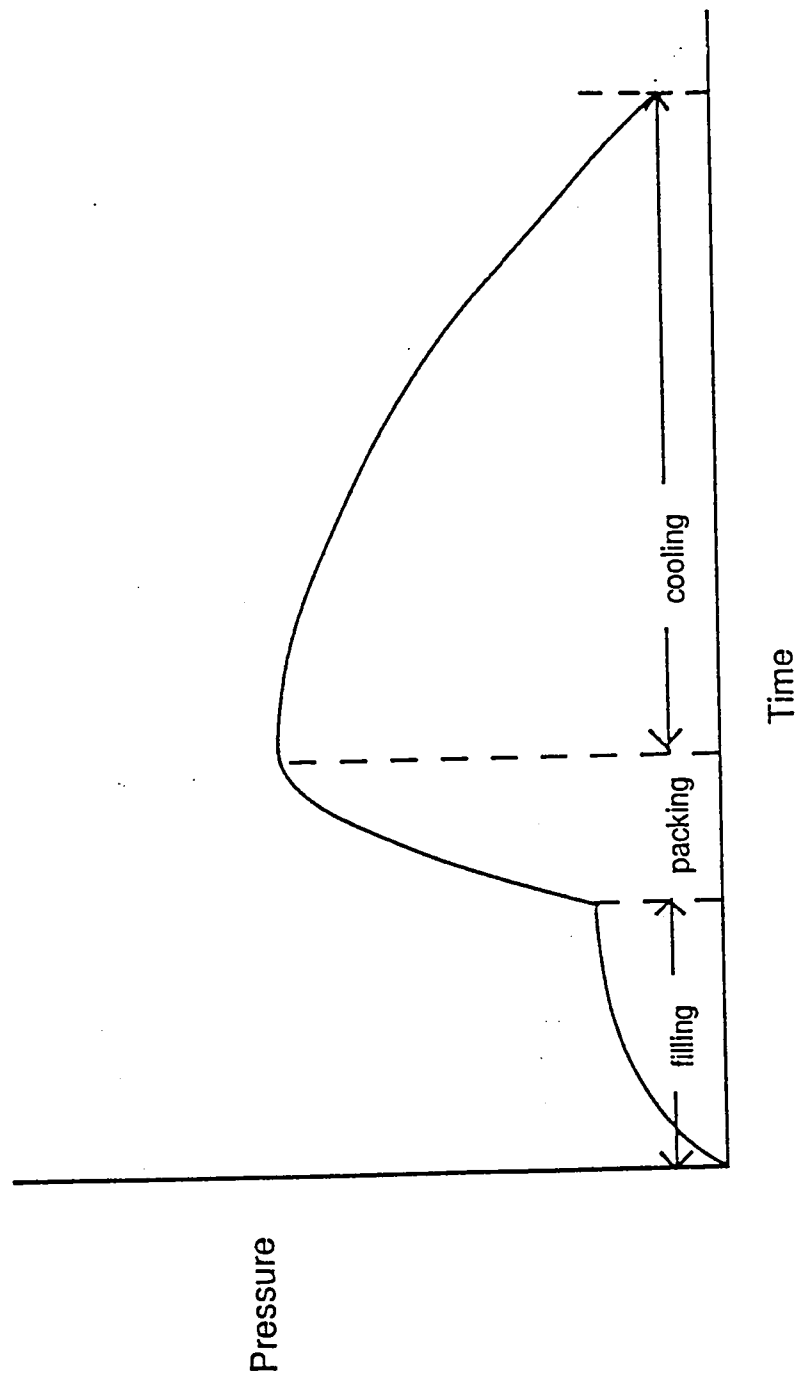


Figure 2.1: Typical pressure curve of the different steps of injection molding.

Until comprehensive computer programs have become available in recent years, studies of injection molding were concerned with the mold filling step along with some work on the packing and the cooling stage. This early literature will now be briefly reviewed.

2.1. Earlier studies on injection molding

The flow of polymer melts into a cold mold cavity is a typical problem in unsteady state non-isothermal flow of viscoelastic fluids. Thus a complete analysis of the entire process is not easy. The pioneering work on this subject was that of Spencer and Gilmore [4,5]. In these works the flow phenomena in the various steps of the injection molding process was studied. Observing the flow front patterns as affected by fill time, temperature, and pressure through a glass window, it was found that the hot polymer flows only in the centre region due to the formation of a solid polymer boundary layer along the mold wall. It was further concluded that the fill time is depended on the polymer melt viscosity and that raising the temperature of the mold lowers the fill time.

Similar studies on flow visualization were done by White and Dee [6]. They studied the flow pattern during injection molding of two rheologically characterized polymer melts. They used both isothermal and non-isothermal conditions in their study. They also used various shapes of molds. In their isothermal system they found

that the mold front as it flows along a rectangular end gated cavity changes shape with its position along the length of the cavity. Considering the melt front advancement and its behavior, mold filling could be divided into three stages. The first stage has to do with the flow of the melt from the narrow constriction at the gate into the mold the melt spreads in a radial manner. Secondly, after filling the corners there is a transition region in which the front changes from a circular shape to an almost flat profile. And the third stage is the one in which the nearly flat front continues to move forward until the mold is filled.

For non-isothermal flow in a rectangular mold the cold wall temperature plays an important role. The mold flow region is again subdivided into three stages: the fluid is radial at the entrance, after the corners are filled there is the development of the steady front shape, and the flow becomes curved (parabolic) in non-isothermal case and the third steady flow of this curved profile. The curvature depend on the nature of the polymer (PS>LDPE>HDPE) which is in the order of the activation energy of the viscosity.

The filling of rectangular cavity was studied by Ballman, Toor and Copper [7] using a transport phenomenon approach, treating the flow as a non-isothermal flow of a non-Newtonian, (power law) fluid.

Pearson [8] suggested the use of lubrication theory while dealing with the fluid mechanism of the mold filling. Using this assumption Richardson [9] showed that Hele-Shaw flow holds for mold filling when the part has a large aspect ratio.

Flow in a thin rectangular cavity in injection molding was studied by Dietz, White and Clark [10]. They studied the orientation development and distribution during the mold filling of amorphous polymers.

The studies noted above were concerned with simple geometries, such as disc or rectangular slabs. For more complicated geometries the modeling is not easy. In order to develop a numerical approach Kamal and Keing [11] proposed a mathematical model which couples the equations of continuity, motion and energy for each step of injection molding, using proper boundary conditions. It takes into account the non-Newtonian behavior of the melt, the temperature and shear rate dependence of viscosity, the latent heat of solidification and the difference in thermal properties of the melt and solid. In order to verify their procedure they first dealt with a rectangular mold. The numerical solution for their case yielded melt fronts which were in agreement with the experimental findings of Spencer and Gilmore [5] and Bayer and Spencer [12].

The post filling steps (packing and cooling) have received less attention until recent years. A thorough review of these recent studies has been reported by Huilier [13]. These studies are recent in computer programing for packing and cooling and are not however a part of the present work.

2.2 Recent comprehensive injection molding programs

More recently comprehensive work in the area of injection molding has been done by the Cornell Injection Molding Project (CIMP) at Cornell University. The project started in 1974 with an aim to do a systematic study of the injection molding process and the development of a proper scientific base for the injection molding process [14]. A computer aided design and simulation software of the entire injection molding process is their main contribution on this area. The theoretical work of the Cornell project has been cited by Hieber and Shen [15]. According to Hieber and Shen for a thin cavity mold (see Figure 2.2), that is, parts with large aspect ratio, the Hele-Shaw approximation is valid. Using a generalization of this approximation in which the rheological equation for an inelastic, non-isothermal, non-Newtonian fluid gives the following equations:

Equation of continuity:

$$\frac{\partial(b\bar{v}_x)}{\partial x} + \frac{\partial(b\bar{v}_y)}{\partial y} = 0 \quad (2.1)$$

where 'b' is the half gap thickness and $\bar{v}_x$ and $\bar{v}_y$ are the average velocities over z.

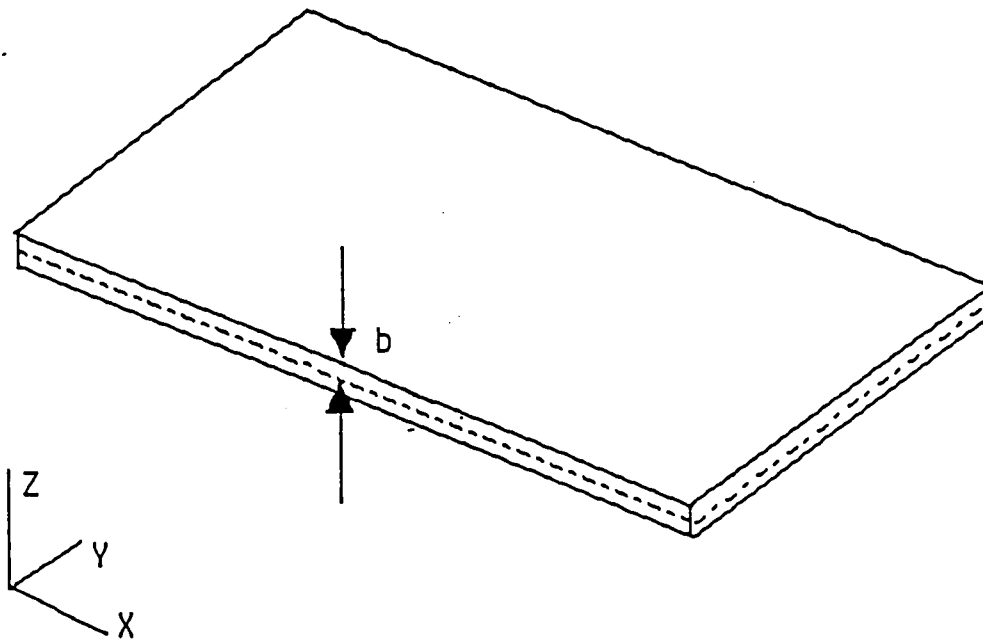


Figure 2.2: Schematic of a part with large aspect ratio.

Momentum equation:

$$0 = \frac{\partial \left(\eta \frac{\partial v_x}{\partial z} \right)}{\partial z} - \frac{\partial P}{\partial x} \quad (2.2a)$$

$$0 = \frac{\partial \left(\eta \frac{\partial v_y}{\partial z} \right)}{\partial z} - \frac{\partial P}{\partial y} \quad (2.2b).$$

where η is the shear viscosity and is a function of shear rate and temperature.

Energy equation:

$$\rho C_p \left(\frac{\partial T}{\partial t} \right) + (v_x) \frac{\partial T}{\partial t} + v_y \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} + \eta \dot{\gamma} \quad (2.3)$$

where C_p is the specific heat of the material, k is the thermal conductivity and $\dot{\gamma}$ the shear rate.

The numerical solution to these coupled equations is done by using a finite element analysis in the plane of the flow and a finite difference method in the thin or gapwise direction. Further work on developing the results and on incorporating a graphical display of results was done by Wang, Hieber and Wang [16].

The work done by the Cornell Injection Molding Program was put together to create a computer program called "C-FLOW", which is marketed by A.C.Tech, Ithaca, New York, which is used in this study. More recently the packing and cooling steps have been treated in the

"C-PACK" and "C-COOL" which are less developed. The entire package of program is marketed under the name "C-MOLD".

A number of computer programs for injection molding process are now on the market (about fifteen, according to Huilier [13]), but based on our review of three of them [17] they are surely similar in principle and based on the general assumptions put forth in the Cornell reports [1,2]. One such program available at the University of Tennessee, Knoxville, is that developed by the Structural Dynamics Research Corporation (SDRC), Milford, Ohio. The main program SDRC is called I-DEAS which is a large integrated design simulation software. In 1988, a module to simulate the injection molding process known as Plastics Analysis was incorporated into I-DEAS. The "Mold Filling" part of Plastics Analysis simulates the filling step of the injection molding process.

Finally then the present work is concerned with the two mold filling programs C-FLOW and Mold Filling.

CHAPTER 3

DESCRIPTION OF THE TWO PROGRAMS

3.1 General description of the two programs

The Cornell Injection Molding Program sponsored at Cornell University by the National Science Foundation started in 1974. One of the first computer programs to come from that work was called "C-FLOW" (later part of the bigger program "C-MOLD", which deals with the entire injection molding process), which is marketed by A. C. Tech, Ithaca. C-FLOW deals with the mold filling step of the injection molding process.

SDRC started on their work on the field of injection molding in 1981 by starting on their Mold Cooling Analysis Program (MCAP), which has to do with the cooling of the metal mold. Later in 1983, SDRC released "Polycool". A modified version of program, "Polycool2" came out in 1985 and in 1986 "Polyfill" which is a simulation program for the filling stage was released. Putting all these together and eliminating of some initial errors, the Plastics Analysis part of I-DEAS was put together in 1988.

I-DEAS is basically a mechanical engineering design program. It has different modules, each related to some definite design or analysis task. These modules are known as families. The two families used for the simulation of the injection molding process are the "Finite Element Analysis (FEA)" and the "Plastics Analysis". The

part geometry is created in the FEA module and then the finite element model is transferred to the Plastics Analysis module for the solution task. The results obtained in the Plastics Analysis are further transferred to FEA for the graphical display of the results.

3.1.1 Nature of the two programs

The basic assumptions and equations used for the analysis of the mold filling process in both programs are the same. In the filling process a highly viscous, non-Newtonian polymer fluid is injected into the mold cavity. The fluid dynamics of the process is governed by the continuity equation, momentum equations and the energy equation. The basic assumptions and other details have been discussed in some details in chapter 2.

3.1.2 Method of analysis

The flow of melt through the mold itself is considered to be thin slit flow and is modelled across the center-line, neglecting the corners and edges (this is called "thin cavity flow" in the C-FLOW program). In the case of runners including the sprue and gates, a hydraulic diameter idea is assumed (this is called "channel flow" in C-FLOW). That is, runners which are not circular in cross-section are treated by substituting an equivalent circular tube using the hydraulic diameter (D_H) idea.

$$D_H = \frac{4(\text{cross sectional area})}{(\text{perimeter})} \quad (3.1)$$

3.2 Detailed description of the two programs

3.2.1 C-FLOW

3.2.1.1 General description

C-FLOW is a useful injection molding simulation software developed by the Cornel Injection Molding Program (CIMP) at Cornell University and marketed by A. C. Tech, Ithaca. The overall approach used for this program is such that it needs minimum input data to give a number of useful results as outputs which could be used to study and optimize various process parameters related to a process.

A detailed description of the theoretical background is reported by Hieber and Shen [15] and Wang Hieber and Wang [16].

The inputs required for the mold filling process simulation are:

a. Part geometry:

The cavity geometry is input into the C-FLOW analysis program as a finite element mesh created by the geometry editor and automatic mesh generator GEOMESH.

b. Material Selection:

The data bank of C-FLOW includes a variety of plastic materials. The required material is selected from this data bank. Materials not included in the C-FLOW data bank can also be incorporated by feeding in the specific characteristic data.

C-FLOW uses a constant melt density, specific heat and thermal conductivity and a non-Newtonian viscosity model as material

parameter. The viscosity curve of a selected material can be seen on the screen. The rheological model used for the viscosity of the material is the modified Cross model with Arrhenius (exponential) temperature dependence [18]. This can be mathematically expressed as

$$\eta = \frac{\eta_o(T,P)}{\left[1 + \left(\frac{\eta_o \dot{\gamma}}{\tau^*}\right)^{1-n}\right]} \quad (3.2)$$

$$\text{where } \eta_o(T,P) = B \exp\left(\frac{T_b}{T}\right) \exp(\beta P) \quad (3.3)$$

Thus, finally, the general expression is

$$\eta = \frac{B \exp\left(\frac{T_b}{T}\right) \exp(\beta P)}{1 + \left[\frac{B \exp\left(\frac{T_b}{T}\right) \exp(\beta P) \dot{\gamma}}{\tau^*}\right]^{1-n}} \quad (3.4)$$

where B , T_b , β , n , τ^* are constants.

Generally the pressure dependence is neglected, that is, $\beta = 0$.

Giving

$$\eta = \frac{B \exp\left(\frac{T_b}{T}\right)}{1 + \left[\frac{B \exp\left(\frac{T_b}{T}\right) \dot{\gamma}}{\tau^*}\right]^{1-n}} \quad (3.5)$$

c. Process conditions:

The process that can be specified as inputs are:

- I. Melt temperature ($^{\circ}\text{C}$)
- II. Mold temperature ($^{\circ}\text{C}$)
- III. Fill time (seconds)
- IV. Ram speed profile (ten step distribution of average flow rate can be used)
- V. Maximum injection pressure (MPa)
- VI. Eject temperature ($^{\circ}\text{C}$)

Two types of analysis can be done, one is a simplified Newtonian and isothermal analysis (called ANALYSIS-EZ) and the other is a rigorous non-Newtonian, non-isothermal analysis (called ANALYSIS).

The important outputs from C-FLOW are

- I. From ANALYZE-EZ
 - i. Melt front contours.
- II. From ANALYSE
 - i. Contour plots of melt front, pressure, temperature and velocity
 - ii. Time plots of pressure and temperature.
 - iii. Gapwise distribution of temperature, velocity, shear rate or shear stress.
 - iv. Shaded image of pressure, temperature, shear rate and shear stress distribution.

3.2.1.2 Procedure for using C-FLOW

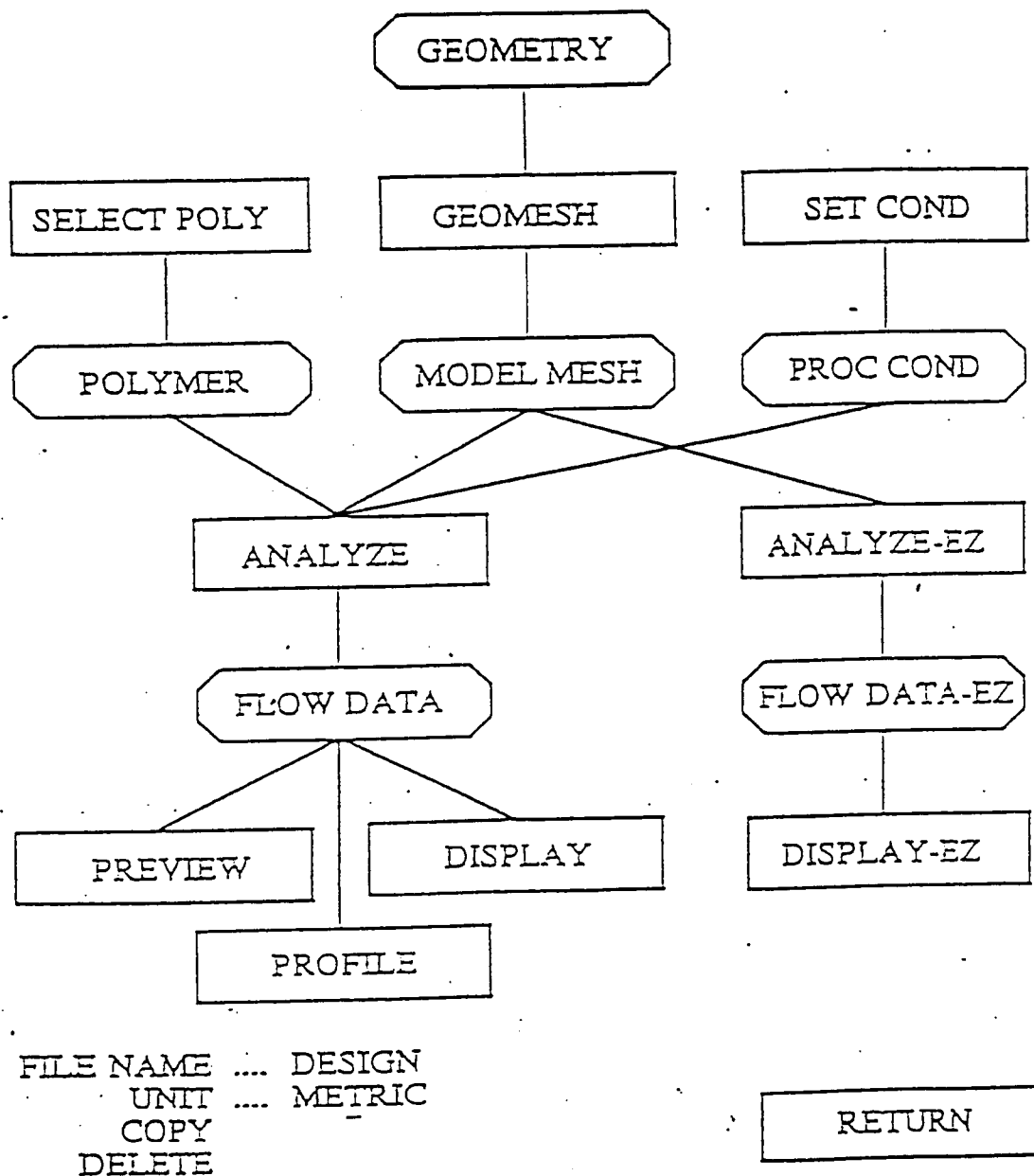
All tasks of C-FLOW are performed by first going into the control panel. The main C-FLOW control panel is shown in Figure (3.1).

The first task is to specify the file name and the unit system to be used. The next task is to input the data into the program by clicking in into the respective boxes of the control panel.

There are two kind of boxes in the control panel: rectangular for program modules and hexagonals for data inputs. If a data file already exists the caption in the data box will be highlighted.

The different tasks indicated by the boxes of the control panel are:

Select polymer:	Selects the polymer from the existing data bank.
Geomesh:	Creates geometry of the part,the runners and channels and the finite element mesh of the part.
Set conditions:	Sets the process conditions for analysis.
Analyze-ez:	Performs a simplified Newtonian and isothermal analysis
Analyze:	Performs the accurate analysis based on non-Newtonian and non-isothermal conditions.
Display-ez:	Displays the melt front contour plot from the isothermal, Newtonian analysis.



C-FLOW 1.5

Figure 3.1: Flow chart of C-FLOW program.

- Preview:** Displays the results of non-Newtonian, nonisothermal analysis; such as melt front contour plots, contour plots and time history plots of pressure, bulk temperature, shear rate, shear stress, velocity distribution, melt front area and melt front velocity
- Profile:** Displays temperature, velocity, shear rate, shear stress profile in the gapwise directions.
- Display:** Displays melt front and pressure, temperature, shear rate and shear stress distribution in shaded plots.

After specifying a file name and the unit system, polymer selection, geometry creation and setting of the process parameters are done. After saving these tasks, the associated boxes are highlighted. The next task is to choose the analysis method, either the isothermal and Newtonian method or the non-isothermal, non-Newtonian method. The associated square box is then selected. The analysis is performed and when complete the box is highlighted. The outputs needed can be observed by selecting preview, profile, display or display-ez.

3.2.2. I-DEAS (Mold Filling)

3.2.2.1 General description

I-DEAS is a versatile program consisting of numerous modules which performs different types of analysis. Each module is known as a family. The injection molding simulation is done by its "Plastics Analysis" family; with the finite element geometry being carried over from the "Finite Element Analysis (FEA)" family, that is, the geometry of the part is created in the FEA module and the finite element model is brought over to the Plastics analysis module where the actual analysis is done.

3.2.2.2 Procedure for using Mold Filling

The sequence of tasks performed for the simulation of the mold filling of an injection molding process is shown in Figure (3.2).

First, the basic geometry of the part is created in the geometry creation task of FEA family and then again in the FEA family's mesh creation task the finite element model is set up. The finite element model is then transferred to the Plastics Analysis module. Here the material selection and the model checking is done and the process parameters selected. The analysis type, whether isothermal or nonisothermal and non-Newtonian, is specified. The mold filling analysis is then done and the results are loaded and carried to the finite element analysis' post processing task to be displayed graphically.

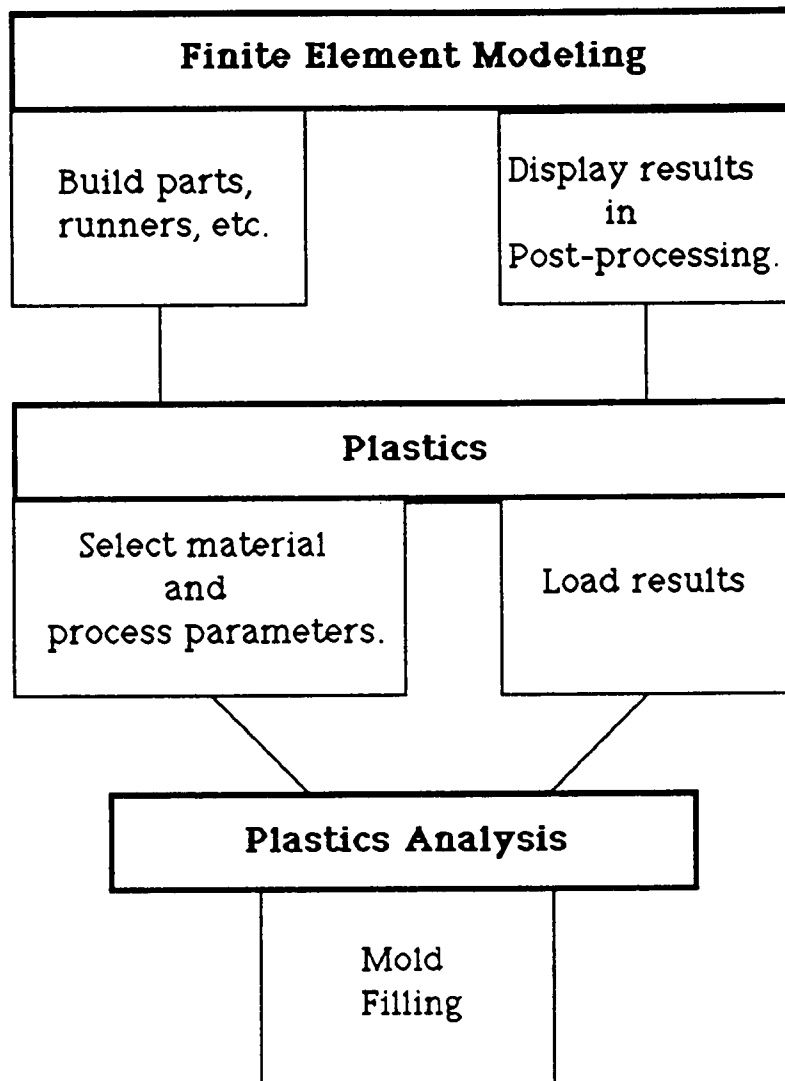


Figure 3.2: Flow chart of I-DEAS' Mold-filling program.

The material selection is from its own material data bank. The geometry is carried over from the FEA family, where it is created. The process parameters are set according to one of the three options, based on fill time, on volumetric flow rate or on pressure. A profile could be described for volumetric flow rate or pressure.

Thus inputs to Mold Filling are:

- a. Material: Selected from its own data bank.
- b. Geometry: Created in another module of I-DEAS (in FEA) and carried over to Plastics Analysis.
Geometry could be carried over from other CAD programs from outside if in proper format.
- c. Process parameters: Process parameters like melt temperature, mold temperature, no flow temperature, pressure, fill time, etc. are specified.
- d. Analysis options: Type of analysis to be done, Newtonian, isothermal or non-isothermal, non-Newtonian is specified.

One of the important step to be performed just after the model is carried over from another family is the 'model checking' step. The model is checked for proper node labeling, proper element size and dimensions. If the model fails in this step the analysis cannot be performed. If failure occurs then the model is transferred back to the FEA module, corrected then transferred back to Plastics analysis and rechecked.

After the analysis is done the specific result datasets of interest are selected and carried back to FEA family. The results are then displayed as contour plots with numerous display options like shaded plots, continuous plots, etc. or as x-y graphs as a post processing task of FEM.

The results obtained from Mold Filling are:

- (a) Pressure: Fluid pressure in the plastic.
- (b) Stress: Absolute instantaneous fluid stress.
- (c) Rate of strain layered: Instantaneous value of (dv/dz) in the plastic
- (d) Flux: The rate of heat flow per unit area.
- (e) Temperature layered: Gapwise temperature in the plastic.
- (f) Temperature bulk: Temperature of an element averaged over thickness.
- (g) Solid layer thickness: Thickness of the two boundary frozen layer.
- (h) Fill time: The time at which the control volume of a particular node is filled. These contours show the pattern of filling.

Important aspect of I-DEAS is that in case of the finite element mesh triangular as well as quadrilateral elements can be used in modeling the part. Holes and inserts are very easily modelled.

CHAPTER 4

RESULTS OF COMPUTER PROGRAMS AND COMPARISON WITH DATA

Two computer programs dealing with the mold filling part of the injection molding process, C-FLOW and Mold Filling have been run and compared to each other and with experimental data. Three geometries of varying complexity have been used for the study: (1) a flat rectangular mold (slab) with internal obstructions, a geometry used by the Cornell Injection Molding Project (CIMP) [3]; (2) a 24" TV cabinet, a practical geometry of considerable complexity (2545 nodes and 4635 elements), which is in actual production by the Philips Consumer Electronics Company; and (3) a simplified version of the Philips' geometry (1366 nodes, 2399 elements). The details of the runs made on these various geometries will now be discussed.

4.1 Simulation of flat rectangular mold and comparison with data

A two-gated rectangular mold with two inserts was used for the purpose of comparing the results obtained from the two programs, as well with experimental results. The finite element representation of this geometry is shown in Figure 4.1. This mold geometry was used by the Cornell injection molding program to

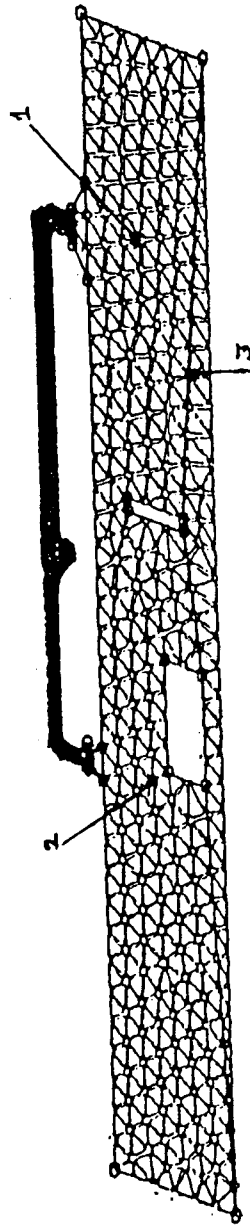


Figure 4.1: Finite element representation of the rectangular slab geometry.

experimentally determine the pressure development at three different location of the mold [3]. For this purpose pressure transducers were positioned at points 1, 2, 3, as shown in Figure 4.1. The experimental results as reported by CIMP are shown as a pressure-time curve in Figure 4.2. The polymer used for the experiment was a commercial acrylonitrile-butadiene-styrene (ABS), marketed by Monsanto under the trade name Lustran Q-714.

The values of the material parameters of importance for an injection molding process are summarized in Table 4.1 and the viscosity curves are drawn out in Figure 4.3.

Mold filling simulations of this mold were carried out using both the C-FLOW and Mold Filling programs.

4.1.1 Geometrical details of the mold

The mold is a two-gated rectangular geometry with two inserts. The two runners leading to the two gates are of different diameter. Though the actual runners were trapezoidal, for the present simulation they have been modelled as circular tubes. The cavity dimension is 74.3 cm by 11.1 cm with two fan gates. The radius of the left arm of the runner is 0.428 cm and that of the right runner is 0.719 cm. The fan gate thickness is 0.25 cm on the left gate and 0.3 cm on the right gate. The overall cavity thickness of the mold is 0.33 cm.

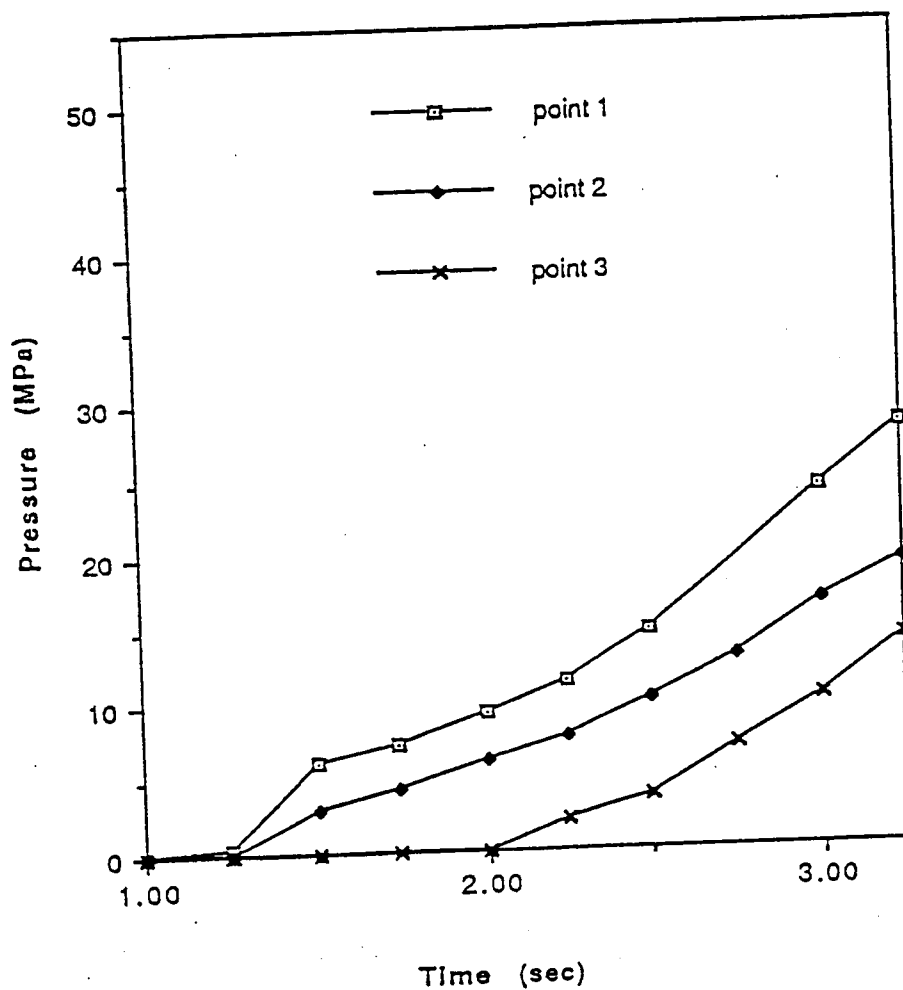


Figure 4.2: Experimental pressure curves at positions 1,2,3 as reported by Cornell project [3].

Table 4.1: Summary of material parameters of the ABS material (Lustran Q-714/Monsanto) used for the simulation of the injection molding process of the rectangular slab [3].

Physical Properties:

$$\rho = 1.02 \text{ gm/cm}^3$$

$$C_p = 2.4E7 \text{ erg/gm } ^\circ\text{K}$$

$$k = 1.8E4 \text{ erg/sec cm } ^\circ\text{K}$$

Rheological constants for the 5-constant viscosity model:

$$n = 0.2984$$

$$T_b = 11440 \text{ } ^\circ\text{K}$$

$$B = 1.456E-5 \text{ gm/cm sec}$$

$$\tau^* = 3.699E5 \text{ dyne/cm}^2$$

$$\beta = 0$$

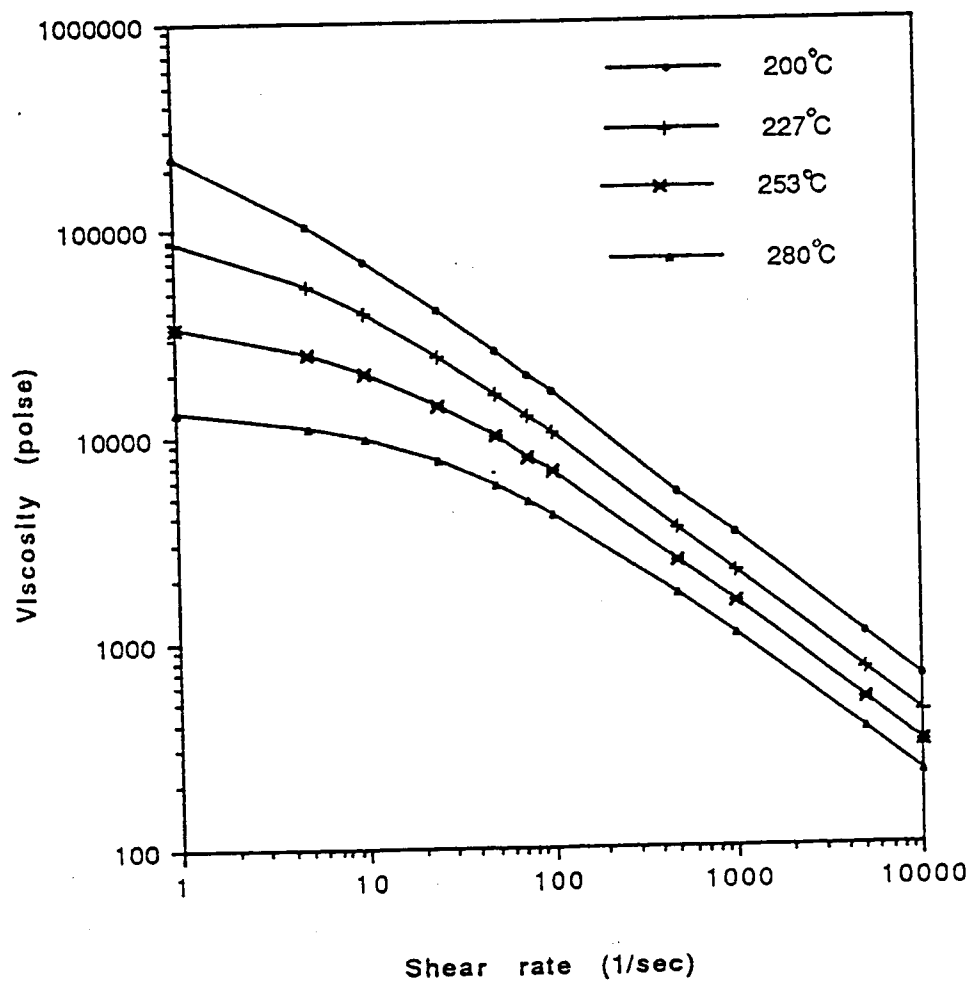


Figure 4.3: Shear viscosity-shear rate curves for the ABS material (Lustran714/Monsanto).

4.1.2 Simulation results and discussion

Using the mold geometry which was used in the experimental studies of the CIMP, simulation of the mold filling steps was carried out using both Mold Filling and C-FLOW. The results were compared with each other and those obtained from mold filling experiment as reported by Cornell [3].

The material used for the experimental study of the mold filling part of the injection molding process by CIMP, as mentioned earlier, was the ABS polymer, Lustran Q-714 manufactured by Monsanto. This material is not present in the existing material data bank of C-FLOW nor in the data bank of I-DEAS (which contains the data bank associated with Mold Filling). But in C-Flow there is provision for adding a new material by specifying its important properties, especially its rheological properties. This cannot be done with I-DEAS in the program as presently available. Thus a material already present in the existing data base had to be used. When comparing the viscosity curves for Lustran Q-714 to viscosity curves for various ABS materials in the I-DEAS data bank it was found that the curves for "ABS1", a generic ABS material, as shown in Figure 4.4, are very similar to those of Lustran Q-714. Thus in the simulation of the rectangular slab using Mold Filling "ABS1" was selected from the data bank.

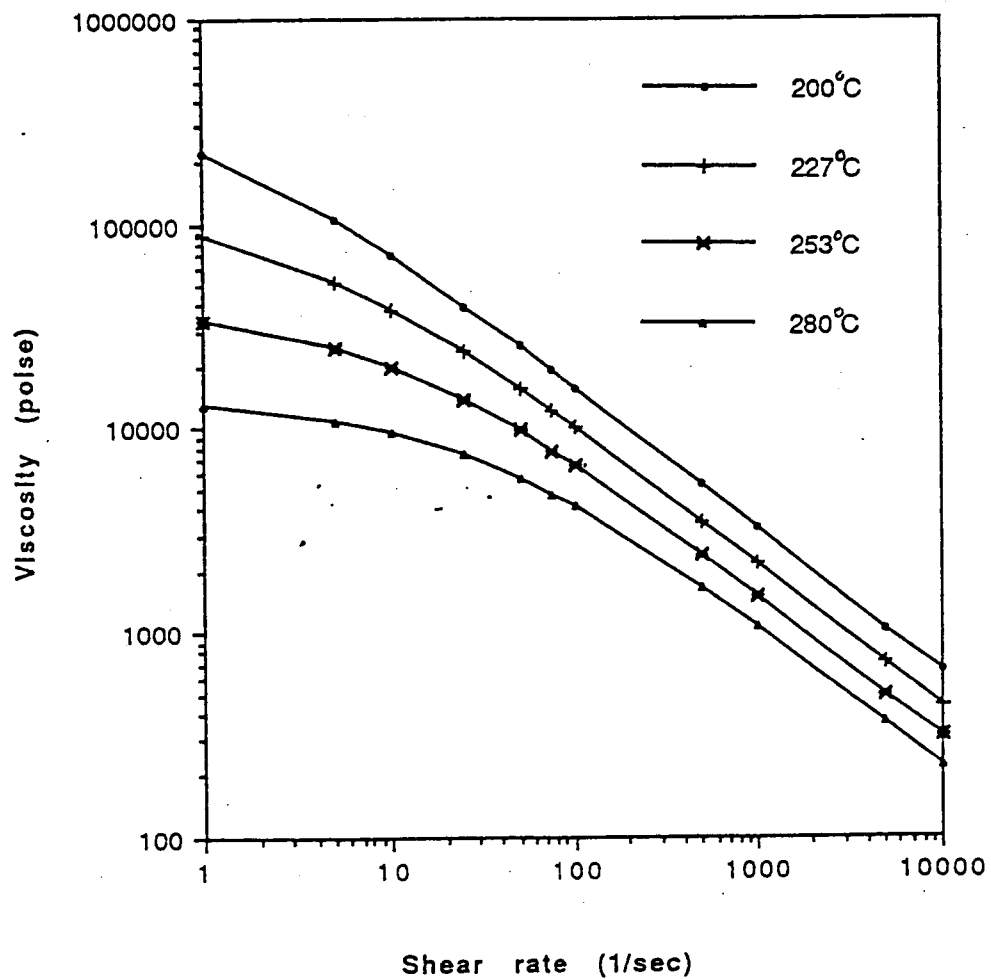


Figure 4.4: Shear viscosity-shear rate curves for ABS-1 of I-DEAS' data bank.

The conditions used in running both programs were those of the experimental runs, namely:

Mold temperature = 40°C

Melt temperature = 225°C

Fill time = 3.25 sec

Maximum pressure = 45 MPa

The comparative pressure plots at the three different locations, positions 1, 2, and 3 (see Figure 4.1), are given in Figures 4.5, 4.6, and 4.7, respectively.

Comparing the results obtained from C-FLOW to that from Mold Filling, as well as that obtained from experimental observations [3], it is found that the results obtained from the two programs were in reasonable agreement with each other and with the experimental data at positions 1 and 2 (see Figures 4.5 and 4.6). At position 3, however the two programs predict pressures which are similar but much higher than the experimental data (see Figure 4.7). This is likely due to the inaccuracies introduced by the heat balance equation in which wall effects are neglected on the edges. If the material is 'seeing' the entire mold in advance of the melt flow, as in case of positions 1 and 2 which are in the near entrance region such effects are usually negligible. These effects are prominent as the material approaches the end of the mold, such as position 3 which is at the end of the mold.

When examining the pressure curves spurious pressure "spikes" are sometimes noticed at the last instant of fill, as shown in

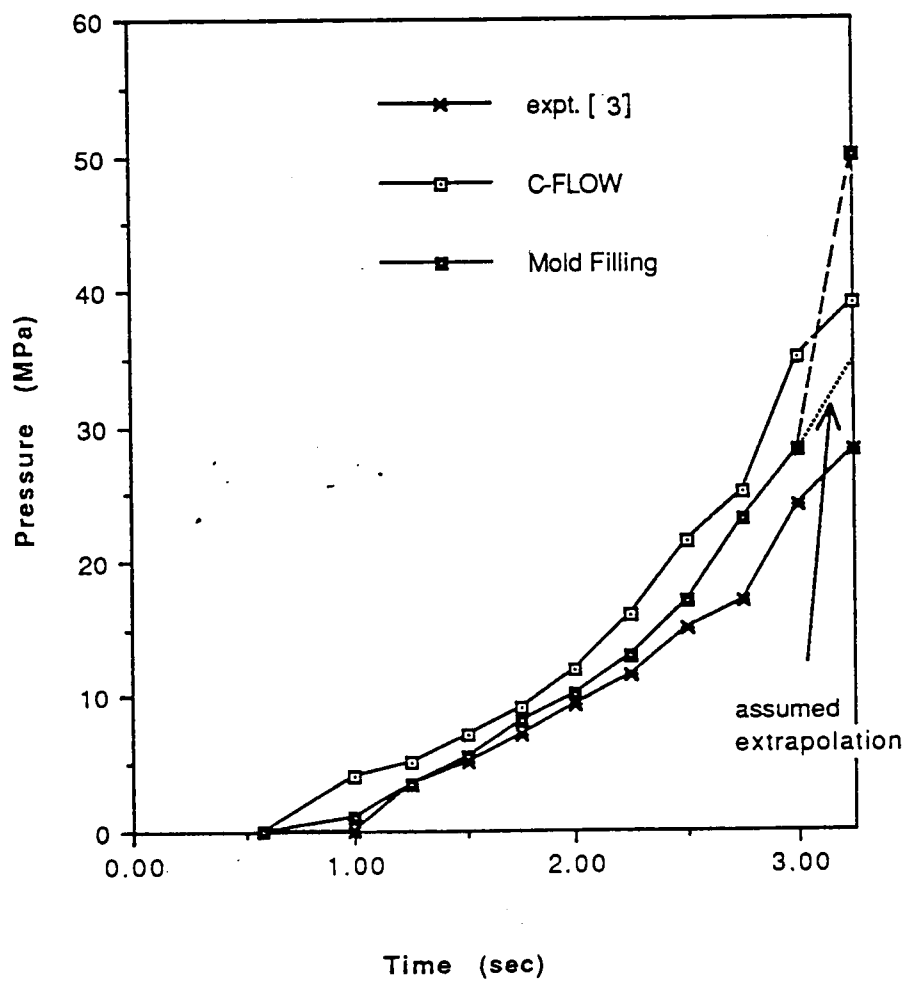


Figure 4.5: Pressure curve at position 1.

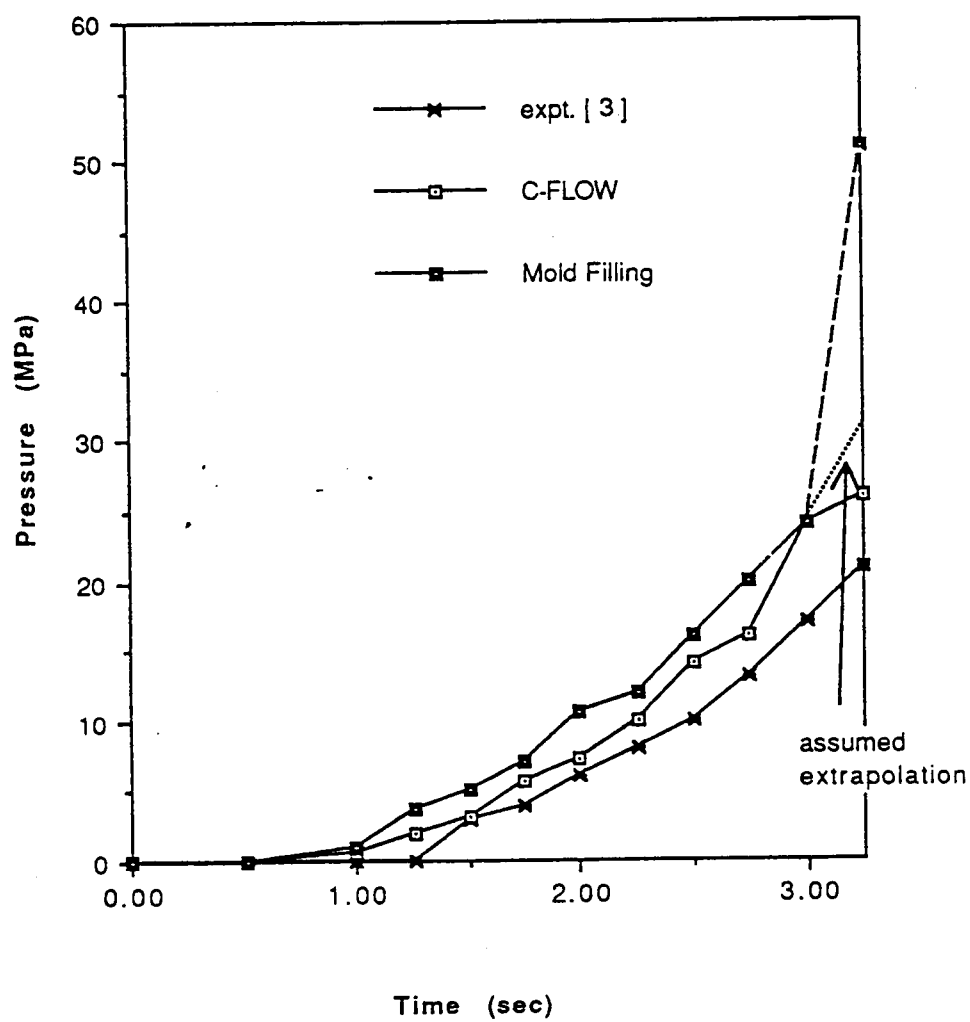


Figure 4.6: Pressure curve at position 2.

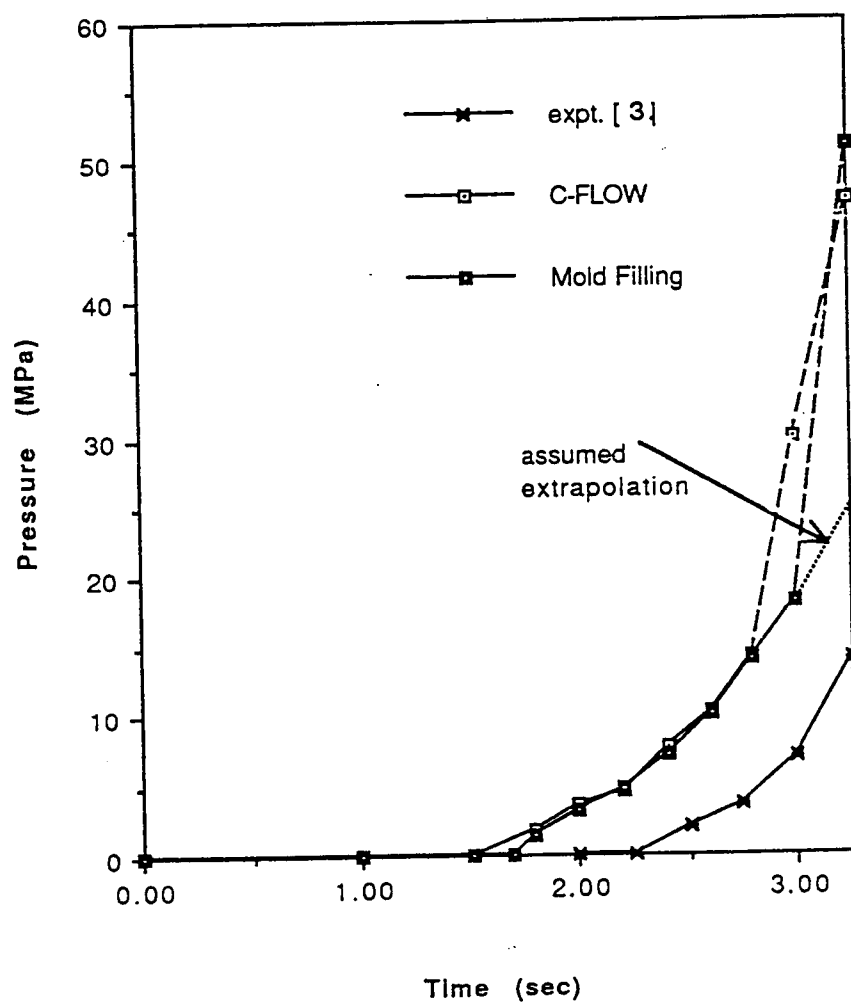


Figure 4.7: Pressure curve at position 3.

Figures 4.5, 4.6 and 4.7. These spikes, shown with dashed lines, were neglected. These spikes are due to numerical problems associated with the filling of many small elements near the end of fill. Generally the mold is filled at a constant volumetric flow rate but the last element may over fill under these conditions and give rise to infinite spike (because the material is incompressible). To avoid an infinite spike the C-FLOW program shifts to a pressure-controlled fill near the end of the fill, the pressure being the maximum injection pressure allowed by the operator. However for reasons that are not entirely clear, for most complicated geometry (the 2545 noded 4635 elements Philips, geometry) the program does not give a realistic value in the pressure-controlled portion. This effect has also been observed by the Philips' group [19]. Using a suggestion of Mr. Ben Ferguson of Philips' Company [19], and our own experience with running other geometries, it was decided to ignore the spike in the pressure curve and to extrapolate the earlier portion of the curve to obtain the final pressure (as shown with the dotted lines). The final pressure obtained in this manner is, then, similar in both the programs.

4.2 Simulation of the TV cabinet using both the Philips' model and the simplified model and comparison with data

Two simulations of the 24" TV cabinet geometry were used in this study: (1) an actual geometry of considerable complexity (2545

nodes, 4635 elements), provided by the Philips Consumer Electronics Company; (2) a simplified version of the Philips' geometry (1366 nodes, 2399 elements) which maintains the overall shape of the complete simulation but omits many small details (grooves, slots, etc.). A photograph of the actual production part is shown in Figure 4.8 and the finite element representation of the Philips' model and the simplified model are shown in Figures 4.9 and 4.10 respectively.

The details of the 24" TV cabinet as manufactured by Philips' was provided to us by the company; along with the process conditions that are used in the plant and in their simulations.

The main objective of creating a simplified geometry was to reduce the run time in the computer and to provide a geometry that could reasonably be used in class projects. The Philips' model was very complicated, giving all detailed features of the actual part. The finite element model consisted of a large number of nodes (2545 nodes and 4635 elements) and it took a long time to execute single set of conditions on the computer (more than four and a half hours on UT's IBM mainframe computer).

Both the models were run on C-FLOW. The material used in the manufacture of the part is a commercial grade of high impact polystyrene marketed by Huntsman under the trade name Huntsman/HIPS:707/FR. According to informations available from Huntsman Company this material is composed of 14-15% flame-retardant, 10% rubber (butadiene), very minute percentage (less than .001%) of zinc stearate (lubricant) and rest polystyrene. Carbon

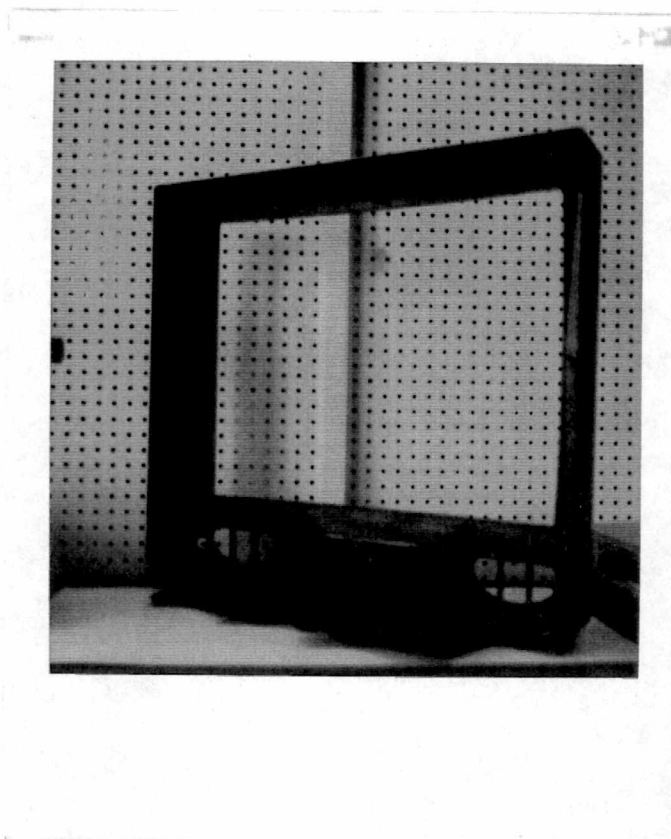


Figure 4.8: A photograph of the actual production part.

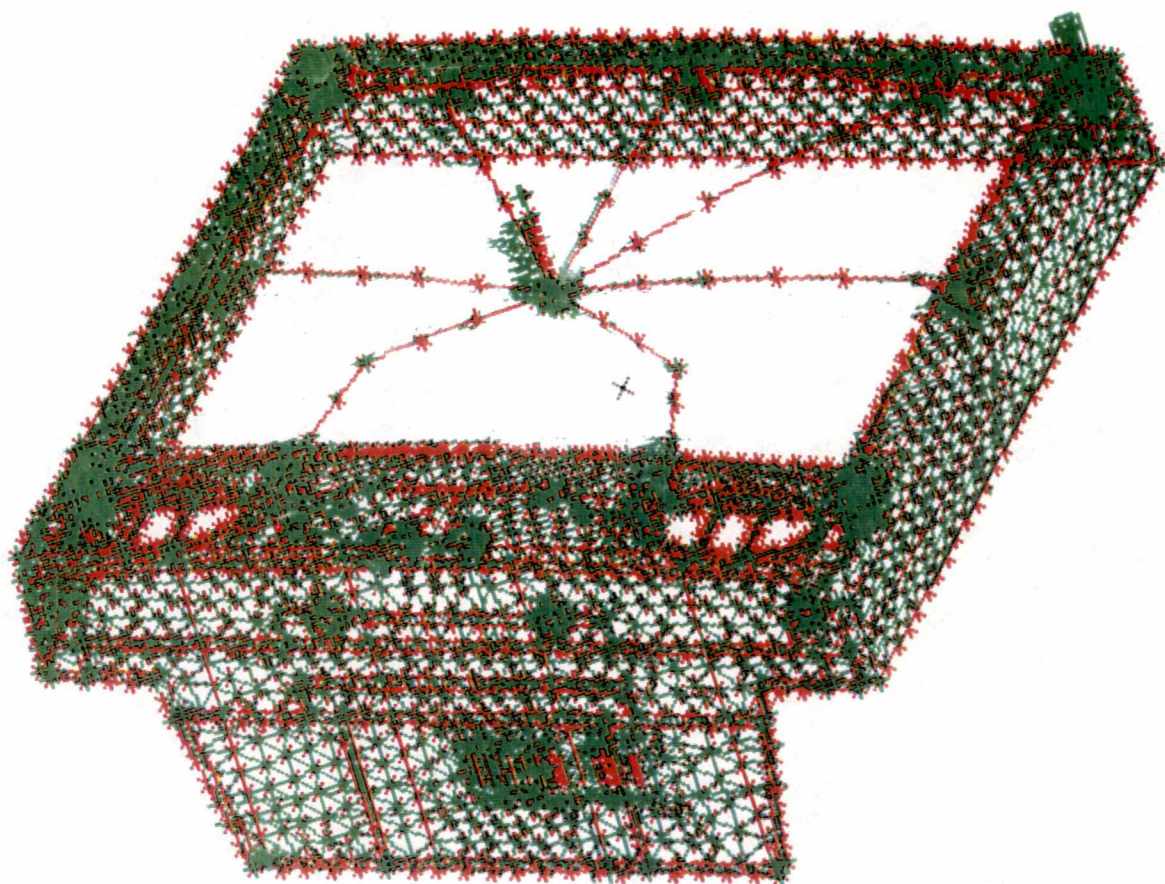


Figure 4.9: Finite element representation of the TV cabinet
(Philips' complete model)

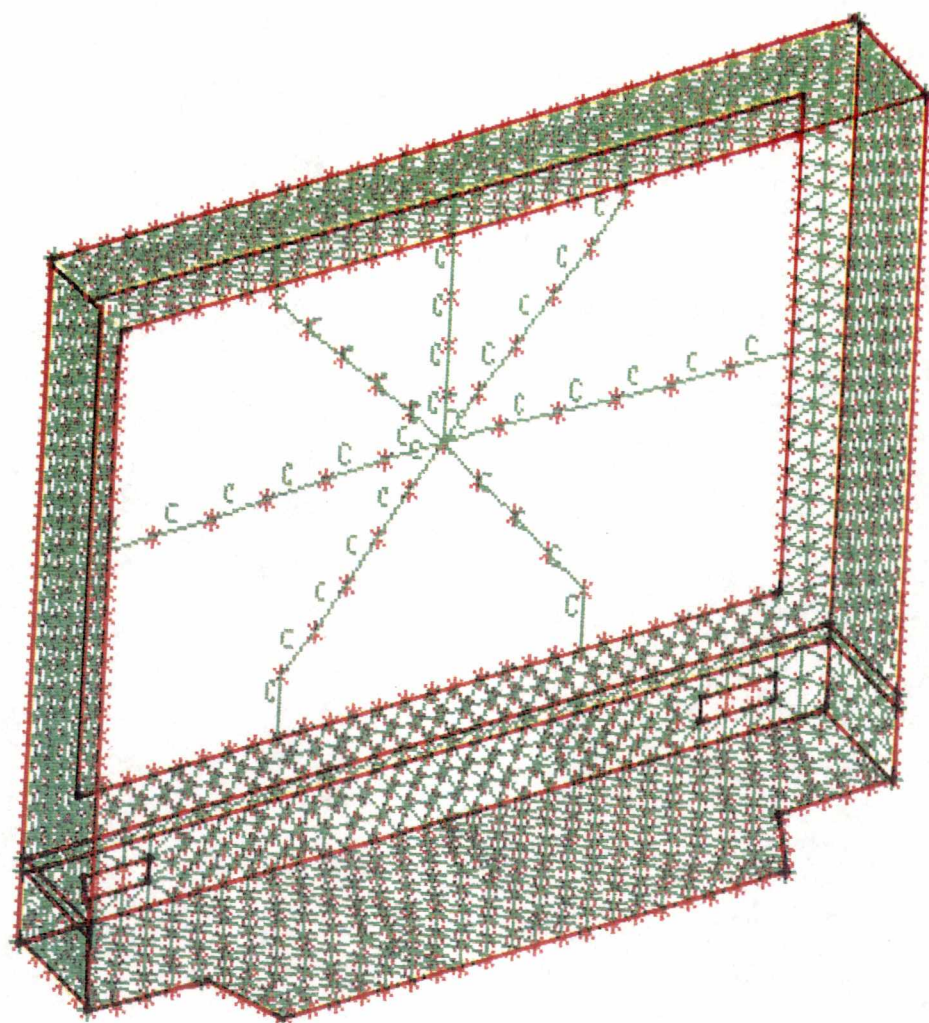


Figure 4.10: Finite element representation of the TV cabinet (simplified model).

black was added to pre-color the material. The material constants needed for the simulation are given in Table 4.2 and the viscosity curves at several temperatures are given in Figure 4.11

The process parameters as actually measured in the plant by Philips [19] are: melt temperature of 248°C, mold temperature of 40°C, fill time of 5.5 sec and maximum pressure for complete fill = 30 to 40 MPa.

There is a considerable range of pressures for "short shots", depending on how much of the mold was filled. Typical values for incomplete filling of the "tongue" portion of the mold are 80-90% of the maximum pressure for the complete fill. These values are summarized in Table 4.3.

4.2.1 Study of a complete fill

Simulation of the mold filling step of the injection molding process was carried out using the same process conditions and the same material as that used by Philips in the plant.

The inlet pressure versus time results obtained from the simulation of both the models are shown in Figure 4.12(a). Figure 4.12(b) is the same plot over a limited pressure range. From the simulation results obtained it was found that for complete filling of the mold a final pressure of 39 MPa is needed for the simplified model, which is in reasonable agreement with the in-plant (production) values of 30 - 40 MPa (see Table 4.3). In case of the

Table 4.2: Summary of material parameters of the high impact polystyrene material (Huntsman/HIPS:707FR) used for the simulation of the injection molding of the TV cabinet [19].

Physical Properties:

$$\rho = 1.09 \text{ gm/cm}^3$$

$$C_p = 1.9E7 \text{ erg/gm } ^\circ\text{K}$$

$$k = 1.81E4 \text{ erg/sec cm } ^\circ\text{K}$$

Rheological constants for the 5-constant viscosity model:

$$n = 0.3233$$

$$T_b = 13437 \text{ } ^\circ\text{K}$$

$$B = 3.913E-8 \text{ gm/cm sec}$$

$$\tau^* = 2.941E5 \text{ dyne/cm}^2$$

$$\beta = 0$$

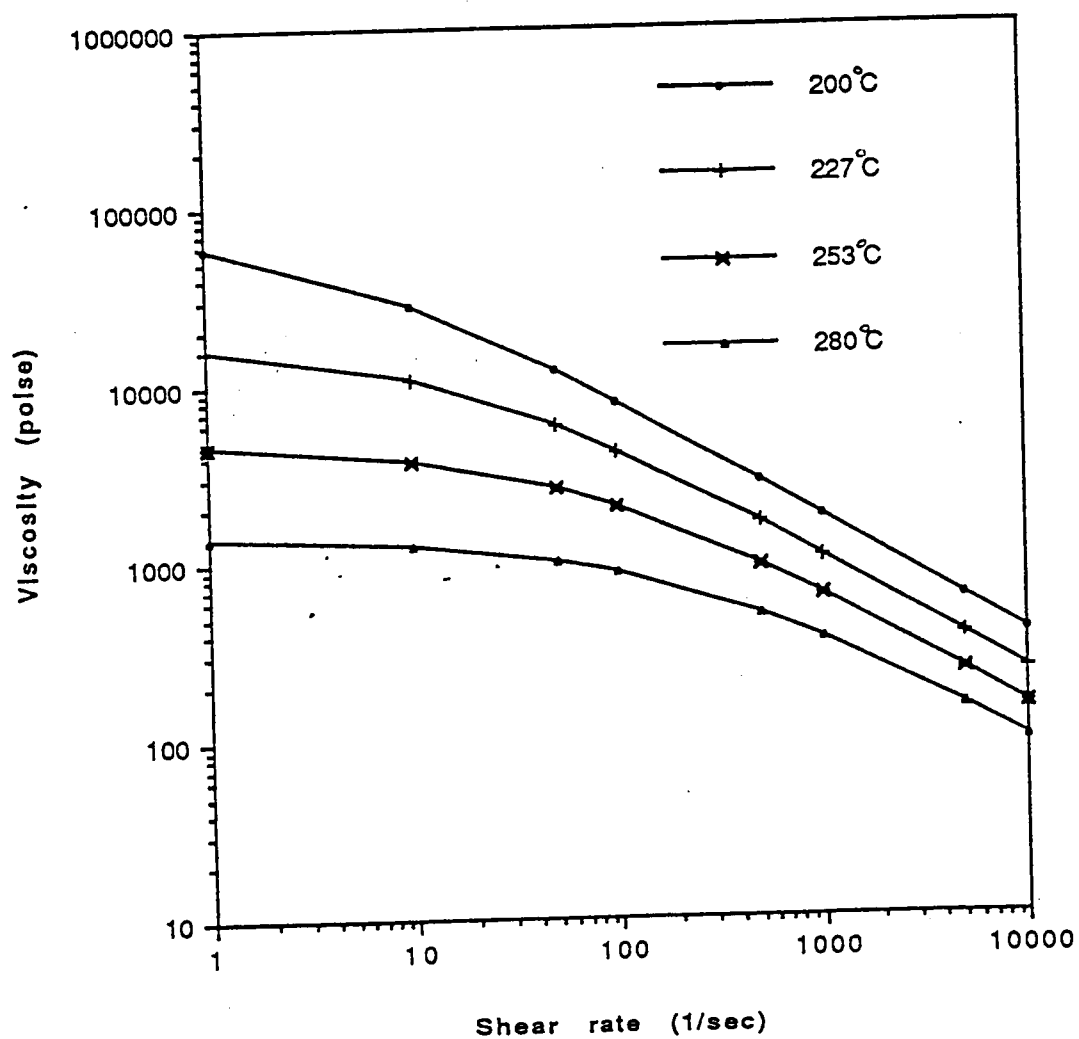


Figure 4.11: Shear viscosity-shear rate curves for Huntsman/HIPS:707FR.

Table 4.3: Operating parameters for the TV cabinet part, as measured in the plant [19].

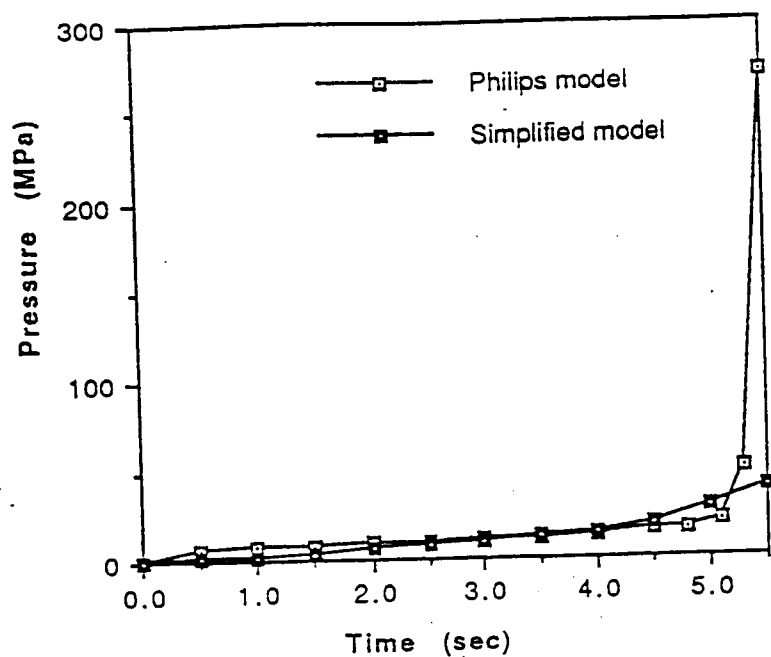
Melt temperature = 248°C

Mold temperature = 40°C

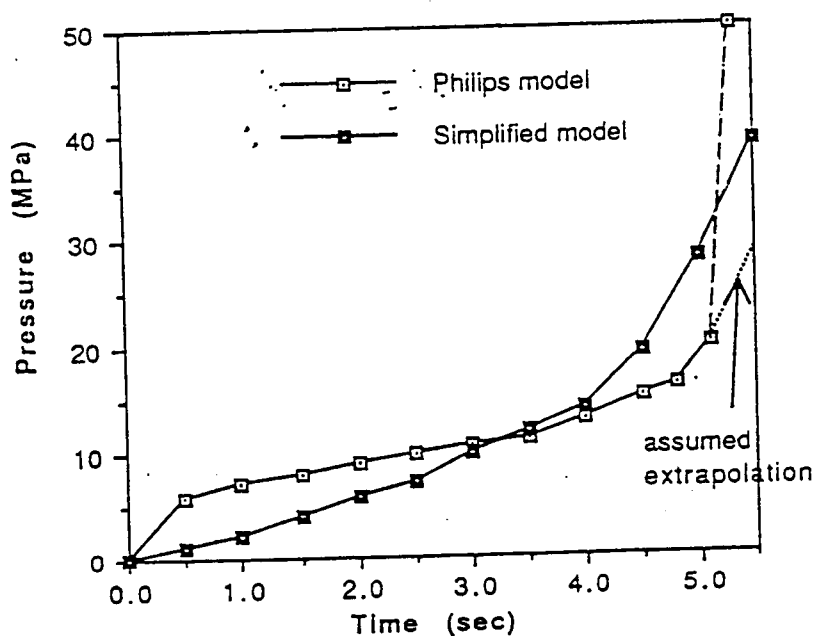
Fill time = 5.5 sec.

Maximum pressure for complete fill = 30 to 40 MPa

Typical "short shot" pressures, percentage of maximum
for complete fill = 80-90%



(a) Results using full pressure scale.



(b) Results using pressure scale of low range (enlargement of results in part (a) above).

Figure 4.12: Pressure comparison of the two models for the TV cabinet for complete fill. (Maximum pressure of 275 MPa for the Philips' model and 40 MPa for simplified model).

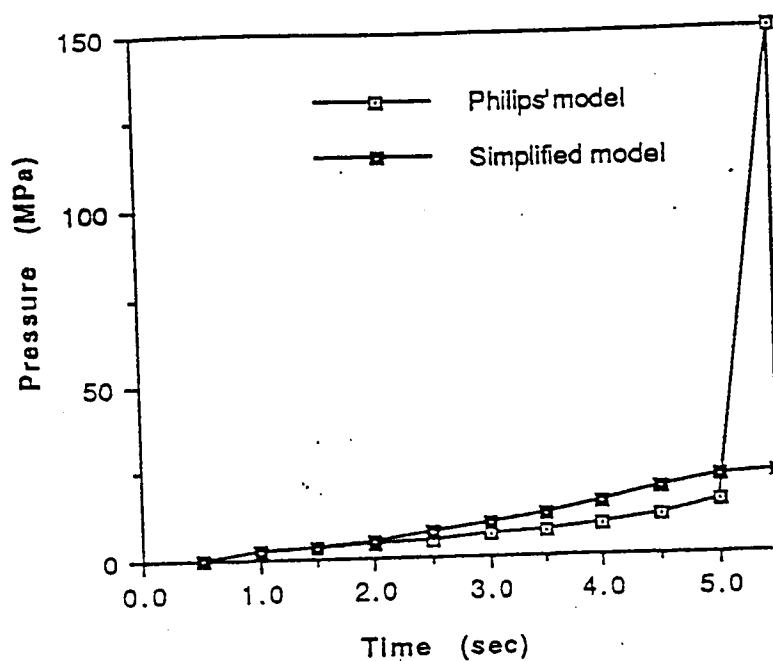
Philips' model, comparing the pressure curve it was found that up to the second from the last time interval the pressures are comparable, but a spurious pressure spike is observed at the last instant of filling, which rises up to 275 MPa. As mentioned earlier, at the suggestion of the Philips' group [19] and from our own experience of running other geometries, the last pressure spike is neglected. Instead in order to obtain an estimated final pressure, the general slope of the curve is followed and is extrapolated to the last time instant. The final pressure obtained by this extrapolation is considered as an approximate final pressure. Following this procedure (as shown in Figure 4.12(a)) the approximate final pressure obtained is 30 MPa. This value is in reasonable agreement with plant data (see Table 4.3).

4.2.2 Study of a "short shot"

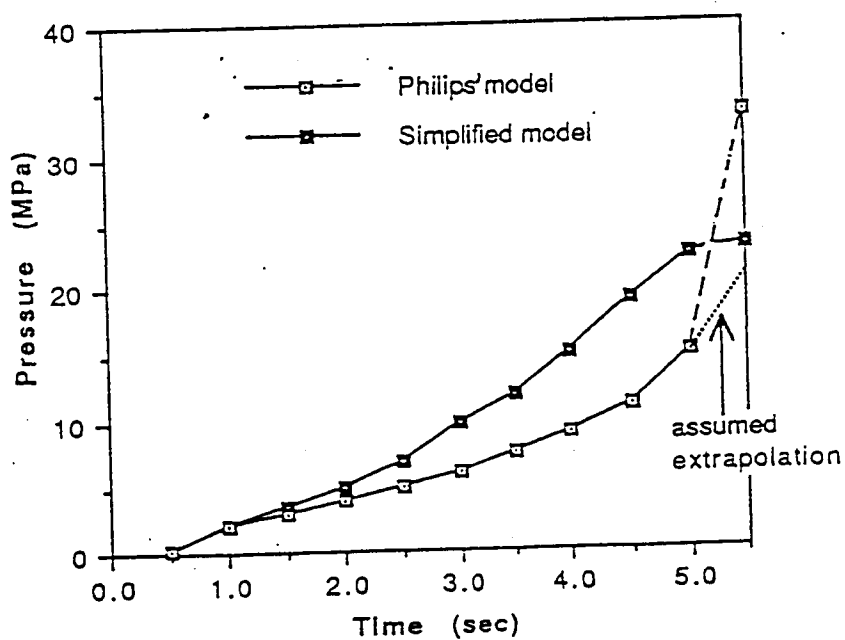
A short shot occurs when the polymer in the mold freezes off without filling the entire mold. This generally happens when the pressure developed equals the maximum input pressure.

In order to study a case where a short shot is observed, the simulation is carried out for both the models, using the same process parameters as for the complete fill except that the maximum inlet pressure is reduced in this case.

The results obtained in both the cases are shown in Figures 4.13(a) and 4.13(b). The contour plot corresponding to the short shot is shown in Figure 4.14 (for the geometry). It is observed that



(a) Maximum pressure of 150 MPa in Philips' model (25 MPa in simplified model).



(b) Maximum pressure of 35 MPa in Philips' model (25 MPa in simplified model).

Figure 4.13: Comparison of results from the two models of the TV cabinet for a short shot.

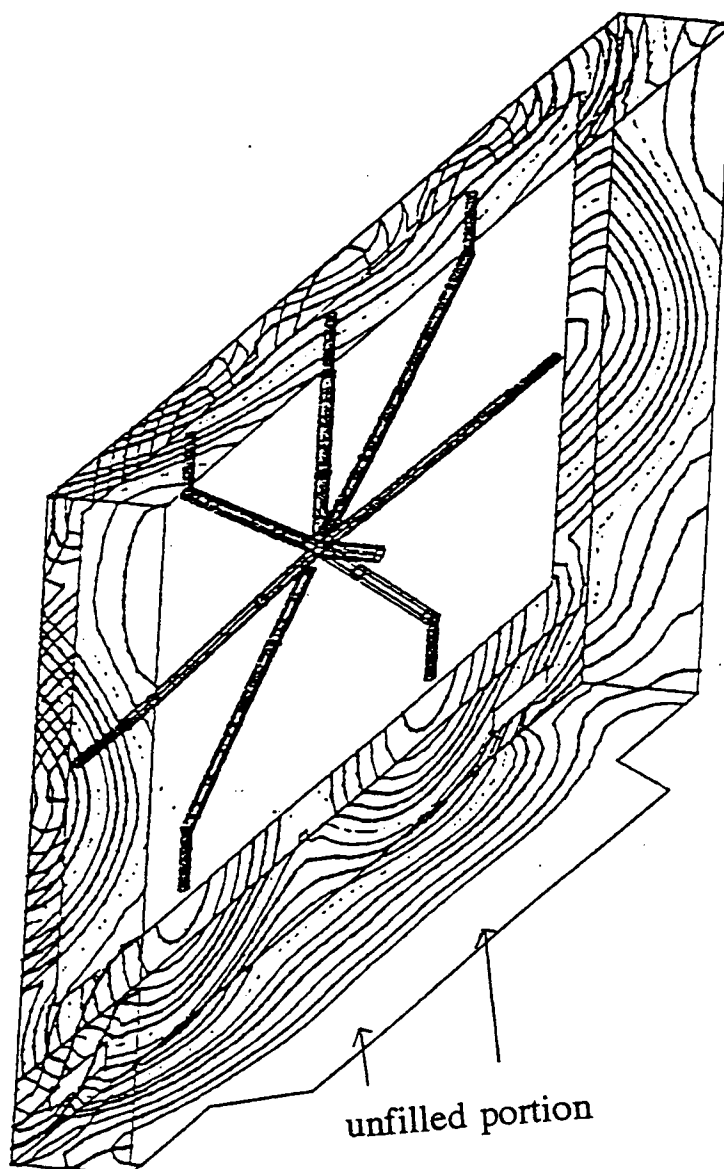


Figure 4.14: Contour plots corresponding to the short shot condition (for the simple geometry).

there is a very clear short shot at a pressure of 25 MPa for the simplified model, whereas for the Philips' model a computer message showing a short shot is given at a pressure of 250 MPa, again displaying a trend to spike from a pressure of 25 MPa at the last time interval. Following the same procedure as in case of a complete fill, neglecting the spike and extrapolating the earlier slope of the curve a pressure of 25 MPa is obtained as a condition of short shot. This is the same pressure as that obtained for the simplified model and is 65% of the maximum pressure required for the complete fill. This compares with about 80-85% of complete fill pressure as observed in the plant (Table 4.3). Given the difficulty of characterizing the exact conditions of a short shot, this is not unreasonable agreement.

Thus it is found that the results obtained for the simplified model and the Philips' model are comparable to each other as well as to the plant data. Thus for an overview study of the TV cabinet mold, as for example, in a class project, the simplified model is adequate. It requires much less computer time (about an hour and a half in the mainframe IBM computers of the University of Tennessee, Knoxville as compared to about four hours for the Philips' model).

4.3 Study of "weld lines" in TV cabinet part

"Weld lines" are formed when advancing melt fronts meet. They are formed in injection molded parts molded in multi-gated molds or molds with inserts. Thus weld lines are formed when the material being introduced at two or more different gates (or flowing around the two side of an obstruction) joins. Weld lines are commonly visible to the naked eye, the visibility being dependent on the molding conditions.

In the actual TV cabinet part supplied by the Philips company prominent weld lines were visible, in some places, especially near the corners. The location of the actual weld lines were in reasonable agreement with those obtained from the C-FLOW program (location of weld lines obtained from the program is shown in Figure 4.15)

To study the nature of the weld-lines with the help of the program, one out of the seven weld lines from the actual part was selected. Three 3/4" square pieces were cut out (with the weld line passing through the center), piece 1 is very near the corner, piece 2 is farther from the corner (where the weld line is not very prominent) and piece 3 is a part without a visible weld line. SEM photographs of parts 1 and part 3 as observed without modification are shown in figure 4.16 (a) and (b) respectively. To understand the nature of the weld planes, the three pieces were quenched in liquid nitrogen and broken apart along the weld lines (see Figures 4.17, 4.18 and 4.19). Piece 3 which had no visible weld line, was scored a

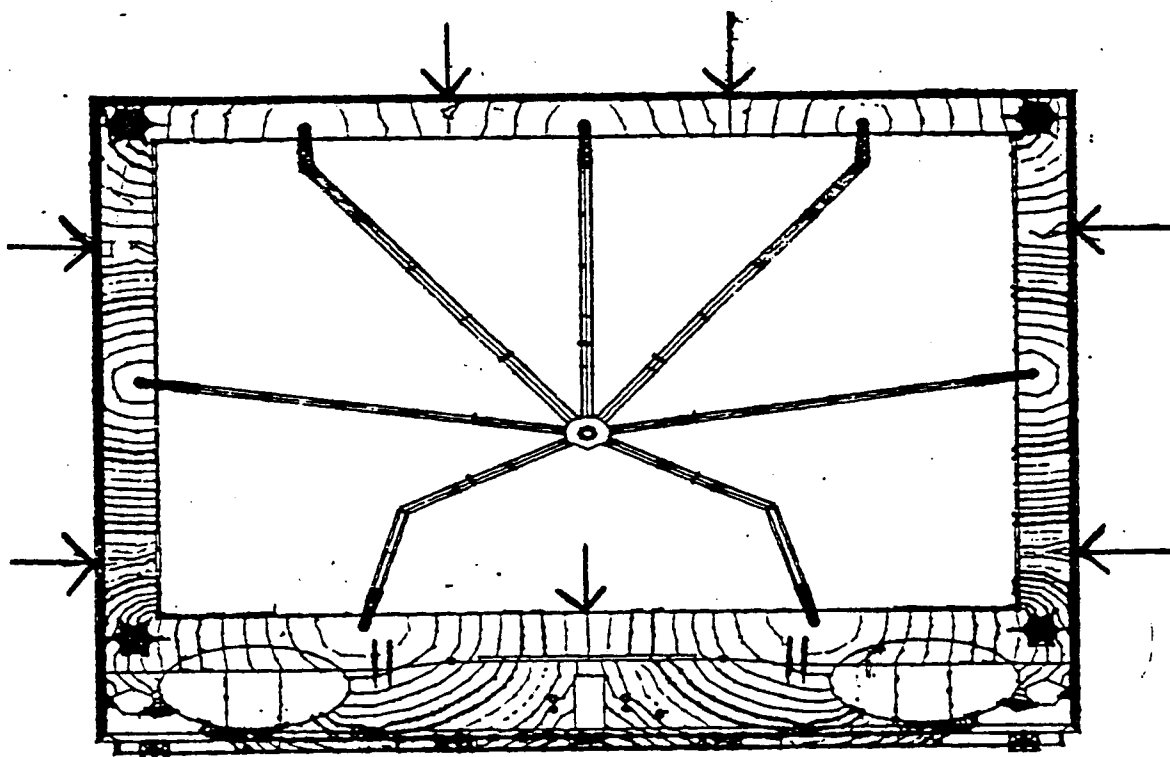
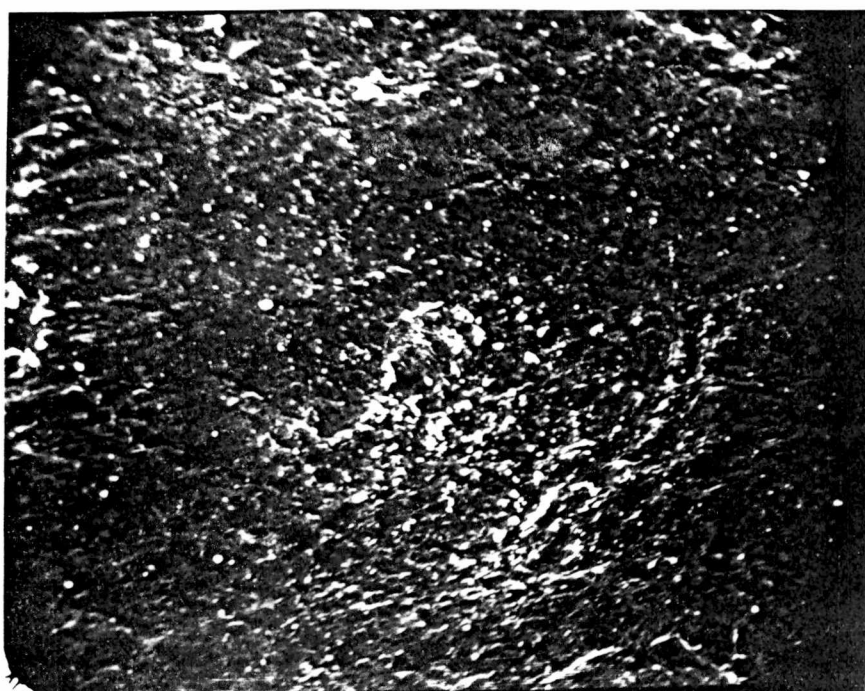


Figure 4.15: Weld line positions from C-FLOW program.



(A) With weld line (in center).



(B) Without weld line.

Figure 4.16: SEM photographs of the surface of as-received production sample.

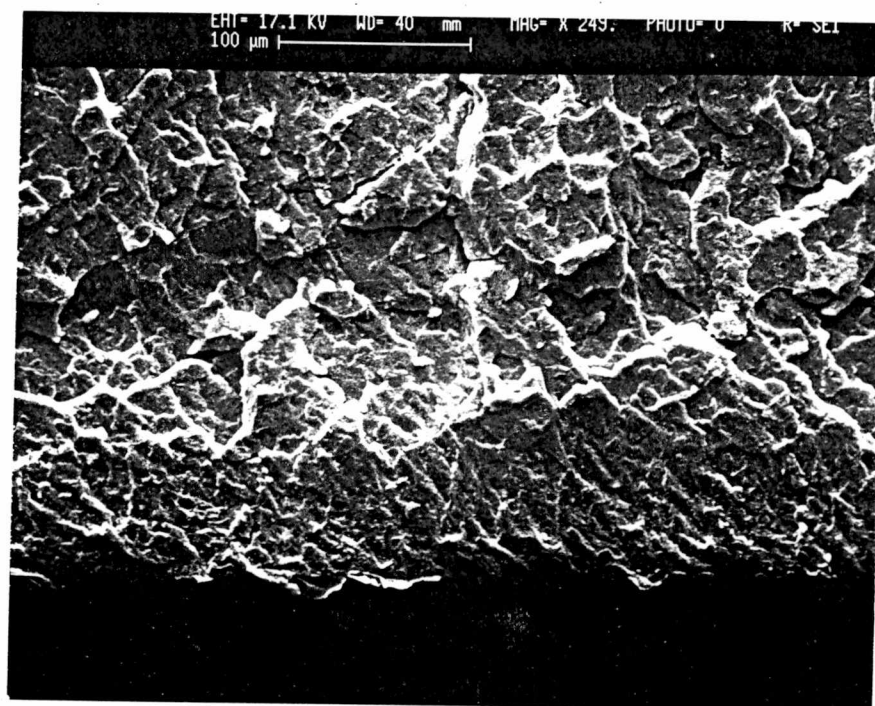


Figure 4.17: SEM photograph of the fracture surface in a region of highly visible weld line weld line (after breaking in liquid nitrogen).

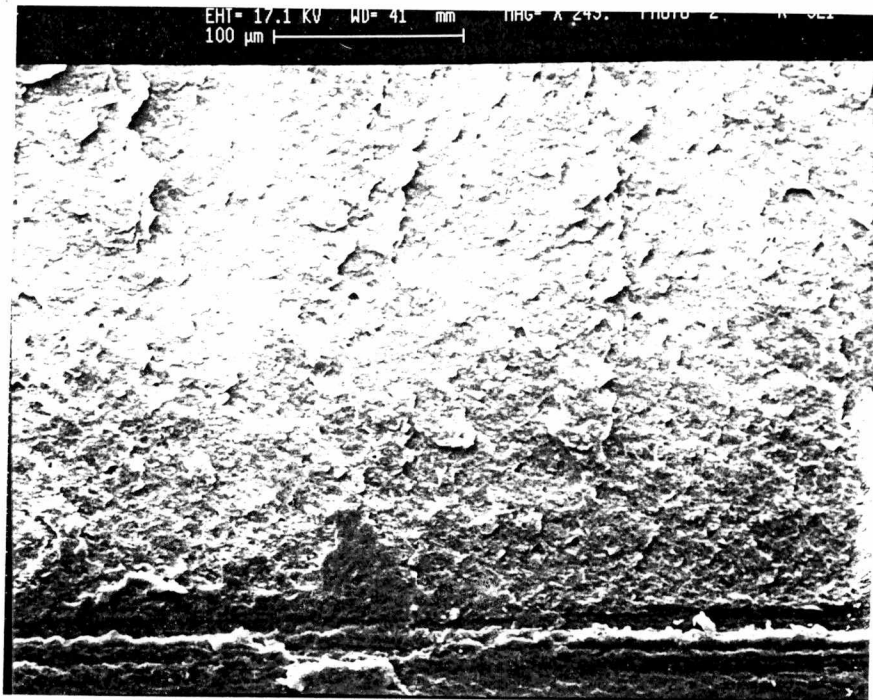


Figure 4.18: SEM photograph of the fracture surface in region of a slightly visible weld line (after breaking in liquid nitrogen) {region at bottom of photograph are due to scoring to induce fracture plane}.

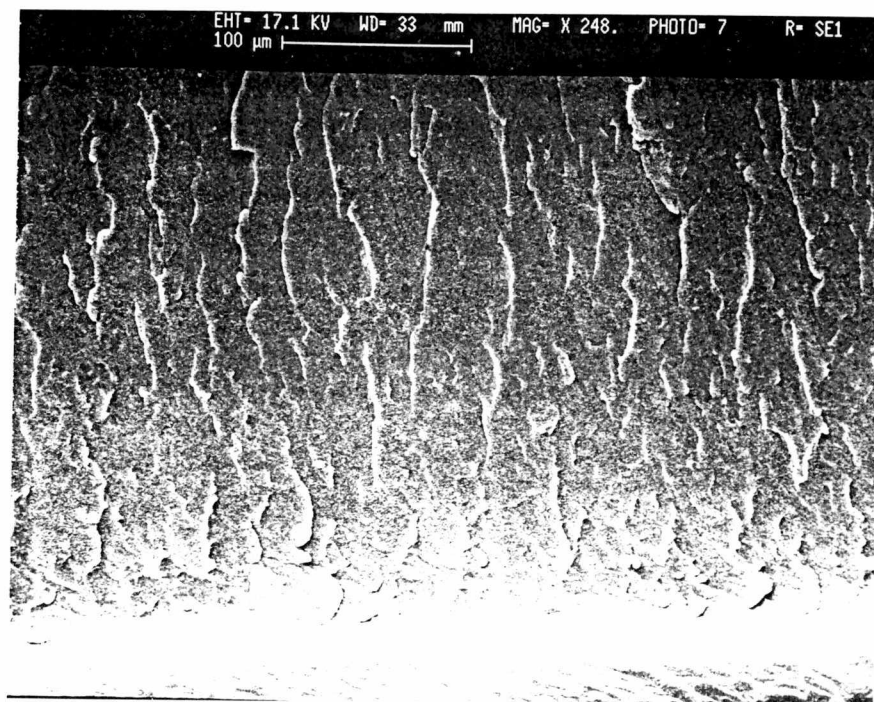


Figure 4.19: SEM photograph of the fracture surface in a region free of weld line (after breaking in liquid nitrogen).
{region at bottom of photograph are due to scoring to induce fracture surface}.

little to induce a well defined fracture plane. Piece 2 also had to be scored to induce a break. The scoring is seen in the SEM pictures of the fracture surface of these pieces as an indentation along the bottom of the photographs and are thus artifacts in the consideration of the samples (Figures 4.18 and 4.19).

In Figure 4.17 (piece 1), the part near the corner with a very prominent weld line, the fracture surface appears to be very irregular. In Figure 4.18 (piece 2), which shows the fracture surface of a weld line which is not very prominent (the region away from the corner) the surface is found to be somewhat smoother. The fracture surface of the part without the weld line (Figure 4.19), piece 3, shows a faceted break, each part of which is nearly smooth. This appears similar to the fracture surface for breaking of PMMA, which is also an amorphous material [20]. In all these fracture surfaces no variation is observed in structure across the thin dimension.

Various ideas can be considered regarding the quality of weld lines. The present author proposed that temperature of the melt front would be an important variable, a higher temperature leading to a healing of the junction and a better quality weld line. Tadmor and Gogos [21] suggested that the angle at which the melt fronts meet is important. If the fronts meet "head on" there is no prominent weld line, whereas if the fronts meet at an angle the weld lines become prominent (see Figure 4.20).

Consideration of temperature as a factor influencing the quality of the weld lines can be made in two ways: first, by considering the

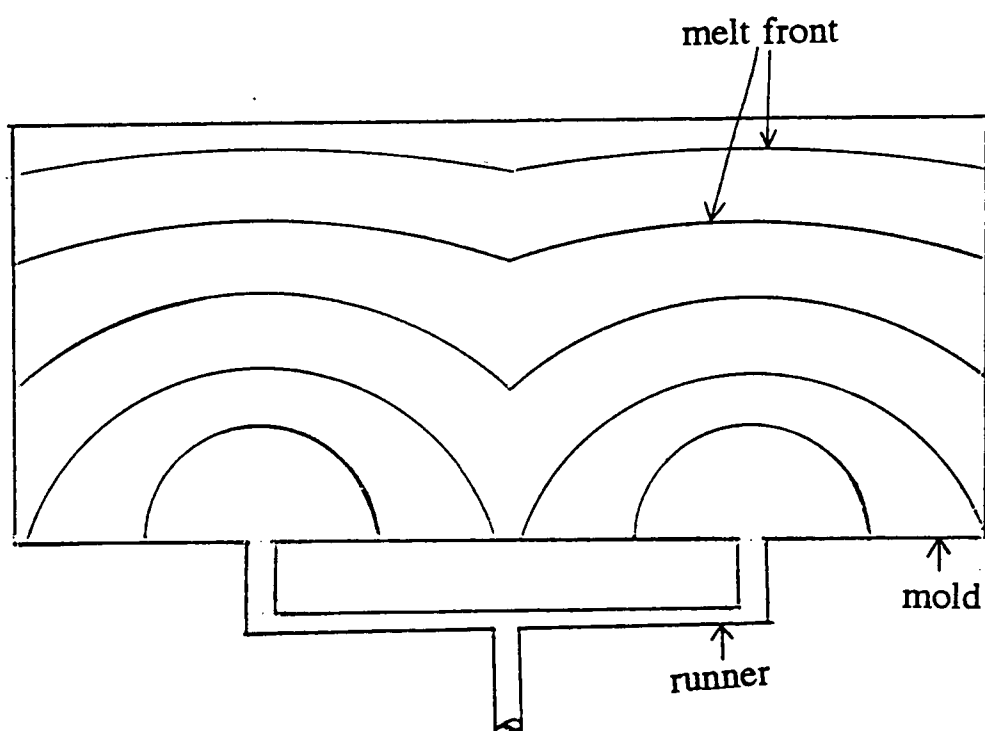


Figure 4.20: Pattern of meeting of melt fronts in a two gated mold

average temperature of the melt (at the time of juncture) as a function of the distance from the corner, and second, by considering the temperature profile through the thickness of the part in the thin dimension. Figure 4.21 shows four points along a weld line, as a function of distance from the corner. The temperature results from C-FLOW are presented in Figure 4.22. The curves are profiles through the thickness the thin dimension at four positions, as identified in Figure 4.21 (position A being a point about 5 cm from the corner, position D being essentially at the corner itself, and positions B and C being intermediate points).

The average temperature at the various positions are not greatly different, taking into account the greatly expanded temperature scale on the ordinate. Position D is, however, somewhat hotter (about 50°C on the average) although this may be due to certain assumptions in the program. The program does a rigorous treatment of the heat transfer problem in the thin dimension, taking into account heat convection, heat conduction and viscous heat generation, but only an approximate one in the long dimension (in the plane of the part). In the mathematical details of the program that has been published [15], the implication is that heat transfer from the thin edge is neglected but it seems unlikely that such heat transfer is neglected altogether, judging from the temperature contour plot as viewed from the top. Probably some simple heat conduction assumption has been made. In any case the profiles are not enough different to make any plausible argument for a

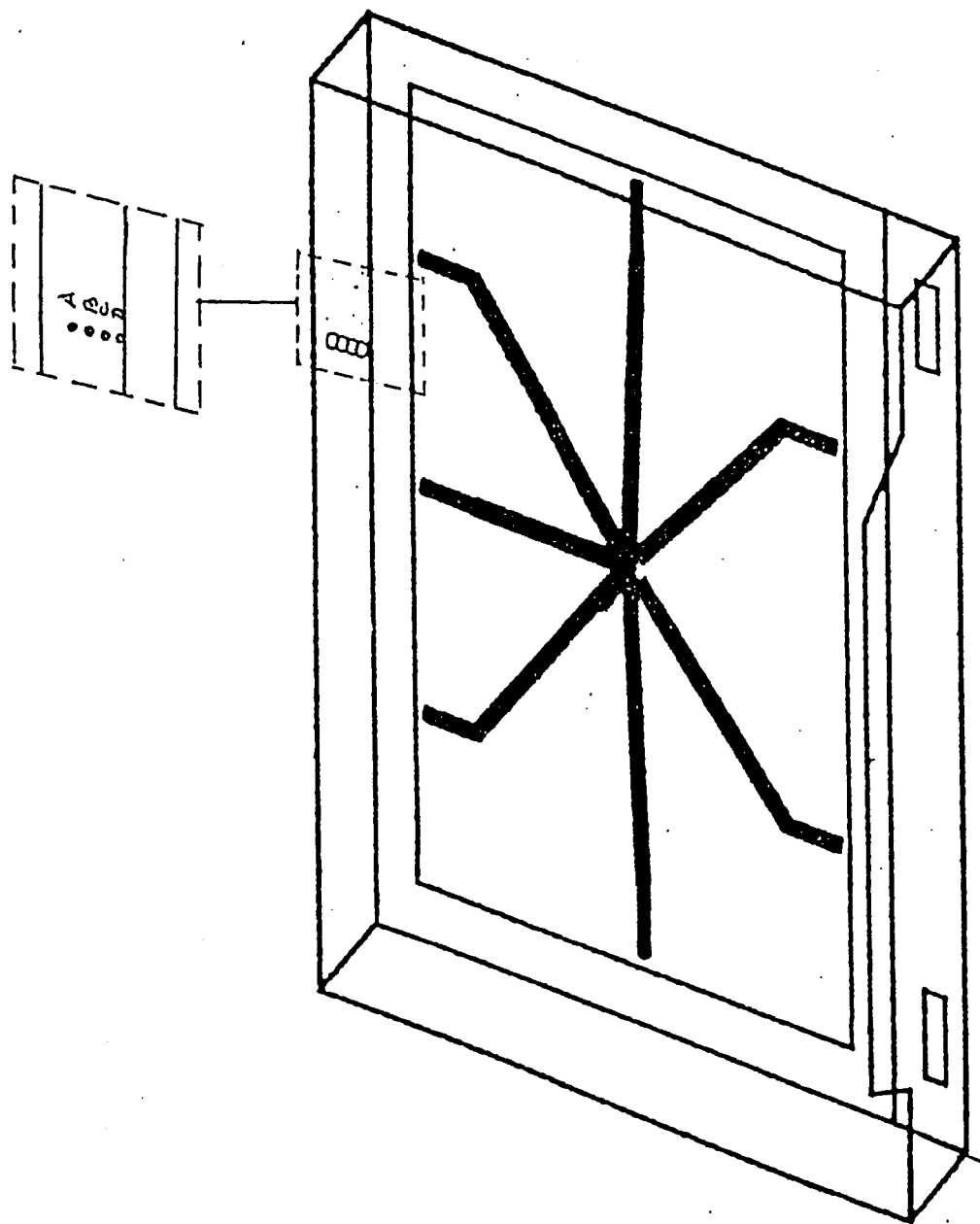


Figure 4.21: Schematic of simplified model for the TV cabinet identifying four points along a weld line generated by the program.

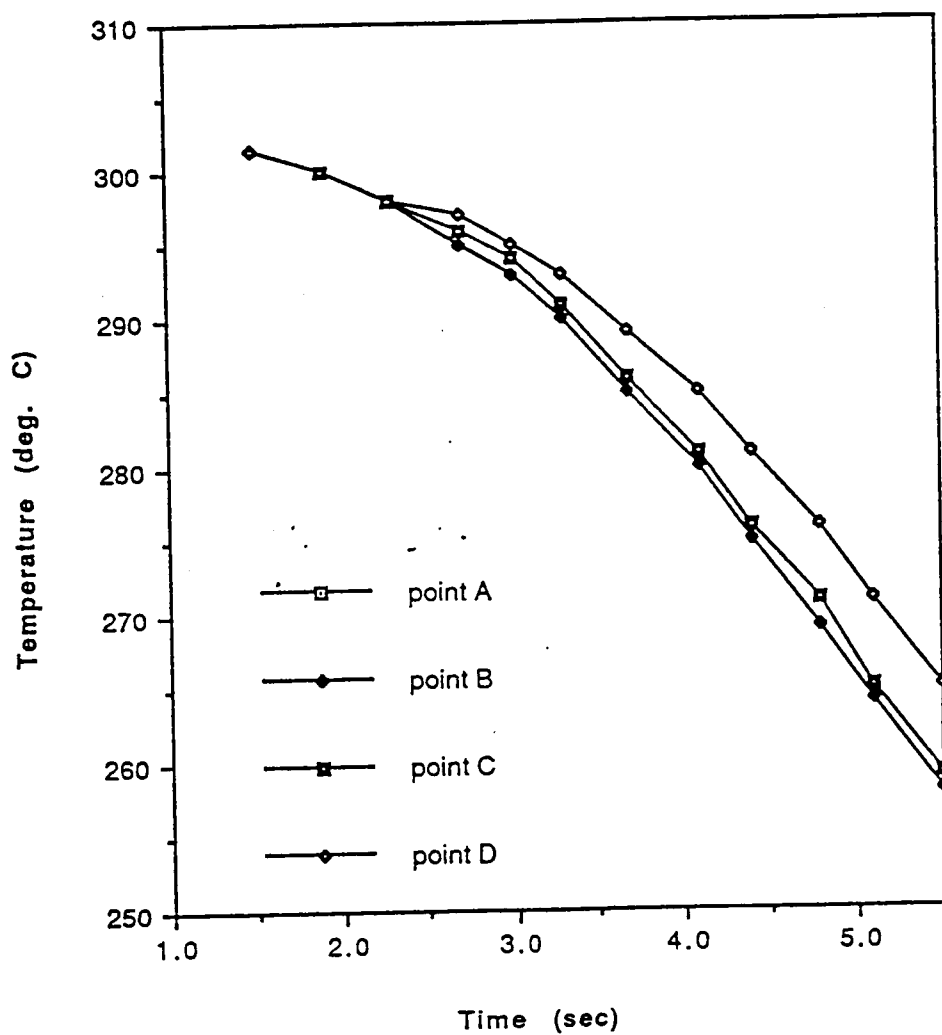


Figure 4.22: Temperature-time curves at various distances from the edge (positions identified in Figure 4.2).

connection between the average temperature and the distance from the edge.

In the case of the gradient across the part (in the thin dimension) there are again only small changes from center to the wall. However inspection of the SEM photographs for the fracture surfaces created when visible weld line were broken (Figures 4.17 and 4.18) does not show any obvious changes across the photograph. Thus it is again difficult to make an argument for an effect of temperature on the quality of the "weld".

The second idea regarding the occurrence of weld line is the angle at which the melt front meets. According to Tadmor and Gogos [20], weld lines occur when the melt fronts meet at an angle (Figure 4.20). This idea was also suggested by the Philips Company [19]. From the contour plots of the melt fronts obtained from C-FLOW programs, which gives the shape of the advancing melt fronts, the angles between the normals of the advancing melt fronts were measured and plotted against distance from the corner, as shown in Figure 4.23. From the figure it is evident that if the quality of the weld line is a function of angle at which the melt fronts meet, then we would see a prominent weld line towards the corner and a less severe weld line away from it to a distance of 5.8 cm after which there is no visible weld line. This result from the C-FLOW program is comparable to what is observed on the actual manufactured part (see Figure 4.23).

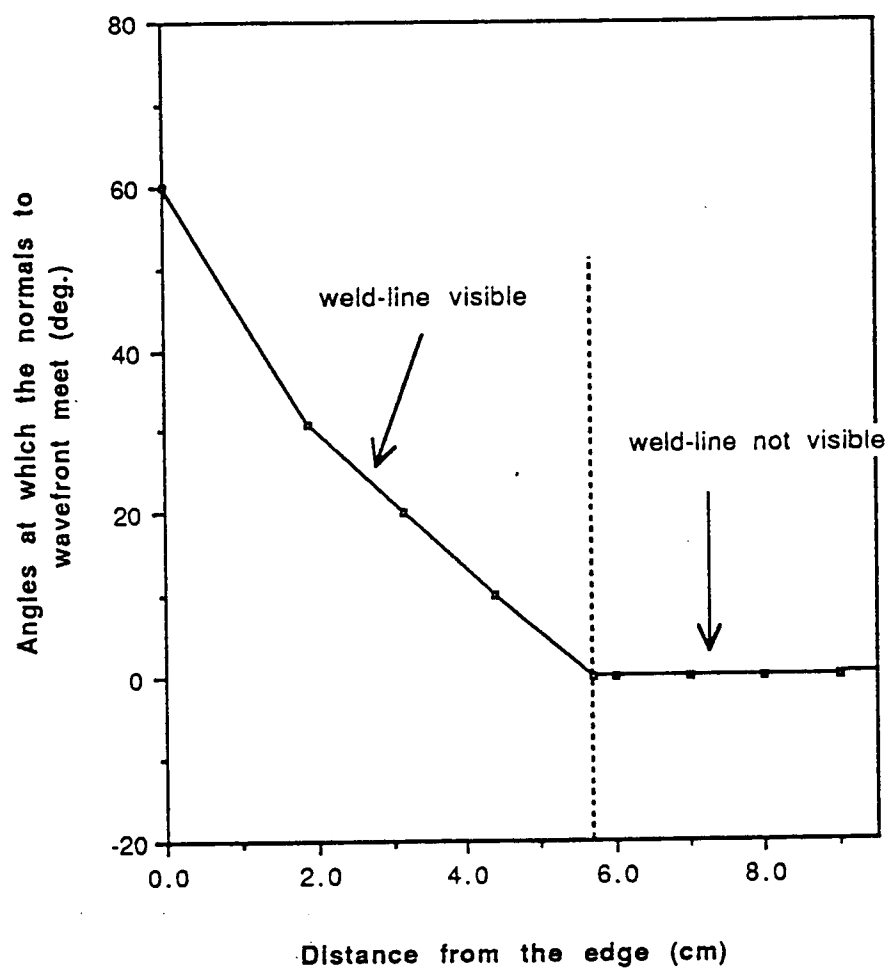


Figure 4.23: Angle at which the normals to wave front meet vs distance from the edge.

Finally it must be said that the factors which make two melt fronts weld together without leaving a visible line are complicated and not completely understood. In the previous discussion, two factors, the temperature of various layers and the angle at which the fronts approach, were considered. The temperature gradient across the thin direction did not appear to correlate with the relatively constant nature of the course structure in that direction, as revealed through SEM photographs, but that is not to say that temperature does not play a role. It is possible that some combination of relatively high temperature and pressure which occur, for example, in the packing step, or the merge of hot weld lines for sometime might heal the lines or at least make them less visible. While the angle at which the melt front meets is apparently an important factor, it cannot be the only factor since weld lines in production parts can be minimized by changing such factors as melt temperature and fill time. A complete study of the weld line problem will require a detailed investigation of many factors.

CHAPTER 5

CONCLUSIONS

The major conclusions of this study are as follows:

1. For the flat rectangular geometry the two programs (C-FLOW and Mold Filling) were in reasonable agreement with each and with experimental data from the literature (pressure vs. time at three points), except that the pressure tap nearest the end of the mold gave predicted pressures that were higher than the measured ones. This is likely due to inaccuracies introduced by the heat balance equations, in which wall effects are neglected on the edges; if the material is "seeing" the entire mold in advance of the melt flow, such effects are usually negligible but become significant as the material approaches the end of the mold.

2. The full Philips simulation of the TV cabinet (2545 nodes, 4635 elements) and a simplified version of it (1366 nodes, 2399 elements) were run on C-FLOW and compared under various operating conditions. In general the results for the pressure-time plots for the two cases were in satisfactory agreement. The full simulation gave a spurious pressure "spike" at the end of the fill, a numerical problem that occurs especially when there is a large number of elements. (Since the program proceeds in discrete time steps, the computer may "overfill" the last element(s), causing an enormous increase in the pressure). The final pressure is estimated by extrapolating pressures near the end of the fill (a procedure used

also by the Philips group). Pressures so estimated for the full simulation were in reasonable agreement with those obtained from the simplified simulation (30 MPa for Philips' model and 39 MPa for the simplified model).

3. For conditions of melt temperature, mold temperature and fill time like those used in production (for molding with a high impact polystyrene, Huntsman/HIPS:707FR), the full simulation, as described above, gave a final pressure of 30 MPa, whereas the simplified version gave a final pressure of 39 MPa. These compare favorably with in-plant (production) pressures in the range of 30 - 40 MPa.

4. Plant experience is that "short shots" occur when the final pressure is, say, 80 - 85 % of the pressures used during fully filled runs. The C-FLOW results showed "short shots" at about 65% of the fully filled condition.

5. The character of "weld lines" (junction lines between two flowing polymer fronts) was studied qualitatively. SEM photographs showed that bad (visible) weld lines showed a coarse structure when broken apart whereas near-invisible weld lines or samples free of weld lines broke with faceted, smoothly cleaved surfaces. No large structural differences across the thin dimension of the weld line were observed, which tends to discredit a criterion (for good or bad weld lines) based on temperature as a primary variable, temperature varying significantly as one moves from wall to centerline. In accord with prior suggestions the quality of the weld line does correlate

reasonably well with the angle at which the two melt fronts meet. This cannot be the only variable in practical molding operations, however, and further studies of this kind are needed.

6. The C-FLOW program is a well-developed, relatively "user friendly" program, producing output plots in readable form. The Mold Filling program, on the other hand, appears to still be under development, sometimes producing, for example, plots with inconsistent scales (varying from log scales near the "origin" to linear scales elsewhere). Also the polystyrene viscosities called from its data bank were almost an order of magnitude too low compared with typical commercial polystyrenes and compared with the Huntsman HIPS that Philips' uses; it required a special computer tape supplied by the vendor to load in one's own rheological data, and there was not time in the present study to proceed in that manner. On the other hand, very complex geometries can be created in Mold Filling. Moreover inserts and holes of various shapes can be modelled easily. Finally, however, C-FLOW is clearly easier to use than Mold Filling and is recommended for use in future class projects.

7. While the complete (2545 nodes, 4635 elements) simulation of the TV cabinet is useful for classroom discussion, especially when compared with the actual physical product, it will not be practical to run this case as a class project because of the long computer times (typically about four hours on the IBM mainframe). The simplified (1366 nodes, 2399 elements) version, however, runs fast enough (typically in about one and half hours) that it could be used. The

geometry involving a flat rectangular mold with obstructions runs very quickly (in about 20 minutes) and could be used for an in-class demonstration.

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