

# SYNTHESIS REPORT

## FOR PUBLICATION

**CONTRACT N° :** BRE2 - CT92-0291  
**PROJECT N° :** BE-5732  
**TITLE :** MODFORM (Modelling of Thermoforming)

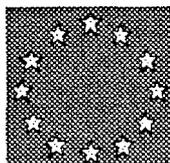
**PROJECT COORDINATOR :** CISI

**PARTNERS :** CISI - AID  
C.S.I (Gruppo MONTEDISON)  
WHIRLPOOL - Italia (substituted to VALFRIO)

**REFERENCE PERIOD FROM (01.10.92) to (31.12.95)**

**STARTING DATE :01.'10.92**

**DURATION :39 MONTHS**



PROJECT FUNDED BY THE EUROPEAN  
COMMUNITY UNDER THE BRIT/ EURAM  
PROGRAMME

NUMBER OF PAGES :  
18

---

**TABLE OF CONTENTS**

<b>0. ABSTRACT</b> .....	<b>2</b>
<b>L INTRODUCTION</b> .....	<b>3</b>
<b>2. TECHNICAL DESCRIPTION</b> .....	<b>4</b>
<b>2.1 MATERIALS CHARACTERIZATION AND NON LINEAR VISCOELASTIC CONSTITUTIVE LAWS</b> .....	<b>4</b>
2.1.1 Experimental Techniques and results .....	4
2.1.2 Foundation of constitutive laws .....	5
<b>2.2 VALIDATION EXPERIMENTS, OPTIMIZATION OF THE PROCESS CONTROL AND SOFTWARE QUALIFICATION</b> .....	<b>9</b>
2.2.1 Experimental program .....	9
2.2.3 Software qualification .....	9
<b>2.3 THE SOFTWARE DEVELOPMENTS</b> .....	<b>10</b>
2.3.1 The mathematical formulation .....	10
2.3.2 Description of the code .....	11
<b>2.4 WHIRLPOOL PART</b> .....	<b>12</b>
2.4.1 Introduction .....	12
2.4.2 Experimental program set-up .....	12
2.4.3 Software validation activity .....	13
<b>2.5 CODE ASSESSMENT BY END USERS</b> .....	<b>13</b>
<b>3. RESULTS</b> .....	<b>14</b>
<b>4. CONCLUSIONS</b> .....	<b>15</b>
<b>5. ACKNOWLEDGMENTS</b> .....	<b>15</b>
<b>6. REFERENCES</b> .....	<b>16</b>

## Title, authors names and addresses

## MODFORM : Modelling of thermoplastic film and sheets forming

<b>A. Latrobe</b>	<b>CISI</b> 6, rue de l'Arcelle Z.I. des Plans 38600 Fontaine France
<b>J. Cormeau</b>	<b>CISI</b> Centre d'Etudes Nucléaires de Saclay BP 28 91192 Gif-sur-Yvette France
<b>L. Coincenot</b>	<b>CISI/AID</b> <b>Piazza</b> dells Repubblica, 32 20124 Milano Italia
<b>F. D'Oria</b>	<b>CSI</b> Bollate Research Center V. Le Lombardia, 20 20021 Bollate (MI) Italia
<b>P. Bourgin</b> <b>T. Saint-Martin</b>	<b>Institut de Mécanique des Fluides</b> University Louis Pasteur de Strasbourg Unité de Recherche Associé au CNRS n° 854 2 rue Bousingault 67000 Strasbourg France
<b>F. Casoli</b> <b>M. Gatti</b>	<b>WHIRLPOOL</b> 21024 Cassinetta di Biandronno Varese Italia

## 0. ABSTRACT

Cisi was the coordinator of this program and was acting through its main offices in France and its subsidiary Cisi-AID in Milano (Italy). The second main contractor, CSI/MONTEDISON, built several well instrumented moulds and actively participated to the simulator specifications and validations.

The Fluid Mechanics Institute in Strasbourg, subcontractor of CISI, has worked on the selection and parameter identification of the constitutive equations that best represent the polymer behaviour in actual thermoforming conditions.

VALFRIO (Portugal) and WHIRPOOL (Italy) have validated the simulator on parts of their production.

This program was combining an experimental program and the development of a process simulator including a new mathematical model.

This mathematical model makes possible to analyze :

- the deformation of the membrane,
- the stress field in the membrane,
- the contact with the mould,
- the evolution of the temperature in the membrane (coupled with the evolution of the temperature of the mould),
- the pneumatic aspects linked to the discharge of the air through the vents.

From the understanding of these fields during the operation, it is possible to deduce the essential result which is the final thickness of the part after forming and cooling. The mathematical model is fully dynamic, what is involved is a true representation of all the transformation stages.

The major results of the experimental program are :

- A new method of strain measurements based on an optical method without contact.
- The characterization of 3 materials : Polystyren, polypropilen and a 2 layer material PMMA/ABS.
- Measurements of the membrane displacements during the forming step and the demonstration of the importance of temperature control during the heating step and of the air vents locations and pressure control during the forming step.

This program has successfully combined the use of simulation and experimental methods to study the dynamics of forming and has demonstrated that significant progress are still to be expected by combining these two approaches.

## 1. INTRODUCTION

The Modform project objectives were essentially :

- to complete the physical knowledge of commonly used materials under usual thermoforming conditions,
- to propose theoretical laws taking into account the so called memory effects,
- to better understand the critical working parameters of the process by running basic experiments on well instrumented moulds,
- . to remove the empirism leading to these parameters settings by providing an innovative software tool using a fully dynamic approach,
- . to validate these result with end users.

The project was divided into 4 subprojects (workpackages)

The materials characterization has been subcontracted by Cisi to Strasbourg University which has run the experiments and formulated the constitutive laws.

The instrumentation of moulds, the basic experiments and the validation of the software were CSI/MONTEDISON tasks. For this purpose , CSI has instrumented several moulds to explore a wide range of processing parameters for 2 types of forming : vacuum forming and Air slip forming. It has also developed an original technique to measure displacements during forming.

The Cisi Group has developed the simulator. The italian subsidiary, located in Milano has been deeply involved in the project by developing the contact and the remeshing algorithms and was the leader for the quality assurance and integration **tasks**.

Two end users have been involved in the project :

VALFRIO in Portugal has contributed to the software specifications but has stopped its activity at mid project.

WHIRPOOL (Italy) has accepted to complete VALFRIO tasks for the validation of the software on parts of their production.

## 2. TECHNICAL DESCRIPTION

### 2.1 MATERIALS CHARACTERIZATION AND NON LINEAR VISCOELASTIC CONSTITUTIVE LAWS.

#### 2.1.1 EXPERIMENTAL TECHNIQUES AND RESULTS

High speed extensimetry has been used to characterise the behaviour of the resin under controlled and well reproducible conditions. A medium speed Instron tensile machine has been modified and fitted with :

- 1) A test chamber with an accurate temperature control (less than  $\pm 0,5^{\circ}\text{C}$ ),
- 2) A high speed optical displacement gauge without contact, using a CCD linear camera (resolution of 15 micrometers per pixel and acquisition rate of 1000 pictures per second),
- 3) A program controlling the exponential displacement of the cross head specially developed for this specific application (high value of test duration of about one tenth of a second and 2000 sampling points).

The set of conditions was the following one :

- 1) Strain rate ranging between  $1\text{s}^{-1}$  and  $10\text{s}^{-1}$  by step of  $1\text{S}^{-1}$ ,
- 2) Extension ratio  $\lambda=L/L_0$  (L: current length,  $L_0$  : initial length) between 2 and 5,
- 3) Temperature ranging from  $140^{\circ}\text{C}$  to  $190^{\circ}\text{C}$  by step of  $5^{\circ}\text{C}$ .

Three materials were tested : high impact polystyrene (HIPS), a composite PMMA/ABS and polypropylene (PP).

In the case of polypropylene, we were faced with the well-known phenomenon of "necking" (i.e. localised reduction of section) which is typical of semi-crystalline polymers.

Two types of rheological behaviors have been observed :

- (i) When the strain rate is lower than some value (say  $5\text{s}^{-1}$ ), the slope increases as the strain rate increases. This dependence on the strain rate is typical of the viscoelastic behaviour.
- (ii) When the strain rate is greater than some value (say  $5\text{s}^{-1}$ ), the general shape of the curves remains unaffected which means that the hyperelastic behaviour becomes predominant.

### 2.1.2 FORMULATION OF CONSTITUTIVE LAWS

Regarding the qualitative behaviour observed, two types of constitutive laws have been studied :

- The hyperelastic constitutive laws,
- The memory integrals constitutive laws.

The major differences between these laws are briefly recalled.

The hyperelastic models : (for example : the Mooney model, the Ogden model).

The stress is derived from a potential using the deformation gradient tensor invariants  $I_1, I_2, I_3$ . Thus, the strain energy depends only on the current state of strain but, in no way, on the strain history. The analyses on HIPS and PMMA/ABS show that the hyperelastic models conform to the experimental behaviour only for high extension rates ( $\dot{\epsilon} > 5s^{-1}$ ).

A very popular model, commonly used in commercially available computer codes of thermoforming is the Ogden model [1] where the strain-energy function is expressed in the form of a series, as follows :

$$W = \sum \frac{\mu_n}{\alpha_n} (\lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3)$$

where  $\mu_n$  and  $\alpha_n$  are constant parameters.

This formulation is strongly connected to the statistical network theory (or Gaussian theory) which leads to an expression for the work of deformation in a pure strain form :

$$W = \frac{1}{2} NkT (\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3)$$

with N : the number of molecular chains per unit volume,  
 k : Boltzmann's constant,  
 $\lambda_i (i=1,2,3)$  : the stretch ratios. The quantity  $NkT$  is equivalent to the shear modulus  $G$ .

The strain-stress relationships  $\sigma_i - \sigma_j = G(\lambda_i^2 - \lambda_j^2)$  ( $i, j=1, 2, 3$  and  $i \neq j$ ) involve a modulus which depends on the degree of cross-linking or the number of chains per unit volume of the network.

The memory integral models : (for example the Maxwell model or the Lodge "rubberlike liquid").

The full stress/strain history evolution has to be known. The generic form can be expressed

$$\text{as : } \sigma(t) = \int_{-\infty}^t R(t-t') \varepsilon(t') dt'$$

with  $R(t-t')$  the memory function.

The difficulties come from the fact that the formulation of the law can be non-linear.

According to the structural interpretations of the memory function and their corresponding forms, several models have been proposed, among which the most convincing one (in terms of physical interpretation of dynamic loading) is the Lodge "rubberlike liquid" [2]. Its constitutive equation is expressed as

$$\left( \underline{\underline{\sigma}} + p \underline{\underline{Id}} \right)_t = \int_{-\infty}^t \mu^\circ(t-t') \underline{\underline{E}}^{-1}(t,t') \left( \underline{\underline{E}}^{-1} \right)^T(t,t') dt'$$

with  $\mu^\circ(t-t') = \frac{dG^\circ(t-t')}{dt'}$  and  $G^\circ$  denotes the relaxation function,

- $\mu^\circ(t-t')$  is the memory function (a positive decreasing function of the time interval  $t-t'$ ),
- $\underline{\underline{E}}^T$  is the deformation gradient tensor,
- $p$  is the (unknown) hydrostatic pressure, to be determined from the stress boundary conditions,
- $\underline{\underline{Id}}$  is the unit tensor,
- $\underline{\underline{\sigma}}$  is the stress tensor.

We assume here that  $G^\circ$  has the following expression :  $G^\circ(\sim) = \sum_{i=1}^n g_i e^{-\frac{t}{\tau_i}}$ , where  $\tau_i (i=1,n)$  represents the relaxation times which are usually determined by means of conventional rheometry.

Several other models such as the Johnson-Segalman model or the BKZ model also exhibit memory effects are based on strong physical considerations. Therefore, they were investigated.

### 2.1.2.2 Fitting **experimental data**

As quoted before, the hyperelastic behaviour is dominant for reasonably high values of the strain rate, typically larger than  $5s^{-1}$ . Therefore several hyperelastic models have been tested (Ogden, HaR-Smith, Mooney-Rivlin and Klosner-Segal), in the sense that their coefficients have been adjusted in order to better fit the experimental data. The Ogden model was found to be the most appropriate. Recall that in uniaxial traction, the Ogden's

equation reduces to: 
$$\sigma_1 = \sum_n \mu_n \left( \lambda_1^{\alpha_n - 2} - \lambda_1^{-\left(\frac{\alpha_n}{2} + 2\right)} \right)$$

where  $\mu_n$  and  $\alpha_n$  are parameters to be adjusted in the sense of the mean-square approximation.

The agreement between the experimental data and the theoretical curve is excellent. However, for small values of the strain rate, a strain rate dependence appears and the hyperelastic models must be rejected because they are unable to cope with a strain rate dependence.

For this reason, several viscoelastic models have been investigated (Maxwell, Lodge, Johnson-Segalman). The Maxwell model was rapidly abandoned because it lead to poor results. The Lodge rubberlike liquid is based on a physical background (molecular network theory) which is richer than the phenomenological basis of the Maxwell model and hence more convincing. Its characteristic parameters are deduced from its spectrum of relaxation times obtained by classical rheometry (small deformation, plate-plate rheometer).

[n uniaxial tension under step loading ;  $\dot{\epsilon}(t) = \dot{\epsilon}H(t)$  where  $H(t)$  is the Heaviside function, the principal stress is expressed by :

$$\begin{aligned}\sigma_1 &= \int_0^t G^\circ(t-t') \left[ 2\dot{\epsilon}e^{2\dot{\epsilon}t-2\dot{\epsilon}t'} + \dot{\epsilon}e^{-\dot{\epsilon}t+\dot{\epsilon}t'} \right] dt' \\ &= 2\dot{\epsilon} \sum_{i=1}^n \frac{g_i \tau_i}{1-2\dot{\epsilon}\tau_i} \left\{ 1 - e^{-\frac{t}{\tau_i}(1-2\dot{\epsilon}\tau_i)} \right\} + \dot{\epsilon} \sum_{i=1}^n \frac{g_i \tau_i}{1+\dot{\epsilon}\tau_i} \left\{ 1 - e^{-\frac{t}{\tau_i}(1+\dot{\epsilon}\tau_i)} \right\}\end{aligned}$$

with  $t > 0$ .

[It can be seen that all the governing parameters are fully determined by preliminary classical rheometry. Such experiments have been carried out with HIPS for various temperature values. In such conditions, it is not possible to further adjust these parameters in order to fit the experimental data. However, an excellent agreement was observed between the theoretical curve stress-time (as defined before) and the experimental data obtained with HIPS. This is an important result *per se* because extrapolation from small strain values to large strain values has been proven possible.

In other words, the theoretical curve drawn by using the 1 D formulation of the Lodge model for the values of the relaxation times (measured on the Rheometrics) fits well with the experimental data obtained on the tensile machine at large deformations. As an illustrative example, Figure 1 shows a comparison between a set of experimental data and the curve obtained with the Lodge model.

The same conclusion was drawn for the PMMA/ABS bi-layer material, considered as an equivalent homogeneous material.

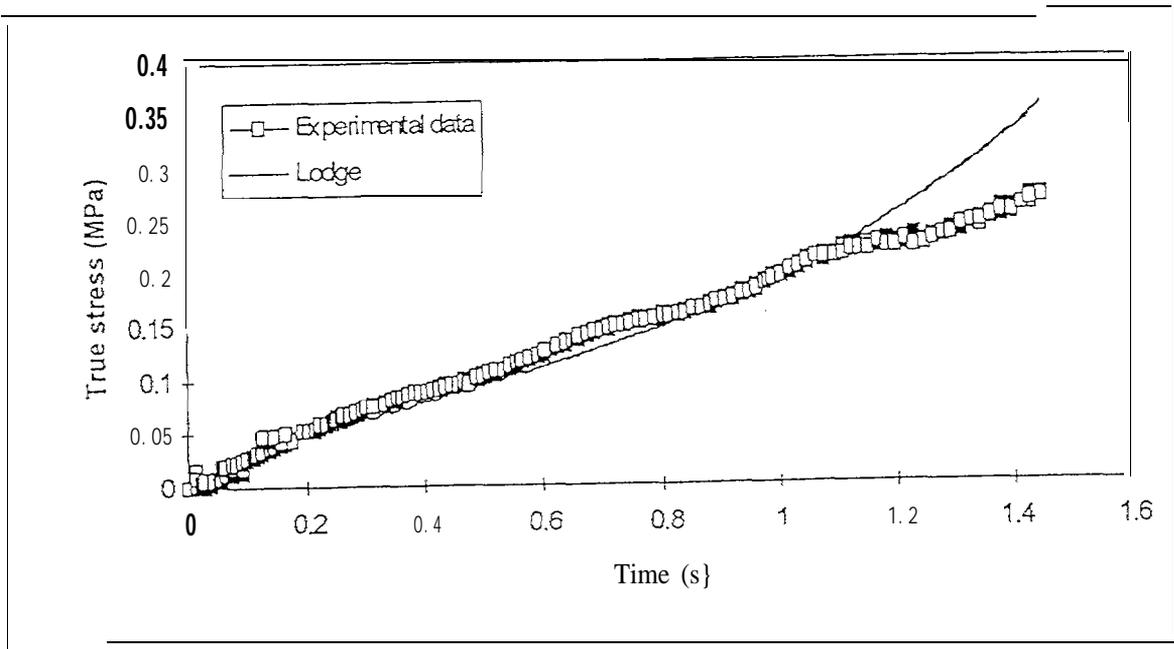


Fig. : 1 Comparison between experimental data and theory (lodge model) for polystyrene at 180°C.

## 2.2 VALIDATION EXPERIMENTS, OPTIMIZATION OF THE PROCESS CONTROL AND SOFTWARE QUALIFICATION

### 2.2.1 EXPERIMENTAL PROGRAM

This experimental program was devoted to the following objectives :

- 1) To perform a technological characterization of the VACUUM(Subtask 2.1) and AIR-SLIP (Subtask 2.2) thermoforming processes through the definition of a set of measurable process parameters to be considered as INPUT and OUTPUT data in the simulation software.
- 2) To obtain experimental data for validating the main assumptions of the simulation model.
- 3) To carry out experiments for the **simulator validation**

To achieve these objectives, a single **station** Vacuum thermoforming machine has been modified and a specially designed transparent mould has been instrumented. A displacements measurements technique using a high speed camera and a computer for the image analysis has been developed. An infrared camera was used for the sheets temperatures analysis.

A metal vacuum mould has also been specially designed and instrumented for analysing the influence of the pressure control during the dynamic phase.

- An AIR SLIP thermoforming machine with pre-stretching and plug facilities has also been instrumented to study the bubble formation and growth analysis (pre-stretching analysis) and the influence of the process parameters(such as pre-blowing and vacuum pressure profiles) on the final thickness distribution.

The moulded articles were tested by means of different evaluation techniques : Thermal dimensional stability, and permeability Tests were performed.

### 2.2.3 SOFTWARE QUALIFICATION

The objectives were to compare the simulation results with the actual experimental data and to identify the strength points and weaknesses of the software.

The simulation results considered as quality parameters of the software evaluation were :

The temperature profile during the heating step, the bubble growth dynamics, the final thickness distribution. The complete results can be considered as satisfactory and better than those obtained with other commercial codes but they have still to be improved for air slip thermoforming, probably because slip is more present in this process than in the vacuum forming process and data are still lacking to propose a realistic model of slipping at the moment.

## 2.3 THE SOFTWARE DEVELOPMENTS

From a future industrial user's viewpoint, a computer-based numerical model of the thermoforming process must provide useful information in order to better understand the physics of the process, to help with part and mould design, and to assist in effective control of the process. The salient features to be taken into account in any prospective computer model are currently listed below, although some additional ones may have to be introduced later as experience is gained :

- (1) Strong geometrical nonlinearities due to large displacements and rotations,
- (2) Severe material nonlinearities associated with large stretches and strains, complex constitutive equations heavily dependent on temperature, and large variations of thickness.

### 2.3.1 THE MATHEMATICAL FORMULATION

After assembly of the element forces, converted back into the global coordinate system, each nodal equation of motion reads

$$M_j \{ \ddot{X}_j \} = \{ F_j^p \} + \{ F_j^g \} + \{ F_j^d \} - \{ F_j^{int} \}$$

where  $\{ F_j^p \}$  = nonconservative, global pressure forces,

$\{ F_j^g \}$  = conservative gravity forces,

$\{ F_j^d \}$  = external nodal damping forces (if any),

$\{ F_j^{int} \}$  = internal global nodal forces, resulting from the assembly of element local equivalent nodal forces transformed into the global coordinate system.

Integration of the above equation of motion is carried out via a second order, single step, explicit, predictor-corrector algorithm.

The principle of Virtual Work provides the local internal nodal forces in equilibrium with the stresses as

$$\{ F_j^{int} \} = \sum_s h [R] \int_s [\bar{B}]^T \{ \bar{\sigma} \} ds \quad (1)$$

In this equation, the (current) element thickness  $h$  is moved outside the integral as it is assumed constant element wise. The real (Cauchy) stress components  $(\bar{\sigma}_{xx} \bar{\sigma}_{yy} \bar{\sigma}_{xy})^T$ , are expressed in the convected coordinate system, following membrane assumption. The local forces are converted back to global coordinates, via the rotation matrix  $R$ .

The stresses are provided by an appropriate constitutive model. If the material is assumed hyperelastic and defined by a strain-energy function  $W(\{\varepsilon\})$ , Piola-Kirchhoff stresses are first evaluated as the gradient  $\{\sigma\} = \frac{\partial W}{\partial \{\varepsilon\}}$

and are further transformed into Cauchy stresses using standard conversion formulas.

If the material behaviour is expressed by a memory integral formula, the stress components are introduced directly into equation (1).

### 2.3.2 DESCRIPTION OF THE CODE

The overall architecture of the code, which can accommodate a variety of constitutive models involves :

- A triangular membrane finite element, allowing for large displacements through use of corotational stresses and strains, but ignoring flexural effects, well adapted to the modelling of thin plastic sheets,
- A triangular panel approximation of the rigid mould, if any; sheet nodes are not allowed to cross the mould surface where a "sticking" boundary condition is applied as soon as a sheet node touches the mould surface,
- A remeshing algorithm used to refine the initial finite element mesh of the sheet depending on the distortion of the final mesh after it has covered the entire mould inner wall,
- Various transient heat transfer subprograms to get an accurate description of the initial temperature field of the sheet heated by radiant panels to forming temperature, before forming pressure (or vacuum) is applied. The temperature is needed with sufficient accuracy in order to determine the strongly temperature-dependent physical constants describing the mechanical behaviour of thermoplastic materials used in thermoforming,
- A second order, explicit, predictor-corrector algorithm to solve the nodal equations of motion of the sheet. "

The architecture of the code is modular. A supervisor manages the variable control and exchanges between the modules which are focused on a function solving. Preprocessing and post processing are handled by external modules through ad hoc interfaces.

## 2.4 WHIRLPOOL PART

### 2.4.1 INTRODUCTION

The industrial test had to be able to validate the simulation software and perform a parametric sensitivity analysis of the process control parameters.

### 2.4.2 EXPERIMENTAL PROGRAM SET-UP

#### 2.4.2.1 Selection of the Production Line

The machine selected to perform the experimental activity was the Thermoforming Machine "RIGON. 5" made by "COMI Zingonia (BG) ITALY".

#### 2.4.2.2 Selection of the Industrial Mold

The mould considered suitable for the experimental activities was a **Freezer Cell type "FR 9M Automatic"** designed by Whirlpool.

#### 2.4.2.3 Selection of Material

The selected material was an High Impact Polystyrene type "SRL 800" manufactured by "ENICHEM" extruded by Whirlpool itself in sheet-form with two different thicknesses.

#### 2.4.2.4 Definition of the Experimental Activities

Two different types of tests were defined :

- experimental trials to characterize the heating system of the industrial WHIRLPOOL thermoforming machine.
- . experimental trials to evaluate the influence of selected process parameters on the final thickness of the thermoformed part.

#### 2.4.2.4. f Heating System Characterization

The experimental activities we carried out consisted in measuring the temperature distribution on the sheet surface in function of two different heating time and in function of different temperature setting of the main heating panels.

The above described thermal measures were performed by an external supplier "Ing. Armando Tonelli - Rovereto - Italy".

#### 2.4.2.4.2 Sensitivity Analysis of Process Parameters

The quality parameter considered as the most important in view of the end application was the thickness distribution in the thermoformed part.

Ten different kind of trial were performed in Trento changing process parameters.

Every sample was measured along the pre-defined cross sectional cuts.

### 2.4.3 SOFTWARE VALIDATION ACTIVITY

The experimental approach and the general criteria to carry-out the software validation activity was shared in Thermal and in Mechanical performances detection.

#### 2.4.3.1 Thermal validation

The temperature distribution on the plastic sheet read with the thermographic analysis was compared with the distribution coming from the software simulation.

#### 2.4.3.2 Mechanical validation

Referring to the Mechanical validation, the wall thickness distribution obtained by the simulation program was compared to those measured experimentally.

### 2.5 CODE ASSESSMENT BY END USERS

This work has been performed during the first half of the contract by VALFRIO, but, due to economical problems, Valfrio has stopped its activities and Whirlpool/Italia has accepted to complete the work.

The industrial tests had to be able to validate the simulation software and to complete the parametric sensitivity analysis of CSI/Montell on industrial moulds.

The more complex industrial mould which has been used was a Freezer Cell type "FR 9M Automatic" designed by Whirlpool.

The selected material was an High Impact Polystyrene type "SRL 800" manufactured by "ENICHEM" normally used to produce a plenty of thermoformed components in Whirlpool.

Nine different heating profiles were selected and with each heating configuration, the temperature distribution was recorded by means of an infrared video-camera installed in front of the machine.

Here's following typical validation results in terms of difference of thicknesses between trials and simulation results.

	TRIALS	error
		0/0
1	Current prod.	<b>21,8</b>
4	Mold Delay (B)	21,1
9	Longer heating	24,7
10	Shorter heating	25,5

The simulation results are considered as satisfactory. They have been compared to the results of other commercial codes and they are better, but they have still to be improved, specially for air slip thermoforming.

It must be emphasized here that the end users have usually very poor data on their processing conditions and such important computational parameters as initial sheet temperatures and vacuum pressure curves are not available, this makes unrealistic to have very accurate predictions.

### 3. RESULTS

Thanks to the combined use of simulations and experiments, a better understanding has been got for:

- the deformation of the membrane *during* the forming step,
- the evolution of the temperature in the membrane (coupled with the evolution of the temperature of the mould),
- the pneumatic aspects *linked* to the discharge of the air through the vents.

This makes possible to simulate the plastics thermoforming process with a reasonable accuracy.

Other major results have been obtained during this program :

- A new method of strain measurements based on an optical method without contact has been introduced.
- The non linear viscoelastic characterization of 3 materials : Polystiren, polypropilen and a 2 layer material PMMA/ABS, has been completed.
- An innovative method for measuring the membrane displacements during the process has been set up and the critical parameters of the process have been highlighted, i.e. : the importance of the temperature control during the heating step and the importance of the air vents location and pressure control during the forming step.

The simulation has clearly demonstrated that significant progress can be made to *remove* the art of this process but the control of temperatures and pressures by the end users must be improved for the simulation to be really predictive.

## 4. CONCLUSIONS

The Modform program has resulted in significant progress at least on three topics :

Materials characterization for thermoformed materials in strain rates ranging from 1 s<sup>-1</sup> to 10 s<sup>-1</sup>, extension ratios between 2 and 5 and temperatures ranging from 140 d°C to 190 d°C.

This characterization has permitted to have a much better understanding of the so caHed memory effects and the typical theological behaviors of the three selected resins have been highlighted.

The Modform simulator can accommodate a variety of theological constitutive models and include a dynamic description of the membrane displacements and transient heat transfer models for a better evaluation of the initial thermal field. Lodge's and Ogden's constitutive laws have been implemented in the computer code.

The experimental program conducted by end users has made possible to improve the technological characterization of the VACUUM and AIR-SLIP thermoforming processes and to check the main assumptions of the simulation model. The simulation results have been compared with experimental data and they are considered as satisfactory and better than those obtained with other commercial codes but they have still to be improved, specially for air slip thermoforming.

## 5. ACKNOWLEDGMENTS

Financial support from the E.C.C.(Brite-Euram programme N°5732) is gratefully acknowledged.

## 6. REFERENCES

1. R.W. OGDEN (1972), Large Deformation Isotropic Elasticity - On the Correlation of Theory and Experiment for Incompressible Rubberlike Solids, *Proc. R. Soc. Lond. A.* **326**, 565-584.
2. A.S. LODGE (1964), *Elastic liquids*, Academic Press.
3. W.N. SONG, F.A. MIRZA, J. VLACHOPOULOS (1991), Finite Element Analysis of Inflation of an Axisymmetric Sheet of Finite Thickness, *J. Rheol.* **35** (1), 93-111.
4. K. KOUBA, O. BARTOS, J. VLACHOPOULOS (1992), Computer Simulation of Thermoforming in Complex Shapes, *Polym. Eng. Sci.* Vol. 32, N°10, 699-704.
5. W.N. SONG, F.A. MIRZA, J. VLACHOPOULOS (1992), Finite Element Simulation of Plug-assist Forming, *Inter. Polymer Processing VII*, **3**, 248-256.
6. H.G. DE LORENZI, H.F. NIED, C.A. TAYLOR (1991), A Numerical/Experimental Approach to Software Development for Thermoforming Simulations, *Transactions of the ASME*, Vol113, 102-114.