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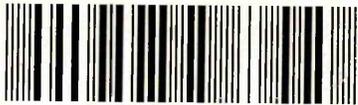
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# Operational Characteristics of the NNPB Plunger in the Glass Container Industry

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A thesis submitted in partial fulfilment of the  
requirements of Sheffield Hallam University for  
the degree of Doctor of Philosophy

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Collaborating Organisation: PLM Redfearn Ltd.

## Declaration

The candidate has not been registered for another award of a University during the research programme.

Work on the Operational Characteristics of the narrow neck press and blow plunger has been undertaken at Sheffield Hallam University since October 1991. The candidate was employed full time as a research student under the of direction of Professor M. Sarwar and supervision of Mr. G. Cockerham, Dr. G.W. Marshall and Dr. D.B. Lewis. This programme of work has been financially supported by the E.P.S.R.C. (formerly S.E.R.C.) and PLM Redfearn Ltd.

Work carried out during the research programme has been reported in the following scientific papers;

- 1 Penlington, R. Sarwar, M. Marshall, G.W. Cockerham, G. Lewis, D.B.

Material Requirements for Narrow Neck Press and Blow Plungers Within the Glass Container Industry.

Key Engineering Materials 86-87 1993 pp55-60

- 2 Penlington, R. Sarwar, M. Marshall, G.W. Lewis, D.B. Cockerham, G.

Wear Mechanisms in Narrow Neck Press and Blow Plungers

Proceedings of the Second Conference of the European Society of Glass Science and Technology. 'Fundamentals of Glass Science and Technology' Venice, Italy, 21-24 June 1993 pp279-284

- 3 Penlington, R. Marshall, G.W. Lewis, D.B. Sarwar, M.

The Wear of Coatings Used on Glass Manufacturing Equipment.

EAST-Report 1993 'New Materials and Technologies in Surface Finishing For Better Corrosion and Tribology Properties' pp86-90

## **Abstract**

Although glass containers are an everyday item the process responsible for their production is not scientifically understood. Developments have occurred slowly over many years, mostly on a trial and error basis and in response to economic pressures. The narrow neck press and blow (NNPB) process has evolved in recent years as a result of attempts to reduce container weight. The fundamental component of the NNPB process is the plunger which is responsible for the initiation of the cavity and control of glass distribution within the container.

The NNPB plunger functions as a form tool and as a heat exchanger, thus requiring a carefully selected range of properties. The Engineer responsible for tooling selection and operation has a limited resource of scientific knowledge to enable the performance of the process to be optimised.

The current NNPB plunger is subject to high rates of wear and is directly responsible for product defects, thermal instability and limits process speed.

The work presented here is a scientific study of current NNPB plunger technology. The plunger has been investigated in relation to the requirements of the glass container forming process. The materials used have been examined, before and after use and their wear modes explained. The thermal properties of the plunger have, as far as is possible, been examined during the forming cycle. When combined with results from the characterisation of transformations occurring in the material, during its service life, operational requirements have been explained. The ability of the NNPB plunger to remove heat from the glass has been investigated, and has illustrated significant deficiencies in the current arrangement. Details are given as to how these deficiencies may be overcome to enable the Engineer to regain control of the process.

As a result of the study many phenomena exhibited by the NNPB plunger are now understood and may be related to the performance of the process.

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## Chapter 1 INTRODUCTION

### 1.0 Introduction

The mechanised forming of glass containers was developed from early hand gathered and mouth blown bottles. As society changed and demand for an increasing number of standardised food and beverage containers developed. The first developments were wooden form tools to aid the manual blowing of bottles but economic growth during the latter half of the eighteenth century paved the way for the invention of the two basic methods of current container production.

In the United States Philip Arbogast obtained US patent 260,879 on May 11<sup>th</sup> 1882<sup>1 2</sup> for a process involving the press, transfer by a two piece neck mould (ring mould) and final blowing in a second mould of wide mouth containers. To produce narrow neck containers a process was developed in England by Ashley. He used two moulds, a neck ring and a plug with the blank mould being inverted to allow the glass to be loaded through the wider base opening. These processes are much the same in principle as those in use today but the machines of the time were only semi-automatic used as an aid to manual operatives.

The first fully automatic machine was developed in 1903<sup>3</sup> by Michael Owens, these rotary machines could replace many workers and as variations were small in the capacity of the ware they produced their use became wide spread with around 200 machines operating by 1915. The Owens machine was prevented from becoming universally accepted as availability was restricted by a licensing arrangement and also because it was only suited to long production runs. For this reason there was still the incentive to produce a machine which could answer all production requirements.

The Hartford Empire Company (now Emhart) introduced a new machine in 1921 which soon became the industry standard and has remained fundamentally the same to this day. The IS (individual section) machine uses the fundamentals established by Arbogast and Ashley to produce both wide mouth and narrow neck ware on a very adaptable machine.

Changes since 1921 have been restricted to developments in the mechanism which feeds the gobs of hot glass to the blank mould, the timing control has been changed from pneumatic to electronic, variations have been made in the routing of cooling air and the number of sections making up each machine have been increased. The production of narrow neck ware by the blow and blow process involves two sets of mould equipment per forming cavity, referred to as the blank side and the blow side. The stages of forming a container, by the blow and blow process, are illustrated in Figure 1.

The gob of glass enters the blank mould under the force of gravity and is then forced to the end of the blank mould cavity and into the neck ring to form the 'finish' of the required form for the closure system to be used. This is referred to as the 'counter-blow'. The plug in the neck ring is removed leaving a small cavity, this initiates the bubble which is then blown within the gob to form the 'parison' preform. The parison, held only by the finish, is inverted for the second forming stage. The blow mould halves close around the parison and support it under the finish, allowing the neck ring to open and return to the blank side to commence forming the next parison. With the parison suspended in the blow mould the blow head covers the opening and blows the container to the finished form. The blow moulds open and a pair of 'take out tongs' remove the container from the forming equipment to then be removed by conveyer for heat treatment. Figure 2 illustrates glass container terminology.

The forming cycle is dependent upon the relationship between the temperature and the viscosity of the glass melt.

The blank stage must remove sufficient heat from the surface layer of the parison for it to remain unsupported during the invert, but the process requires the redistribution of thermal energy within the parison such that the cooled surface layer is reheated to a point where its viscosity is suitable for blowing to the final form.

The blow and blow process is very versatile and can produce a wide range of container sizes from small cosmetic bottles to large chemical flasks and containers of irregular non-symmetrical section, but suffers from two economic drawbacks.

Firstly because the position of the bubble within the parison cannot be controlled the distribution of glass within the finished container is unlikely to give an even wall thickness and therefore the volume of glass employed has to be sufficiently large to allow the thinner wall sections to have the required minimum strength requirements. The melting of glass is energy intensive and accounts for around 33%<sup>4</sup> of the total cost of glass container production. Excess glass in containers thus raises production costs significantly, as well as subsequent transportation and handling costs.

Secondly, it is recognised that the bubble within the blow and blow parison does not remove any heat from the glass<sup>5</sup>. This limits the surface area of glass from which heat may be removed. The increase in area in contact by use of a metallic plunger by the press and blow process, Figure 3, allows a significant increase in production speed.

### 1.1 The narrow neck press and blow process

Production rates given by Doyle<sup>6</sup> for an eight section double gob machine producing 300g containers are 152 containers per minute for blow and blow and 168 for press and blow, but if weight reductions due to the predictable glass distribution with press and blow are taken into account then the equivalent container could be produced by the press and blow process at a rate of 192 containers per minute, an increase of c26%.

To maximise the potential of the press and blow process the narrow neck press and blow (NNPB) process (Figure 4) was developed in the late 1960's. The most significant difference between the production of narrow neck containers by the blow and blow and the press and blow process is the effect of the plunger upon the glass's physical redistribution during the forming process.

To allow the parison to be inverted without distortion it is supported by a skin of glass which has been cooled by contact with the metal mould tooling, for the blow and blow process this is only the external surface whereas with a press and blow parison the internal surface has also been cooled. The result of this is that the parison is formed quicker but it has the disadvantage that both the external and internal surfaces have to reheat from the bulk of the parison to allow a successful final blow. This leads to higher residual stresses in an NNPB produced container which have to be correctly relieved in the annealing lehr if final container strength is to be optimised.

The economics of glass container production have concentrated development upon increasing production rates and reducing the weight of glass required for each container<sup>7 8</sup>. But as production speeds have increased and defect rates in containers have been reduced, increased demands have been placed upon mould equipment. This has been reflected in a rise in the cost of mould equipment.

Ensor<sup>9</sup> gives the cost as 2% of production cost in 1960, rising to 5% in 1970. Sidler<sup>10</sup> considered the cost to have risen to 9.7% by 1988.

A summary of literature relating to mould equipment prior to 1970 is given by Ensor<sup>9</sup>. The properties required of a mould material are given as;

- Good Machinability
- Ability to produce a good surface finish
- Resistance to thermal checking
- Low thermal expansion
- High thermal conductivity
- Resistance to growth
- Resistance to oxidation
- Resistance to wear
- Density or homogeneity
- High graphite particle distribution

Each requirement is discussed with the assumption that the main material used for the manufacture of mould equipment would be grey cast iron with only brief reference to nickel and copper based alloys.

The use of cast iron is well documented and it has remained the main material for mould manufacture despite several unfavourable characteristics which result from the thermal demands of the forming cycle. The mould cavity must be able to operate during repeated cycles of contact with a hot abrasive mass at c1000°C - 1200°C and then be subject to relatively cool air draughts across the recently heated surface. Various studies have been made of cast iron as a mould material and its ability to resist thermal cracking, physical growth, scaling and mechanical damage.

A typical composition for a glass mould grey iron is given by Angus<sup>11</sup> as Total Carbon 3.5-3.77%, Silicon 1.6-2.3%, Manganese 0.45-0.65%, Sulphur <0.12% and Phosphorus <0.35% with the possible addition of 0.15-0.25% Titanium. This iron in its fully annealed ferritic structure will give

good resistance to cracking but if annealed to give a spheroided pearlite would give a good combination of wear resistance and resistance to cracking. In a detailed study of container mould properties, Ensor<sup>12</sup> discusses the various factors affecting mould performance, thermal shock resistance, resistance to dimensional changes, resistance to oxidation and growth and resistance to surface breakdown. The importance of alloying elements such as chromium, molybdenum and vanadium are described and a typical iron composition is given as Carbon 3.3-3.5%. Silicon 2.2-2.4%, Manganese 0.5-0.7%, Sulphur <0.1%. Phosphorus <0.1% and Titanium 0.08-0.1%. The optimum graphite form and distribution are described and related to the differing thermal properties of coarse and fine grain cast irons concluding that to prevent thermal cracking and breakdown of the glass contact surface a compromise is made and a fine graphite structure with a lower thermal diffusivity is desired whereas towards the rear of the mould a coarser graphite structure may be used to aid cooling.

## 1.2 Thermal considerations

The effect of the thermal cycling has been examined<sup>13</sup> for differing graphite forms in relation to surface roughness, glass wetting angle and fatigue strength, and for differing compositions. The thermal cycling was found to initiate cracks<sup>14</sup> at the metal-graphite interface of 30 $\mu$ m to 1.0mm length into the body of the mould, this was reduced by the addition of aluminium (1.25%) to the iron to strengthen the ferrite matrix and intergranular boundaries to delay crack propagation.

The use of cast iron is widespread<sup>11</sup> because it is relatively cheap, easy to machine and possesses acceptable thermal properties and some of its deficiencies<sup>15 16 17</sup> have been overcome. Lubricants<sup>18 19 20 21 22</sup> are applied to the glass metal interface aid forming, but as production speeds

increase the demands upon the thermal capacity of cast iron have become critical. An important property of good mould equipment is its ability to remove heat from the contact surface at the required rate, this property is often described as the thermal diffusivity and is a relation between the thermal conductivity, specific heat, and density of the material.

$$\text{Thermal diffusivity (mms}^{-2}\text{)} = \frac{\text{thermal conductivity}}{\text{specific heat x density}}$$

Comparison of the relationship between thermal diffusivity and operating temperature for cast iron and aluminium bronze illustrates not only that cast iron has far from ideal properties but also that any study of mould materials must compare the physical properties pertinent at the operating conditions (Figure 5).

Aluminium bronze, typical composition Ni 14.0-15.5%, Al 9.2-10.2%, Zn 7.5-9.5% has found widespread usage in neck rings and bottom plates, but in general, difficulties have been found due to pitting of the glass contact surface of blank moulds due to the sulphur in mould lubricating dopes<sup>12</sup>. Tooling manufactured from aluminium bronze is significantly more expensive and more difficult to machine, weld and repair. Stainless steel has also been considered for use as a mould material but although it is commonly used for long cycle time pressed products, e.g. TV screens and lens glasses for cars etc.

A significant property required of mould cavities is the surface condition at the glass contact surface in terms of physical form but also chemical and thermal properties. Studies have been carried out which have measured the influence of increases in cavity roughness upon the quality of the glass surface produced<sup>23 24</sup>. It must be recognised that with current lubrication practices the nature of the contact with the cavity surface must be viewed as a composite system where the glass is actually in contact

with the carbon interlayer. Golden<sup>18,19</sup> has studied the physical nature of this surface but little is known of the chemically reactive or thermal properties of this interlayer.

The nature of intimate contact between hot glass and metallic surfaces has been studied by Fairbanks<sup>23 25</sup> and from this work it is clear that the nature of the chemical conditions occurring during the intimate contact of hot glass, metallic solids and any gasses requires further study. Only when this has been done can it be said that the use of metallic materials to deform molten glass is understood. Although work in this area has been carried out<sup>26</sup> it has only been applied to the practical forming of glasses by the application of surface treatments to repair damage during forming and prevent future damage during subsequent handling and filling processes.

There is very little literature which relates specifically to the NNPB plunger. Seidel<sup>27</sup> stresses the importance of the plunger to the efficient production of the lightweight glass containers and the monitoring of the process by recording plunger motion characteristics.

Schumacher<sup>41 42</sup> report some plunger deficiencies and makes a strong commercial case for the use of plungers cast from a nickel based alloy of very similar composition to that which is currently used as a wear resisting coating. Schumacher also illustrates the deficiencies of powder alloys containing tungsten carbide<sup>28</sup> form use at glass contact surfaces where release of material into the glass may occur.

Babcock and McGraw<sup>29</sup> recognised that for a full understanding of the glass forming process, from an engineering point of view, the following must be understood;

- The spatial and time distributions of temperature in both the glass and mould metal throughout the forming cycle.
- The stress acting at all points in the glass, at all stages of the cycle.
- The effect of these forces and temperatures on both the motion of the glass during forming and upon the final strength, appearance, and other physical attributes of the finished product.

### **1.3 Aims and objectives**

It is clear from the above that the narrow neck press and blow process is far from understood. The aim of this study of the operational characteristics of the NNPB plunger is to increase the knowledge available and to further improve the understanding of the NNPB process for the production of lightweight glass containers.

The aim of this study will be achieved by examination of the following;

- Characterisation of NNPB plunger substrate and coating materials.
- Analysis of wear and failure modes.
- Assessment of plunger operating temperatures and thermal cycling during the forming process.
- Analysis of the NNPB plunger cooling system.

## Chapter 2 MATERIAL CHARACTERISTICS OF THE NNPB PLUNGER.

### 2.1 Introduction

The plunger operates as a form tool and heat exchanger, its primary purpose is to accurately distribute the glass within the blank mould (Figure 6) whilst it is also required to remove thermal energy from the inner surface of the parison. These two features are the most significant factors in the production of lightweight glass containers, i.e. the accurate distribution of glass which allows a weight reduction and the removal of heat energy from the inner surface of the parison which enables the parison to be formed at a higher production rate.

The NNPB plunger has been derived from the traditional wide mouth press and blow plunger from the '62' process on the IS machine. This comprises a steel substrate with an overlying layer of a hard facing weld material machined to the required geometric form. The heat transfer is carried out by thermal energy being conducted through the composite wall of the plunger and then being carried away by air flowing within the bore of the plunger (Figure 7).

### 2.2 Substrate Material

The NNPB plungers examined during this study employ a plain carbon steel substrate in preference to the cast iron originally used when the process was developed. The reason for using plain carbon steel is that it offers a cost advantage, better machinability and also better coating adhesion and integrity are obtained. The plain carbon steel employed for the substrate (BS, 970:080 - A40) has the nominal composition specified in Table 1.

The microstructure of an unused plunger shows a ferrite/pearlite microstructure typical of a normalised steel, plate 1

Examination of the microstructure, by standard metallurgical techniques, of the substrate material of used plungers shows evidence of two forms of microstructural change. Plate 2 shows the partially spheroidised pearlite<sup>30</sup> at a region a little over mid way between the tip and the finish. Plate 3 shows the more complete spheroidisation at the tip after the same service life, 459.5 hours (c345,000 glass forming cycles).

element	mass %
C	0.36 - 0.44
Si	0.05 - 0.35
Mn	0.60 - 1.00
S	0.060 max.
P	0.060 max.
Fe	balance

Table 1. Plunger substrate material (BS, 970:080 - A40)

The existence of spheroidised pearlite indicates that the substrate has been cycling above and below the lower critical temperature ( $A_1$ ).

The second form of microstructural change examined was found on a plunger which was removed from after 1052 hours (c789,075 glass forming cycles). Grain growth and graphitisation can be seen in Plate 4 at the hottest region. This occurs when there is thermal cycling above the lower critical temperature ( $A_1$ ) but below the upper critical temperature ( $A_2$ ). The temperatures at which these transformations occur depend upon the rates of heating and cooling but will be in the region of 720°C and 775°C<sup>31</sup>. In

the spheroidised state the substrate will have minimum hardness and maximum ductility.

### 2.3 Coating Material

The coating currently employed is manufactured by the Deloro Stellite company sold under the name Deloro SF40s which has been developed to provide coatings up to 2 mm thick by the spray and fuse process on cylindrical components.

SF40s is a nickel based powder welding alloy with the following nominal composition specified in Table 2.

element	mass %
C	0.25
Si	3.5
B	1.7
Fe	2.5
Cr	7.5
Ni	balance

Table 2. SF40s powder welding alloy nominal composition

The powder is in the size range 38 - 106 $\mu$ m diameter produced by atomisation. Atomised particles flow into the application torch well, produce less slag, less porosity and a harder deposit. Typical powder particles are shown in Plate 5 and the structure of a particle including some entrapped porosity is shown in Plate 6.

The coating is produced by the spray and fuse technique in three stages.

Preparation - The substrate surface is cleaned and prepared by shot blasting and pre-heating taking care to avoid any oxidation of the surface.

The powder is applied in a flame spray to produce a layer of semi-molten particles, Plate 7. The thickness of applied layers is between 1-3 mm with a 25% shrinkage allowance for fusing.

The coating is fused and densified using a multi jet oxy-acetylene burner. At around 1100°C the rough sprayed surface becomes molten and has a glazed appearance. At this temperature the coating forms a metallurgical bond with the substrate and porosity is removed.

Plate 8 shows the microstructure of a typical plunger coating.

The self fluxing Ni-Cr-Si-B alloy has the following constituent components<sup>32</sup>

- Nickel - Used as a matrix, imparts impact resistance (ductility) and some corrosion resistance.
- Chromium - Primarily for corrosion and hot erosion resistance, it also acts as a hardener.
- Boron - Used as primary hardener.
- Silicon - Used as a fluxing agent, forms SiO<sub>2</sub> cleaning the surface.

The additions of boron and silicon to the nickel lower the melting point and allow fusion by oxyacetylene torch. The nickel and boron form a Ni-Ni<sub>3</sub>B eutectic at 1083°C and the addition of silicon further reduces the eutectic temperature by combining with the surface oxide on powders to form borosilicates. The presence of Ni<sub>3</sub>B has been confirmed, in this study, by the use of x-ray diffraction. These fluxing agents help to reduce and absorb any oxide on the substrate surface. This cleaning allows a

metallurgical bond to form during the fusing and densification of the deposit.

#### 2.4 Examination of coating material

Examination of the coatings for bonding and porosity indicated a good bond to the substrate. Porosity was found in two forms, entrapped gas porosity and intergranular porosity. The entrapped gas porosity was only evident in the tip area and it is suggested that this may be a deficiency of the application technique. This may result from a lack of operator control over application rate and temperature at the tip area as material may be effectively 'over sprayed' on the back side of the plunger tip. This entrapped gas porosity may be seen in Plate 9.

Intergranular porosity was evident in some plungers, Plate 10. It is suggested that this is the result of incomplete fluxing during densification.

As will be seen later the fluxing component of the powder system is thought to contribute to a form of critical container defect, therefore any increase in the proportion of flux in the composition should be avoided. The existence of intergranular porosity is detrimental to coating performance for two reasons.

- Physical voids in the coating bulk represent barriers to the flow of thermal energy through the plunger wall. This will give rise to local increases in temperature.
- The mechanical properties of the coating will be significantly reduced in an area where voids in the material matrix act as stress concentrators and fail to adequately support the abrasion resisting hard particles during mechanical loading.

The existence of these two forms of porosity was also in evidence when machined surfaces of plungers were examined. The geometric form of the plunger is obtained after coating

application by turning and in some instances honing. The profile resulting from the turning operation has an orientation at  $90^\circ$  to the direction of glass flow during the container forming operation. The industry has developed a practice of longitudinal honing to reduce the effects of the turning operation. Examination of the profile of an 'as new' surface by Rank Taylor Hobson form tallysurf gave a roughness measurement in the order of  $R_a$   $0.7\mu\text{m}$  and  $R_t$   $6.5\mu\text{m}$  measured along the plunger axis, i.e. parallel to the direction of glass flow. Typical machined surfaces are shown in Plate 11 & Plate 12 and illustrate that although the surfaces may optically have a smooth surface there exist areas of subsurface weakness, torn surfaces where the hard particles have ploughed along the surface and smearing of matrix material. All these features offer sites for the initiation of wear.

A metallurgical examination of the coatings was carried out by scanning electron microscopy and elemental distribution maps were obtained using energy dispersive x-ray analysis (EDX) and wavelength dispersive x-ray analysis (WDX). These show the distribution of elements within the microstructure of the coating, Plate 13. As the solubility of nickel in boron is low (c0.1 wt%) the abrasion resistance of these alloys is a function of the hard borides (nickel borides) and carbides (chromium carbide) present within a supportive matrix of nickel.

The application of Ni-Cr-Si-B spray and fuse alloy coatings to glass mould equipment has been fully characterised by Knotek and Steine<sup>33 34 35 36 37 38</sup>. Their examination included analysis of a range of coating compositions applied to the common mould materials, cast iron and steel, as a hard facing treatment. This included application to the whole glass contact surface, baffles, plugs, plungers etc. and as protection and a repair medium for exposed corners of blank and blow moulds. Results are reported of the reactions at the coating surface and the interface with the substrate

materials were examined at temperatures appropriate for glass forming applications.

### Chapter 3 WEAR AND FAILURE ANALYSIS OF THE NNPB PLUNGER

The failure of NNPB plungers and effect upon containers is not well documented in the literature with sparse reference and even less detail. Many researchers refer to scoring of the plunger surface by the abrasive nature of the glass producing features referred to as comet tails and strength reducing defects and contamination in glass containers<sup>39 40 41 42</sup>. Ensor<sup>12</sup> more correctly recognises the wear mode as being a function of the operating temperature and relative material hardness at that temperature.

Due to the serious nature of the inclusion of wear debris within glass containers there is little reference in the literature to the nature of this feature although Schumacher<sup>41 42</sup> gives figures for the weakening effect upon container bursting strength. Despite materials used in the figures quoted not being representative of current industrial practice, the magnitude of problem is recognised.

Lubitz<sup>39</sup> recognises the importance of the wear resistance of NNPB plunger coatings, stating that;

"If separations of metal particles, from the plunger surface appear, they can become attached to the inner surface of bottles. These particles, called 'black specks', reduce impact resistance and other physical parameters seriously".

Examination of worn plunger surfaces allows wear of the plunger surface to be divided into two categories, wear to the taper section and wear around the tip.

#### 3.1 Taper Wear

Wear on the taper section takes the form of an abrasive wear scar known as comet tails. Typical comet tails are

shown in Plate 14. It can be seen that a hemispherical crater occurs at the head of an abrasive wear scar running towards the plunger tip. The fragments of plunger material removed in the glass have been described by Wasylyk<sup>39</sup>;

"Black specks - Elongated (high length-to-width ratio) metal particles lying on the bottle surface with their long axis generally parallel to the bottle axis. Such black specks typically arise from the plunger surface in narrow-neck-press-and blow-forming operations...."

The wear scars are surrounded by areas of microcracking. The exact mechanism causing the crater to form is unknown. There are two suggested modes of comet tail formation;

- i. Evidence of interlining of the microcracks can be seen on the plunger surface, Plate 15, this may initiate a crack perpendicular to the direction of glass flow resulting in un-anchored coating material. An idealised concept of initiation is as laid out in Figure 8. Matrix softening and propagation of a crack through the coating allow a clump of particles to be released from the surface into the glass. This mass of hard particles is then drawn along the plunger towards its tip as the plunger is withdrawn from the parison.
- ii. An alternative to this is the generalised unlubricated sliding contact wear model presented by Hutchins<sup>43</sup>. For a metallic surface protected by an oxide layer in sliding contact the shear stress lies below the surface. It is suggested that a 'plasticity-dominated' wear mode exists where subsurface cracks propagate throughout the material resulting in delimitation of the material. Hutchins also draws attention to the generation of localised temperature rises at the contact surface due to dissipation of energy related to

the sliding motion. The magnitude of the temperature is dependent upon the normal force and the relative velocity of the surfaces. He reports that transient temperatures may lead to phase transformations in metals during contact at room temperature. It can be seen that the potential for localised melting of the matrix during glass contact is considerable. This model suggests that the cracks visible on the plunger surface may be the manifestation of a subsurface weakness leaving a 'raft' of material to be pulled along the plunger surface adhered to the glass.

As highlighted by Ensor<sup>12</sup>, mould tooling properties must be considered at the environmental conditions at which they operate. In the case of the NNPB plunger literature<sup>44 41 42</sup> gives the plunger operating temperature as 500 - 550°C. At this temperature the coating will have a hardness in the order of 280 - 250 Hv. This examination has reassessed the plunger operating temperature in view of the high rates of wear. Plunger surface temperatures, as will be demonstrated later, have been found to rise to around 900°C in extreme cases. The significance of this is recognised when considered in relation to the material hardness at this temperature region. The plunger surface hardness may fall to as little as 40Hv, Figure 9.

### 3.2 Tip Wear

The tip of the plunger shows another form of wear, in which there is more evidence of deformation rather than material removal. The significant difference in the operating environment is the angle of contact with the hot glass, the tip has an angle of contact of between 45° and 90° whereas the taper section has a contact angle which is often less than 2°.

A typical plunger tip surface can be seen in Plate 16. Micro cracking over the hard particles and deformation of

the matrix. The original machined surface and evidence of entrapped gas porosity is also visible.

In addition to material deformation and microcracking the plunger tip is associated with a critical container defect known as 'spike' which is a small projection of glass usually at the base of the container. A spike is a serious defect for if it is not picked up by the container producers quality system and reaches the general public the repercussions for the glass producer are considerable. Within the glass industry it is believed that a spike may occur for the following reasons;

- The plunger is too hot due to a blocked hole in cooling tube.
- The plunger is dirty.
- Hot spots on plunger tips.
- Gas in parison making it weak.
- Lubrication swabbing technique incorrect.
- Damaged plunger material.
- Faulty plunger material.
- Loose plunger adapter.
- Glass too hot.

The plunger being too hot is the most common explanation for the occurrence of a spike. During the course of this investigation it became apparent that this explanation was erroneous. The main explanation for this is that the plunger tip is not the hottest region, and that spikes do not get pulled by the plunger at its hottest region. Visual inspection of the tip of plungers removed from the machine for causing this defect suggested that entrapped gas porosity at the tip may provide a geometrical feature within which glass may become mechanically keyed.

Examination by scanning electron microscopy has shown this explanation to be incorrect. As can be seen in Plate 17 the glass (light areas) is evenly spread over the surface with minimal material appearing in the pores.

Examination of the surface composition indicated a higher than expected concentration of silicon. This suggests that there is a chemical affinity between the silicon oxide at the surface and the glass, which is the primary cause for spikes. This hypothesis, supported by the findings of Knotek<sup>37</sup> in a study of the temperature related reactions of Ni-Cr-Si-B coatings at the surface and the substrate interface. Results suggest that at temperatures below 800°C there will be an enrichment of the surface layers by silicon whereas above 800°C the significant element at the surface will be chromium. This is supported by temperature measurements of plunger tips and also by the time relationship of these elemental distributions. The rate at which these transformations would take place, during thermal cycling and glass contact, in the glass forming environment is unknown. The relationship between the time for transformations to become significant and the rate at which material is removed from the plunger surface is of interest. The plunger tip does not undergo rapid material removal thus allowing for the redistribution of the elements, whereas at the hottest region on the plunger surface material loss is at a rate which in extreme cases prevents the formation of an effective oxide layer. Hot bands have been observed being exceedingly bright with a glazed appearance with little patches of mottled 'skin' drifting on their surface. This suggested cause of spike formation is the reason that it has not been suggested that coatings with higher concentrations of silicon should be assessed as a method of reducing porosity levels.

### **3.3 Oxidation of the plunger bore**

Plungers removed from the forming machine due to overheating were examined for wear on their taper sections. During the course of this examination it was found that there was considerable oxidation of the internal bore of the plunger, Plate 18.

The distribution of the thickness of a typical oxide layer is shown in Figure 10. It can be seen that for most of the plunger's length it is reasonably uniform but is substantially thicker at the hottest area of the plunger. The formation of the oxide layer will substantially reduce the heat transfer properties of the plunger wall. This is due to the lower value of conductivity for the oxide and also to cracks and delamination of the layers of oxide resulting in insulating air layers, this can be seen in Plate 18.

The formation of the oxide is self sustaining in that due to the formation of the oxide the external surface temperature of the plunger will rise causing a rise in substrate temperature which leads to an increase in the rate of oxide formation. This causes a rapid decline in the operating performance of the plunger and considerable coating loss.

The formation of oxide on the plunger bore is thus related to taper wear and once the oxide layer reaches some critical thickness the rate of taper wear results in the plunger being removed from the forming machine. The plunger then undergoes cleaning, re-coating and re-profiling before being returned to the machine with the internal oxide layer intact. In this way the operating life of the plunger becomes shorter and shorter resulting in increased machine down time and production of poor quality containers.

## Chapter 4 THERMAL ANALYSIS

### 4.1 Introduction

The NNPB plunger is a vital component in the thermal system which removes heat from the glass to allow it to support its own mass in its newly formed geometry. For this reason any thermal analysis of the NNPB plunger must begin with some reference values.

The NNPB plunger presents particular difficulties when any attempt is made to monitor its thermal performance. Due to its position in the bed of the IS machine below the blank mould and neck ring (Figure 11) it is only accessible during the forming cycle to the most rudimentary of contact measuring techniques, and then only the very tip of the plunger is accessible. Hard wired methods using embedded thermocouples are not practical as any intrusion into the coolant would have a considerable effect upon the flow and temperature distribution. It would also be exceedingly difficult to remove any leads from the bed of the machine whilst allowing for the vertical motion of the plunger cylinder. For these reasons temperatures have been predicted by measurement of the intensity of thermal energy emitted from the surface of the plunger in the Infra red region.

### 4.2 Thermal Image Analysis

This method has no effect upon the function of the forming cycle but can only be used where there is line of sight. For this reason it offers a practical, safe and unintrusive method for predicting the temperature of mould tooling during those parts of the forming cycle when the area of interest is visible from the side of the machine. This limits the suitability of this technique for items of mould tooling where other methods, thermocouples etc., are

practical. In the case of the NNPB plunger this is the only technique which is available if all relevant considerations are taken into account.

The use of thermal image analysis has been applied to glass container forming to assess the efficiency of the Vertiflow cooling system for blank moulds<sup>45</sup>. Tests were carried out to assess the emissivity of a cast iron blank mould over the region of the operating temperature with standard lubricant applied to the surface. Variations in the inlet temperature of cooling air could be monitored and mould surface temperatures stabilised whilst trials with lightweight bottles were carried out.

The prediction of temperature distributions within glass gobs has also been attempted<sup>46</sup>. The differing transparency of glass at different wavelengths was used to predict a surface temperature for the gob and a weighted average internal temperature by using image analysis equipment which only responded to predetermined narrow wavelength bands. Temperatures within the gob were predicted for a flint glass container produced by the blow and blow process.

Wavelength ( $\mu\text{m}$ )	Depth of measurement (mm)
0.7 - 1.0	100 - 125
2.2	50 - 75
3.8	12
5.1	1.5
7.9	surface
8 - 14	surface

Table 3 Depth of measurement into clear glass given by Tattam<sup>47</sup>

Figures for approximate depth of measurement into clear glass are given by Tattam<sup>47</sup>, Table 3. It is also reported that for most glass applications it is not necessary to adjust emissivity settings to much below unity, this is a major misconception.

#### 4.2.1 Background Considerations & Practical Aspects.

There are several significant considerations which need to be taken into account when applying radiation thermometry to a practical situation. The most important factor being that real materials are not black body radiators, i.e. they do not absorb all incident radiation at their boundary. This has two implications, firstly when viewing the thermal radiation of a body a proportion of the radiation seen to be coming from that body will in fact be radiation from the surrounding (background radiation) reflected from the non black body surface. The second complication relates to this reflection of radiation and can be considered as internal reflections, therefore only a proportion of the total radiation relating to the absolute temperature of the body will actually be emitted from the surface.

With certain assumptions in the practical situation it can be assumed that the proportion of energy leaving the surface 'spectral emissivity', (E) plus the proportion reflected 'spectral reflectance',  $\rho$ , is equal to unity for a given wavelength.

$$E(\lambda) + \rho(\lambda) = 1$$

and

$$\text{Spectral emissivity } E = \frac{\text{Radiation emitted by an object at temperature } T}{\text{Radiation emitted by a blackbody at temperature } T}$$

Therefore when applying radiation measurement to a practical situation requiring a definition in terms of temperature it must be remembered that the emissivity of the body for the given wavelength must be known. This is further complicated by the fact that for many materials the value of emissivity will change with temperature. This is particularly important for metallic materials with surface oxide layers and phase changes etc.

Material	Condition	Temperature °C	Emissivity
Aluminium	unoxidised	25	0.02
		100	0.03
		500	0.06
	oxidised	200	0.11
		600	0.19
		100	0.55
Nickel	polished	38	0.05
	oxidised	38	0.31
		260	0.46
		538	0.59
		1093	0.86
	unoxidised	25	0.05
		100	0.06
500		0.12	
1000		0.19	
Paint	flat black	24	0.94
	gloss black	24	0.92
Steel	polished	24	0.10
	oxidised	25	0.80

Table 4 Emissivity values for LAND TI 35sm thermal imager

From Table 4 it can be seen that for some metallic bodies the background radiation may be a significant component of

the total radiation detected by a measuring instrument, Figure 12. It is also of significance that some materials have a value of spectral emissivity which may change considerably and in a non-linear manner with temperature.

Another potential source of error is the loss of radiation, into the atmosphere, between the target object and the detector. Losses in atmospheric air are mainly due to gasses in the air, water vapour, carbon dioxide and ozone, and the scattering effects of dust particles and water droplets. The absorption varies with wavelength and infra red detectors are designed to respond to 'windows' in the absorption spectrum. In addition the imager must compensate for the small losses within the 'window' used by the use of a user definable coefficient and target distance.

An important parameter in characterising roughness effects is the optical roughness which is a ratio of the root mean square roughness height ( $\sigma_0$ ) to the wavelength of the radiation ( $\lambda$ ) When the optical roughness of  $\sigma_0/\lambda \leq 1$  the surface can be considered optically smooth. When considering what effect reflections may have on a practical situation the effect of surface roughness must be considered. Surfaces considered as rough and light scattering to the human eye, spectral response 0.4 to 0.75 $\mu\text{m}$ , will be optically smooth at 3.5 $\mu\text{m}$ .

The theory of energy emission may be easily applied to optically smooth pure metals but in most practical situations there will be deviations from the theory due to impurities on or in the surface of the material. The most common contaminants are thin layers of foreign materials deposited by chemical reaction. For example thin layers of metallic oxide. Metallic oxides or other non metallic surface contaminating layers will generally have higher values of emissivity than the pure metallic bulk.

#### 4.2.2 Methodology for Temperature Prediction

Practical procedures for radiation measuring require the selection of a suitable instrument, this predetermines the wavelength of radiation which will be measured. Also the resolution both in terms of spatial separation and radiation level. The instrument will have characteristics in terms of field of view, the rate at which it can cope with a moving object, etc.

For use in the industrial setting there are also several other important aspects as the equipment must not only operate in the harsh environment of the glass plant but must also be safe to operate. Practical considerations are things such as cooling for the detector, for example thermoelectric cooling being far superior to the liquid nitrogen which requires frequent topping up and is liable to spill out of the camera when it is in a situation where it cannot be used exactly horizontal.

The instrument used during the course of this investigation was a LAND TI 35sm manufactured by Land Infra-red Ltd. This instrument is very suitable for use in an industrial environment due to its size, weight and ability to function as a self contained battery operated unit.

### Specification

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Temperature range	-20 to 1500°C blackbody temperature
Focusing range	0.5m to infinity
Frame frequency	25Hz
Field of view	16° x 16°
Detector	Thermoelectrically cooled HgCdTe
Spectral response	low range - 3.5 to 5µm med/high range - 3.9µm
Correction factors	Emissivity Background temperature Target distance Atmospheric absorption coefficient

Table 5 Selected specifications - LAND TI 35sm

The method of data storage is also important for the practical application, the ability to gather and store large volumes of raw data for later analysis at a remote location is a primary requirement. The LAND TI 35sm has the ability to store images on video tape which can be played back to a software analysis package. In addition to recording continuous images, at 25 frames per second, the TI 35sm can also store a sequence of still images recorded at 0.08 second intervals to an internal memory. All forms of image can be analysed by the software package and for the NNPB plunger application the timed sequence of images is invaluable. A typical image 'as gathered' is shown in Figure 13.

The Land Image Processing System (L.I.P.S.) is a software processing package for data gathered by the TI 35sm. It allows the storage and manipulation of images, including processing and analytical functions. Colour may be added to the 64 greyscale image from the camera as well as such features as noise filters, image enhancement, and addition or subtraction of images. Temperature information may be

displayed in many forms which allow the examination of points or areas which can be displayed as multiple points, profiles, histograms, isotherms and averages. In addition the software allows the correction factors, for emissivity etc., to be set for each point or area regardless of the values current at the time of data gathering.

The process of interpreting the images obtained requires some experience as the initial information presented by the addition of temperatures to an image may be misleading. An example of this is a situation where there is not a uniform oxide condition on the target surface. For this reason a visual image may be as important as the thermal image.

During the course of this investigation an attempt has been made to assess the validity of plunger temperatures obtained from thermal image analysis. The following factors have to be considered when examining image data for the NNPB plunger;

- Geometry - The NNPB plunger, when viewed from the side of the IS forming machine appears as a vertical cylinder surrounded by the blank moulds and their holders. To reduce the reflective influence of these large heat sources measurements are only taken from a narrow strip along the vertical centre line of the plunger.
- Surface condition - As a value for the emissivity of the surface has to be assumed the visual examination of the surface will give an indication of the existence of oxide layers etc. With experience quoted emissivity values can be adjusted to take account of changes in the surface condition, for example layers of burnt on lubricant, which may have very different emissivity values from the bulk material.
- Background - The background will not only account for the source of reflections but also for the degree of atmospheric attenuation, at glass forming temperatures if

data is not gathered during mould lubrication only losses due to CO<sub>2</sub> are considered.

Actual emissivity of target	Actual temperature of target °C		
	500	600	700
0.3	-44.6	-82.3	-116.9
0.4	-28.8	-52.5	-74.1
0.5	-14.1	-25.3	-35.6
0.6	0.0	0.0	0.0
0.7	13.3	23.6	33.1
0.8	26.0	45.9	64.3
0.85	32.2	56.6	79.4

Table 6 Error recorded due to incorrect emissivity setting for an assumed value of 0.6 (results form TMERROR software)

Table 6 and Table 7 give an indication of the magnitude of error which may occur following incorrect assessment of the practical situation.

Actual background	Actual temperature of target °C		
	500	600	700
20	-58.5	-40.5	-31.3
60	-58.6	-40.4	-31.2
100	-58.0	-40.0	-30.9
200	-52.4	-36.4	-28.2
300	-34.6	-24.4	-19.1
400	0.0	0.0	0.0

Table 7 Error due to incorrect assumed background temperature setting of 400°C E = 0.6 (calculated from TMERROR software)

Figure 14 to Figure 21 show temperature distribution histograms recorded, for the whole time the plunger is visible (c 1.44 seconds) on a plunger with no internal oxide layer showing two hot bands. The rate of cooling of the external surface to the atmosphere can be predicted from such images as they were gathered in a timed sequence with 0 = start of invert.

#### 4.2.3 Surface temperature profile

Background information provided by Giegerich<sup>48</sup>, Babcock and McGraw<sup>29 49</sup> and others<sup>5 50 51 52 53 54</sup> which relates to measured temperatures at glass contact surfaces. As blank and blow moulds are of substantially greater wall thickness, it is possible to profile the temperature through the bulk of the material. Much of the information available of temperature profile within the larger cast iron tooling components has been obtained by the use of thermocouples of various designs

As has been outlined elsewhere the application of similar techniques to the NNPB plunger is not feasible, so thermal image analysis was used to give an indication of the temperatures occurring on the surface of the NNPB plunger. Results obtained by this technique are only available when the plunger is visible, i.e. during the invert. At this point, the plunger is approaching the coolest part of its cycle, gob load and pressing causing a rapid rise in surface temperature, the down plunger stroke removing the plunger from the glass initiating the cooling and the invert removing any radiation effects allowing further cooling. Using the cycle timing as a framework, the plotted cooling of plunger surface during the invert and figures for suggested surface temperatures during initial contact the following curve for the temperature cycle was derived.

The plunger tip will have a considerably different temperature profile than the area around the container

finish, the contact time is significantly longer and also the volume of glass surrounding each area is very different. This can be seen from the temperature contours and glass distribution in Figure 22 and Figure 23. The temperature contours for the 'Glassflow' distribution prediction analysis software and parison outline can be used to give an indication of the quantity of heat energy at each location.

The nature of glass distribution within the blank mould cavity can only be predicted. Two possible modes of glass redistribution during the pressing stroke are outlined in Figure 24 and Figure 25. The exact position of the glass during the pressing stroke dictates both the thermal cycle and temperatures at each point on the plunger surface. This has least consequence at the tip which is in contact with the glass from the moment it is loaded until the start of the invert movement. The duration of contact at the finish will be for a short portion of the pressing stroke immediately prior to the invert. The situation at the intermediate points is open to speculation. A temperature profile has been interpolated from known values, expected values and theoretical assumptions. Due to the wide variations in plunger surface temperature for different sections on the IS machine and for differing plunger designs, it is open to some variation in actual temperature or temperature range.

The position of the gob within the blank cavity will affect the temperature distribution in several ways:

- Areas of mould or plunger surface in contact with the glass will receive thermal energy by conduction and radiation within the scope of the combined heat transfer concept described earlier.
- The parts of mould surface which are in 'line of sight' of the gob will receive radiant energy.

- Some areas of the mould surface or neck ring will receive reflected radiant energy.
- Other parts of the mould tooling will receive conducted energy by nature of physical attachment, of significance to this study is the portion of the plunger below the ring plate.

Seidel<sup>27</sup> examined plunger motion in relation to forming parameters by use of a proximity sensor mounted in the plunger cylinder mechanism. The purpose of this examination was to monitor the movement of the plunger over the last 25 mm of its stroke in relation to time and also its final position with a view to obtaining such information as changes in gob weight/volume, tooling alignment and worn mechanisms. According to Seidel plunger motion is linear up until the last 3 - 4 mm of travel. This implies that there is little resistance to motion during the initial glass distribution within the blank cavity, with the resistance occurring during the final settling into the neck ring and upper corners at the baffle.

When predicting the glass distribution within the blank cavity one must make an assumption as to the position of the gob at loading, taking into account the following considerations:

To what extent does it hang up on any shoulder (a convex profile part way down the blank cavity) within the cavity? This is the location<sup>54</sup> of maximum damage to the blank mould surface.

During the initial stage of the plunger stroke, does the gob lift with the plunger?

Whilst the plunger motion is upward is there any counter flow of glass towards the neck ring, or does this only occur when the cavity above the plunger is full?

From observation and examination of plunger and mould surfaces it must be assumed that for any one cavity profile any combination of these distributions may occur.

Evidence to suggest this includes:

- Observation of gobs loading into the middle region of the cavity and then sagging.
- The distribution of pitting (due to thermal shock) on shoulders of blank moulds.
- Pronounced regions of wear on plunger surface.
- The result of too little plunger travel is exhibited as an under filled finish suggesting that the final movement of glass is into this region.

From this background information a temperature/time profile has been predicted for the surface at the tip of the plunger and a point at the finish. The profile given in Figure 26 assumes that the plunger is operating without a significant layer of oxide on the internal bore. The exact temperature range will vary with time for a plunger with reduced heat transfer properties at the 'hot band' below the tip, a suggested temperature profile for a plunger in poor condition can be seen in Figure 27.

#### **4.3 Cooling System of the NNPB Plunger**

To ensure the removal of thermal energy from the inner surface of the parison the plunger acts as a heat exchanger. The plunger contacts the glass and energy is transferred into the wall of the plunger. To prevent the plunger wall increasing in temperature until it reaches that of the glass and thus not removing any energy from the glass energy must be removed from the plunger bore. This is achieved by inserting a tube up the bore of the plunger

and forcing air to flow through this tube, along the inner wall of the plunger material and then exhausting into the atmosphere through holes in the adapter which mounts the plunger on the piston rod of the operating cylinder. In an attempt to encourage turbulent flow an arrangement of small holes are drilled in the cooling tube. In turbulent flow fluid particles do not stay in their own flow layers (streamlines being parallel and smooth) particles undergo random fluctuations of instantaneous velocity and path. This random movement of the fluid particles causes mixing. This mixing causes the kinetic energy of the fluid to be more evenly distributed within the flow, the result of this, in the case of the NNPB plunger, is greater heat transfer to the cooling air. A criterion which describes the nature of the flow pattern is the Reynolds number.

$$\text{Reynolds number} = Re_D = \frac{\rho VD}{\mu}$$

Reynolds number is used to indicate the non dimensional ratio of inertial forces to viscous forces.

For Reynold numbers  $\leq 2200$  flow is considered as laminar whereas for Reynold numbers between 2200 and 10,000 flow is in transition with turbulent flow at the contacting surface and laminar where flow is less restricted.

For Reynold numbers above 10,000 flow will be fully turbulent, the significance of this is demonstrated by a typical plot of heat transfer coefficient vs. Reynolds number, Figure 28.

Considering the practical application, turbulent flow increases the efficiency of the cooling system.

The inclusion of holes in the cooling tube is intended to induce both turbulent flow and also to mix cooler air direct from the tube to reduce the bulk temperature of the air, thus maintaining the temperature differential between fluid bulk and that in the hydrodynamic boundary layer.

There are three considerations which underlie the efficient usage of cooling air.

1. Flow should be turbulent to encourage mixing of flow to increase heat transfer.
2. Increased flow velocity will aid turbulent flow and heat transfer. Therefore maximum flow velocity should be directed to the area where most heat is to be removed
3. Velocity of flow should not approach the velocity of sound, in order to avoid the associated discontinuities, shock wave and choked flow.

The current configuration of the narrow neck press and blow plunger cooling system was examined to enable an assessment to be made of its performance in line with these criteria.

## Chapter 5 COMPUTER MODELLING OF FLUID FLOW IN THE NNPB PLUNGER COOLING SYSTEM

### 5.1 Introduction

The nature of the fluid flow within the NNPB plunger is such that during the forming cycle is complex and beyond the scope of observation, measurement or physical simulation. This prevents the engineer from achieving efficient or, as is currently the situation, satisfactory cooling of the plunger. The purpose of the mathematical model is to begin to predict the nature of flow within the cooling tube, the effect of the heat transfer properties upon the surroundings and the result of any physical or property changes which may occur.

The model sets out to examine the heat transfer and fluid flow within the plunger and to predict the general constraints appropriate to the application. A model of the complete plunger cooling system is beyond the scope of this initial study of the gross effects of the plunger and its operation.

Prediction of heat transfer and fluid flow processes can be achieved by two main methods:

#### Experimentation

Accurate information regarding a physical process is often gained by direct measurement, in full scale tests or if appropriate small scale simulations. However, for many situations direct measurement is not appropriate, possible, or would be of prohibitive cost.

#### Theoretical Calculation

A mathematical model can give a theoretical prediction of the physical situation and through the use of computer

technology theoretical calculations may be of significant value.

The advantages of a theoretical calculation may include:

- Low cost,  
Many physical situations are large and complex where an experimental study would have considerable cost.
- Speed,  
Due to the ability of a computer to hold large amounts of data and to examine a range of situations and give comparisons, optimisation may be achieved much quicker than through physical modelling.
- Scope of data,  
A computer model by nature of its construction may give data for many variables throughout the domain being examined rather than just at the measurement locations
- Simulation of real or ideal conditions,  
A mathematical model can be used to simulate conditions which are hostile, dangerous, or impossible to physically monitor.

However, when considering theoretical calculation, certain considerations must remain. The model must be designed in such a way that the validity of results can be gauged, and the scope of the model known. Often a theoretical calculation will give a prediction of the nature of a flow field, for example, rather than specific values in regions such as complex turbulent flows or combustion reactions.

For some situations an analytical solution or experimental investigation are not possible. In such a situation a predictive model may be used to indicate the nature of the flow field and to give comparative performance indicators rather than specific values which cannot be validated.

The NNPB plunger presents such a situation and the predictive model may be used to give an indication of the nature of the cooling efficiency. To enable the NNPB plunger cooling model to provide quantitative results certain reference points are required. In this instance reference data related to the supply of air to the plunger, pressure, flow rate, temperature etc., would allow initial conditions for the model to be established.

As has been previously related the plunger does lend itself to direct measurement of its external or internal characteristics. Data relating to the supply of air to the IS machine and the NNPB plunger was obtained from previous work on plunger cooling<sup>55</sup> and on assessment of other cooling medium<sup>56</sup>. In addition to this data was obtained from measurements carried out during the unsuccessful development of some small laboratory experimental equipment. A salt bath, at c500°C, was used to heat a plunger mounted on a reciprocating mechanism whilst measurements were taken of inlet air, exhaust air, volume flow rate and plunger surface temperatures. Examination of plunger cooling by this method was discontinued because it was felt that the arrangement did not sufficiently replicate the practical situation. The development work did support the expectation<sup>56</sup> that the cooling air is at a significantly high temperature when it enters the cooling tube. This occurs because the air is in contact with hot material as it is fed through the bed of the IS machine and to the cooling tube via the piston rod of the plunger actuating cylinder. This results in the difference between the air temperature and that of the inner wall of the plunger not being as large as may have been expected.

## 5.2 Computer model of cooling air flow in the NNPB plunger

The model of the plunger was constructed in several stages.

Familiarisation with the software, gaining an understanding of how the practical situation and the software parameters may come together.

Development of 2-dimensional models. This was an important stage in the development, as a 2-D model, due to the reduced number of cells required, will tend towards a converged solution in a significantly shorter time than a full 3-D computational grid. Areas explored at this stage included the use of stepped walls, due to a software constraint, to represent the geometry of the plunger, the spacing required for the computational grid, and the ability of the model to simulate the radial holes in the cooling tube.

The third stage was used to give an indication of uninterrupted flow through a significant length of cooling tube. This model was in three dimensions, and included the variable cross-section resulting from the taper geometry of the plunger and cooler. Due to a restriction in the number of cells available in the software package this model could only represent a 15° sector of plunger and also could not include live computational flow cells to represent the radial holes in the cooling tube. In an attempt to overcome this problem a computer trial was carried out with a model that employed inlet and outlet cells at the radial hole positions to generate a flow situation. the nature of the model when modelling a compressible flow inlet and outlet cells are only open boundary cells with bi-directional flow abilities which is controlled by nature of their predetermined pressure value. The procedure with this experiment was to examine the local pressure field at the region in question and to set up a low pressure entry/exit cell on the inner wall of the cooling tube and a relatively higher pressure cell on the outer wall. In this

way a flow of fluid through the wall of the cooler was simulated. The practical outcome of this trial was that the nature of the flow field was so unstable that any attempt to carry out any corrections to the relative pressure figures in order to achieve a constant mass flow rate through the system was unattainable. Due to the large number of cells the time taken for the flow field to develop sufficiently prevented any feel being obtained and pressure values being balanced.

To overcome the drawbacks of the first three dimensional model, a physically smaller portion of plunger was modelled. This served two very important purposes.

A model of sufficient grid geometry and cell spacing was possible to enable the radial holes in the cooling tube to be physically included in a 15° sector.

The physical examination of the worn plungers and observation of the plunger in use illustrated the key importance of the thermal properties of the tip area. In addition the first three-dimensional model highlighted the tip area as a possible location for choked flow or sonic shock wave.

The detailed modelling of the flow regime in this area was seen to be of major significance to the whole thermal system.

The tip area also encompassed the area which prompted many of the questions which arose from personal observation and also infra-red analysis of the plunger surface temperature. The existence of the hot band, its positioning in relation to glass distribution, i.e. heat input, and the position of the cooling tube was not easy to logically explain, (Figure 29) and one of the possible solutions was that there was a discontinuity in the pattern of cooling air flow.

### 5.3 The FLUENT package

The Fluent computer package produced by creane. x Incorporated USA. is a general purpose programme for modelling complex fluid flows. The version used (V3.03) will simulate a wide range of fluid flow problems including; Steady or non-steady state single phase gas or liquid flows, compressible and incompressible laminar and turbulent flows, isothermal or mixing flows with heat conduction through solid boundaries, fluids with reacting or non reacting particles or droplets, chemical and surface reactions, combustion, radiant heat transfer and gravity/buoyancy effects.

The Fluent package is based upon a finite difference procedure to solve the Navier-Stokes equations of fluid flow. Finite difference methods are a technique for the solution of partial differential equations, it requires the domain for which the solution is being sought to be replaced by a finite set of points. Approximate values for each variable are found for these points by an iterative process considering all neighbouring cells which starts from arbitrary initial conditions and converges to a solution which satisfies the governing equations.

Each iteration consists of the following steps.

- The U, V, and W momentum equations are each solved using guessed pressures.
- A pressure correction equation is then used to provide a correction to the pressure field and subsequent local velocity corrections.
- A turbulence model based on the kinetic energy of the fluctuation motion and the kinematic rate of dissipation is solved to give the distribution of the effective viscosity.
- Values for enthalpy and turbulence properties are then obtained using these updated values.

- These steps are repeated until the error returned is decreased to a predetermined value.

For a full description of the 'Fluent' package reference should be made to the User Manual. Operational details relating to the functioning of the package will not be described here.

#### **5.4 The 'FLUENT' model of cooling at the NNPB plunger tip.**

Following the development stages outlined above the flow field at the tip of the plunger has been analysed. The geometrical layout of the initial plunger model was defined by computational cells in the following manner.

The cells form a representation of the physical form by virtue of their properties. The following cell types were used:

Live computational cells, in which governing equations will be solved subject to surrounding 'boundary' non live cells - Fluent does not allow live cells on the edge of the domain.

Symmetry cells - geometry and flow pattern are mirrored across the plane of symmetry. There is no flow, heat transfer or shear stress across the symmetry plane.

Cyclic cells - cyclic cells are used by Fluent to allow sections of flow to be modelled to reduce the computational resources required. In combination with symmetry cells a model may employ cyclic cells at the edge of the domain which are paired with cyclic cells at the opposing boundary. Flow variables are matched, and what enters through one cyclic domain will leave by the opposite boundary. In the case of the NNPB, being a sector of a cylindrical geometry based on polar co-ordinates, it has all flow variables including pressure matched at cyclic cells.

In cells - inlet cells exist to allow fluid to enter the flow domain and in the case of the fixed pressure boundaries employed in the NNPB model, exit the model. 35 individually definable types of inlet cells may be used to establish pressure, temperature and flow properties at the entry to and exit from the domain.

Wall cells - wall cells are used to denote the physical boundaries to the flow domain. The wall cells provide boundary conditions for the fluid - wall interface. A full range of properties may be defined for wall cells, including thermal conductivity, temperature, flow properties, wall roughness etc.

Fluid Temperature K	Fluid Viscosity $Ns/m^2$	Specific Heat Capacity ( $C_p$ ) $J/kgK$	Thermal Conductivity $W/mK$
250	$1.3409 \times 10^{-5}$	1005.3	$2.2270 \times 10^{-2}$
300	$1.8455 \times 10^{-5}$	1005.7	$2.6240 \times 10^{-2}$
350	$2.0718 \times 10^{-5}$	1009.0	$3.0030 \times 10^{-2}$
400	$2.2870 \times 10^{-5}$	1014.0	$3.3650 \times 10^{-2}$
450	$2.2597 \times 10^{-5}$	1020.7	$3.7070 \times 10^{-2}$
500	$2.6719 \times 10^{-5}$	1029.5	$4.0380 \times 10^{-2}$
550	$2.8466 \times 10^{-5}$	1039.2	$4.3600 \times 10^{-2}$
600	$3.0239 \times 10^{-5}$	1055.1	$4.6590 \times 10^{-2}$
650	$3.1771 \times 10^{-5}$	1063.5	$4.9530 \times 10^{-2}$
700	$3.3324 \times 10^{-5}$	1075.2	$5.2300 \times 10^{-2}$
750	$3.4812 \times 10^{-5}$	1085.6	$5.5090 \times 10^{-2}$
800	$3.6290 \times 10^{-5}$	1097.8	$5.7790 \times 10^{-2}$
850	$3.7661 \times 10^{-5}$	1109.5	$6.0280 \times 10^{-2}$
900	$3.9025 \times 10^{-5}$	1121.2	$6.2790 \times 10^{-2}$
950	$4.0250 \times 10^{-5}$	1132.1	$6.5250 \times 10^{-2}$
1000	$4.1466 \times 10^{-5}$	1141.7	$6.7520 \times 10^{-2}$
1100	$4.4325 \times 10^{-5}$	1160.0	$7.3200 \times 10^{-2}$
1200	$4.6934 \times 10^{-5}$	1179.0	$7.8200 \times 10^{-2}$

Table 8 Temperature dependent variable definition of the computational fluid for all NNPB plunger tip models

The initial model - 16.13mm long, maximum plunger internal diameter - 7.668mm, was set up with the radial holes in the cooling tube (Figure 30) with cell locations and properties as set out in the data file, Appendix 1.

The physical properties given in Table 8 were defined for the computational fluid in all the plunger tip models.

The initial model was based on steady state conditions and the flow field was solved for two initial thermal situations at the plunger surface. These were set-up to represent each extreme of the thermal cycle of the plunger's external surface as indicated in Figure 26 and Figure 27. The boundary conditions for these two thermal conditions were defined as in the model data files, Appendix 1.

The flow field generated by this model is illustrated by Figure 32. The flow field is represented by vector arrows, giving flow direction and magnitude for each computational cell.

When this flow pattern is examined with reference to the guidelines given earlier the following points are noted;

The velocity distribution does not suggest efficient cooling with the maximum velocity occurring within the cooling tube, nor at the plunger wall.

Examination of this flow field in more detail gives a further indication of the poor cooling performance. The tip area, Figure 33, shows the considerable reduction in flow velocity which occurs due to the rapid increase in cross sectional area. There is also an area of re-circulation at the end of the cooling tube wall.

The radial holes in the cooling tube wall exist to initiate turbulence and encourage mixing of the flow at the plunger

wall. The flow pattern which exists at the radial holes, Figure 34 to Figure 36, shows considerable re-circulation, both in the flow pattern at the wall and within the hole. The re-circulation that occurs within the flow at the wall falls into two categories. It can be seen that there is lateral re-circulation around the wall of the plunger this will result in mixing of the flow as required. There is also a small region of return flow (Figure 34) towards the tip of the plunger, this causes an area of stagnation, where heat transfer will be considerably reduced. This inefficient cooling pattern manifests itself as hot bands on the plunger's external surface.

In response to the results of this examination of the NNPB plunger cooling system a modified cooling tube arrangement was examined for improved cooling efficiency. This modified cooling tube needed to respond to the deficiencies of the original geometry. To achieve this the following changes were required;

- The velocity of flow at the plunger wall was to be increased, this must be achieved without increasing the velocity within the tube.
- To avoid problems associated with transonic flow the velocity must not exceed Mach 0.8 (c  $260\text{ms}^{-1}$  at room temperature) the maximum desired velocity by this project.
- Re-circulation within the radial hole should be avoided.
- The flow along the plunger wall must not stagnate due to re-circulation of the flow from the radial hole.

To achieve these objectives the following changes were made;

- The cooling tube diameter was increased to balance the cross sectional area within the tube to that between the tube and the plunger wall (Figure 37).
- The cross sectional area of the radial hole in the cooling tube was reduced.

The geometry of this modified cooling tube is shown in Figure 38. This modified cooling tube was analysed using the same boundary conditions as for the original model.

The flow field resulting from these changes to the cooling tube can be seen in Figure 39. Examination of the flow pattern reveals that the velocity balance has been achieved and that the velocity along the plunger wall has considerably increased. The detail of the flow field shown in Figure 40 to Figure 44 shows that the re-circulation at the tip has been reduced and that in the radial hole eliminated. There is also no stagnation of flow.

To quantify the improvements in cooling performance the temperature gradients occurring at the plunger wall of each model can be compared. The steeper the temperature gradient at the wall the greater the heat transfer into the cooling air.

Although dimensionless the figures in Table 9 give a good indication of the relative thermal performance of the two cooling tube geometries. They also indicate that the improved flow pattern also gives considerably improved heat transfer properties. The poorest performing area of the new geometry is at cell  $I = 20$  this is immediately downstream of the turbulent zone created by the flow through the radial hole in the cooling tube wall, it may be the case that the flow through the hole should be reduced to encourage more even heat transfer properties along the whole wall of the plunger.

Temperature Gradient at plunger wall		
'I' Cell reference	Initial cooling tube geometry	Modified cooling tube geometry
5	34.5	72.0
10	32.25	62.0
15	30.0	53.0
20	27.5	37.5
25	21.5	53.5
30	-7.75	73.0
35	32.5	72.0
40	33.0	62.0
45	28.5	55.5
50	32.25	44.5
55	28.75	23
Average	26.64	55.27

Table 9 Relative temperature gradient along the plunger wall.

These improvements in the flow pattern and thermal properties of the NNPB plunger could be applied to the practical situation to allow the IS machine operator greater control over the forming parameters and quality of product. If the rate of cooling achievable following

improvements in the geometry of the cooling tube was such that the plunger was removing excess heat from the glass, resulting in 'chill' defects. Then rather than reduce the pressure in the supply manifold the timing should be adjusted to shorten the duration of air flow. This may have the beneficial affect of reducing the thermal cycling of the plunger materials.

## Chapter 6 DISCUSSION AND FUTURE WORK

The narrow neck press and blow process is of significant economic importance to the glass container industry. It provides answers to many of the demands of the modern consumer. Reduced container weight requires less energy, produces less waste, offers a material which is more suited to recycling than plastic and for the marketing of products has a higher perceived value. For these reasons it is important that the NNPB process undergoes a technological advance of both the production process and the product.

When this project was initiated, it was soon evident that there was little scientific understanding of the NNPB process, it was in existence because technology had been applied to process developments which had been facilitated by the high level of 'hands on' ability of those involved at all levels in the day to day operation of the glass container plant. Much is said within the glass industry of a 'Black art', and the need exists for some of this field of knowledge to be recorded, scientifically evaluated and then applied to technological advances in both current production technology and also to fresh opportunities in container forming.

The lack of published information regarding some of the aspects of glass mould tooling caused slow progress at some stages of this study. With differing industrial practices and terminology what is reported may be open to some degree of interpretation. The glass industry at times gives indications of being open and willing to share knowledge but frequently this is misleading. Within such a system it often pays to listen with an open mind and to consider what may not be being said as much as what is actually being reported.

The plunger must always be viewed with a consideration for the parameters of the process, the prime objective being to produce glass containers of high quality at a high

production rate. The most significant advances in process technology would be achieved if the plunger was able to fill the following criteria:

- The plunger cooling system must have the ability to satisfy the demands of process set-up, not be a constraint on cycle time.
- Material removed from the plunger surface must be negligible.
- The plunger must retain its original thermal characteristics for its full operating life.
- The plunger should have a negligible effect upon container strength, either through loss of material or through stress generation.
- The plunger must have no chemical affinity with the molten glass.
- Small modifications to plunger profile should be possible to allow for job flexibility.

Many of these demands placed upon the plunger by the process were unknown until this examination was carried out.

This programme of research has analysed the performance criteria and operational characteristics of the NNPB plunger. This has included examination of the following:

- An investigation of the NNPB forming process and the characteristics of lightweight containers
- The requirements of lightweight container forming equipment
- Characterisation of current NNPB plunger technology, materials, production technology etc.
- Examination of wear and failure modes exhibited by the current NNPB plunger
- Development of a method for predicting plunger surface temperature during the forming process
- Analysis of the properties of the NNPB plunger cooling system
- Development of a programme of advancement.

Despite the lack of much directly applicable literature much of the work which has been carried out examining the performance of other components (primarily Grey cast iron blank and blow moulds) has parallels with the NNPB plunger although it became evident at an early stage that the nature of the contact between other mould components and the glass and that between the NNPB plunger and the glass is very different. Blank and blow moulds etc. form an initial contact with the glass and cause a rapid cooling of the glass surface, cause rapid contraction of the surface and then undergo heating at a much reduced rate. The plunger contacts the glass and then undergoes movement forcing it to maintain intimate contact with the glass. The exact nature of the contact at the glass/plunger interface is unknown during the pressing stroke but could be considered to be similar to that which is thought to occur during the production of press ware, when the glass is thought to flow from the bulk and effectively roll onto the surface. Hence during the pressing stroke there is no sliding contact between the glass and the plunger. When the plunger is withdrawn there is considerable sliding contact between the glass and the plunger surface.

This study has examined the wear modes exhibited by the NNPB plunger. The significance of the thermal condition of the plunger at each stage of its life upon the surface wear and the production of defective containers has been illustrated. The growth of the oxide layer and subsequent reduction in heat transfer ability of the plunger leads to instability of the plungers performance and a rapid reduction in service life. Not only does the engineer lose the ability to control the process, but the formation of the oxide layer, in causing a rise in surface temperature, leads to the continued and more rapid growth of the oxide. The practical implication of this is that the plunger begins to overheat, as the oxide layer reduces the heat transfer, causing a loss of material from the plunger

surface. When material loss reaches an unacceptable level, or the plunger is removed from the machine for another reason, the plunger is degreased, shot blasted and resurfaced with the NiCrSiB powder alloy. The plunger is returned to the machine. The plunger may have been returned to its original profile but its heat transfer properties are unimproved. This leads to progressively shorter and shorter periods on the forming machine, resulting in an increasing quantity of defective product and machine down time. The use of a corrosion resistant barrier coating on the internal bore of the plunger prevents the initial formation of any oxide layer and also any build up over the operating life of the plunger, allowing stability of the operating parameters and optimisation of the plunger performance.

To allow optimisation of the plunger the machine operator needs to regain control of the process, often full theoretical production speed is not reached due to insufficient cooling. Plunger cooling setting is 'on' for the maximum time allowable on the setting mechanism. The answer to insufficient cooling has always been to turn up the pressure in the supply live, this has caused the air velocity in the cooling tube to approach Mach 1, and obtain the undesirable features of transonic flow. This study has examined this system, identifying critical defects and has put forward some design rules for increasing the efficiency of the cooling system. When these rules are applied to the production equipment a significant increase in cooling ability will be obtained. This in turn allows the technology of the plunger to be designed rather than constrained by process requirements. The full optimisation of the NNPB plunger would involve the analysis of the full forming process. It is acknowledged that the use of a plunger to achieve the weight reduction has disadvantages. These include the longer reheat/rundown following invert to allow stresses generated in the parison during pressing to relax and also because, unlike the blow and blow process,

the thermal gradient through the wall of the parison is bi-directional due to heat having been removed by the plunger. There is also the reduction in final container strength due to flaws in the glass produced during the forming process. To achieve full optimisation of the plunger some of these aspects need to be understood in order to apply a specification to plunger design which extends past current requirements of geometric form and the ability not to stick to the glass.

The potential exists for a plunger which will run at a controlled temperature for its entire operating life and from which negligible material will be lost into the containers produced.

Current NNPB plungers fail to run at predictable temperatures due to inefficiencies in the cooling system. These include;

- Poor cooling tube design.
- Inaccurate or insecure location of the cooling tube giving unbalanced cooling performance.
- The build up of oxide on the plunger bore.

This study has examined the design of the cooling system, as a result of the knowledge gained advances may be made in cooling tube design. The mechanical location of the cooling tube within the IS forming machine is a matter for the machine fitter.

The prevention of oxide formation and the resultant reduction in the heat transfer properties of the NNPB plunger would lead to an improvements in process control and product quality. A preliminary examination of a barrier coating to prevent this oxide formation has been carried out. A coating based upon nickel-boron was deposited from a solution onto the internal bore of the plunger prior to the application of the Ni-Cr-Si-B spray and fuse alloy. This technique is ideally suited to the NNPB plunger because

unlike electro plating techniques an anode is not required and the geometry of the component does not affect the deposition rate. A small number of NNPB plungers with a 25µm internal coating of 'electroless' nickel-boron underwent a trial on an IS forming machine. As a result of this trial, when after over 1000 hours operation there was no oxide formation on the bore of the plunger, further work is being carried out to examine the practical application of this technique to NNPB plungers. This technique allows the thermal properties of the plunger to remain stable over the full working life of the plunger.

The application of thin film coatings on an improved substrate material has demonstrated some potential, this also offers knowledge which may be applied to other items of the mould tooling set to enable current lubrication practices to be discontinued. The loss of plunger material and lubrication of mould cavities are two issues with broad implications for the glass container industry. As consumer protection measures become more advanced and health issues receive more prominence it is possible that both these points will receive significant attention and changes may be forced upon the glass container industry.

The fundamental operating characteristics of the NNPB plunger have been characterised in this study. Much of this has been done whilst considering the plunger in isolation. Therefore an expansion to include other process parameters and to re-examine the narrow neck press and blow process as a whole offers potential for an increase in our knowledge of glass forming processes. The nature of the interface between glass and form tool during deformation is unknown but of considerable importance when attempting to improve the quality of the containers produced. With a deeper understanding of the whole NNPB process the quantity of heat to be removed by the plunger could be optimised to prevent excessive stressing of the internal surface of the parison and not only could reheat/run down time, and thus

process cycle time, be reduced but also container strength could be maximised for a given glass mass. Hence stress and flaw reduction must become areas of technological examination.

This study has made progress towards the objectives set out by Babcock and McGraw<sup>29</sup>;

- The spatial and time distributions of temperature in both the glass and mould metal throughout the forming cycle.
- The stress acting at all points in the glass, at all stages of the cycle.
- The effect of these forces and temperatures on both the motion of the glass during forming and upon the final strength, appearance, and other physical attributes of the finished product.

This examination has contributed to the available scientific knowledge of the narrow neck press and blow forming cycle although there is still considerable scope for scientific investigation of the inter-relation the glass and the form tooling before the above objectives can be considered to have been achieved.

The further study of the cooling system of the plunger employing the theories outlined here offers potential for greater control of the thermal properties not only of the narrow neck press and blow plunger but also of the traditional wide mouth press and blow plunger where similar conditions exist but to a slightly less critical degree.

## Chapter 7 CONCLUSION

- 1) The wear and failure modes associated with narrow neck press and blow plungers have been identified as;
  - Material loss from the plunger surface, comet tail wear scars, resulting in contaminated containers of reduced strength.
  - Chemical affinity between the plunger tip and glass causing 'spikes' in containers.
  - Oxidation within the bore of the plunger which reduces the heat transfer properties of the plunger and results in accelerated surface wear.
- 2) The temperature distribution at the plunger surface has been recorded and the thermal cycle during the forming process has been predicted. This is the only plunger operating parameter where direct measurement is possible and as such is of considerable importance to the assessment of both plunger material and cooling performance.
- 3) The cooling system has been examined and the nature of the cooling performance has been mathematically simulated. Deficiencies in the flow pattern and heat transfer ability have been characterised and related to features, such as the hot band, existing at the plunger surface. Modifications to the cooling arrangements have been suggested which overcome the reported deficiencies.
- 4) This examination has brought together several areas of scientific investigation, by considering the plunger, its cooling system and the forming process as a whole. This approach has allowed the inter-relation of

findings to enhance the level of knowledge gained by the study.

- 5) The results of this examination will enable the following improvements in the manufacturing process for lightweight glass containers to be made;
  - Plunger materials may be reassessed for suitability or changed through the understanding of the wear and failure modes present.
  - The formation of an oxide layer on the plunger bore may be prevented by the application of a barrier coating.
  - The surface temperature of the plunger may be monitored, when visible, and the thermal cycling of the surface predicted. This provides information on the functioning of the process, the plunger materials and the monitoring of any improvements made.
  - The performance of the cooling system can be improved by changes to the cooling tube geometry.
- 6) The above information is of prime importance to the operational life of the plunger. This information may be used to extended plunger life and improve the quality of the glass container product.

Chapter 8 FIGURES

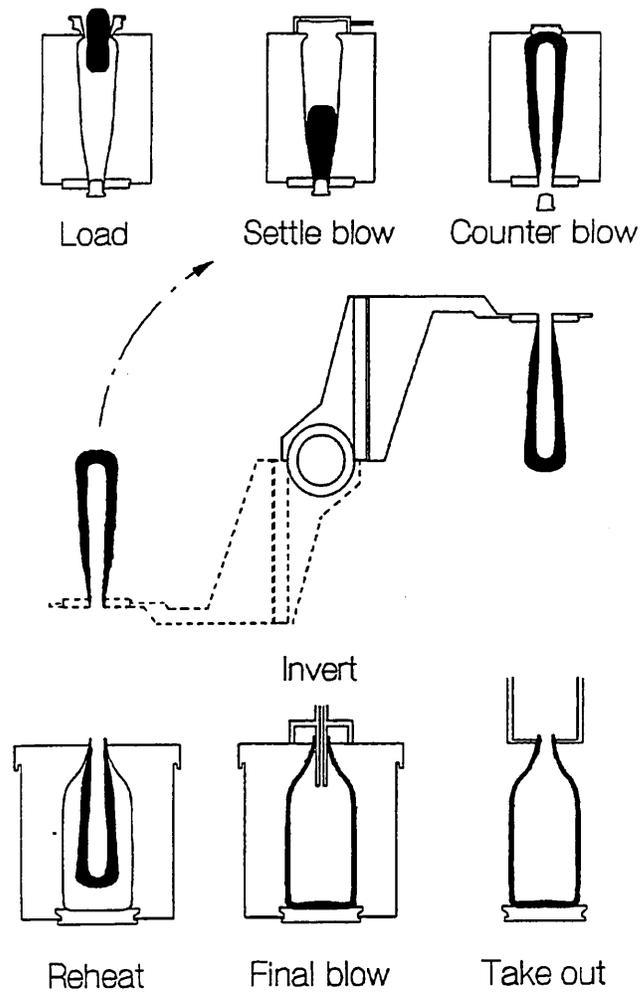


Figure 1. Blow and blow container forming process.

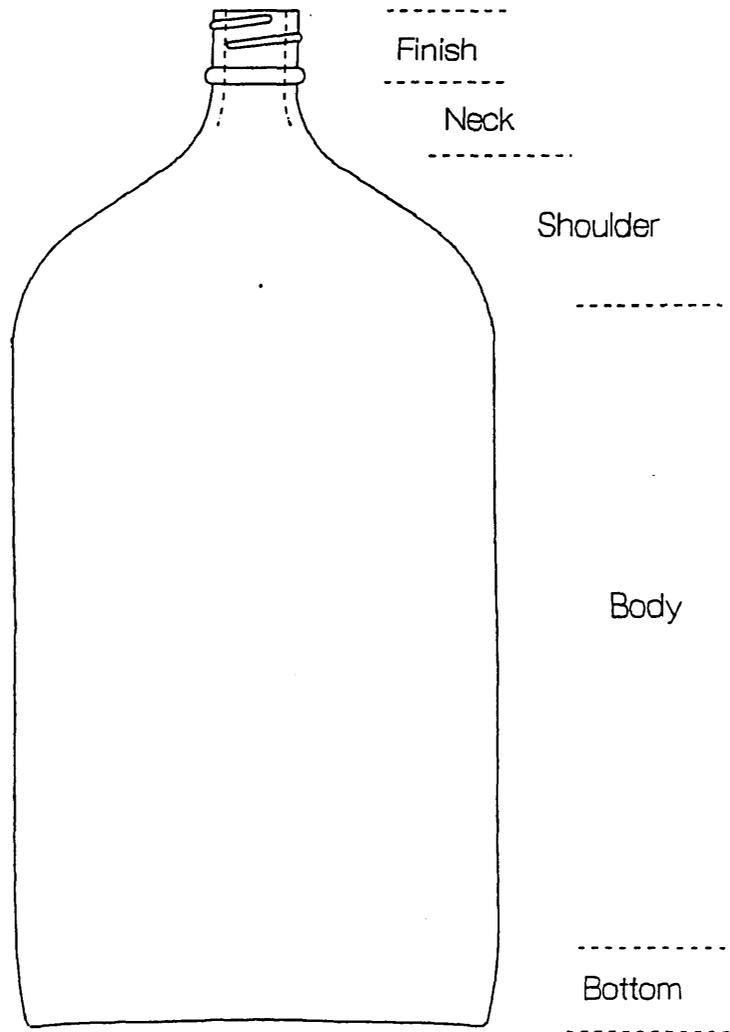


Figure 2. Glass container terminology

to B.S. 3447 : 1962

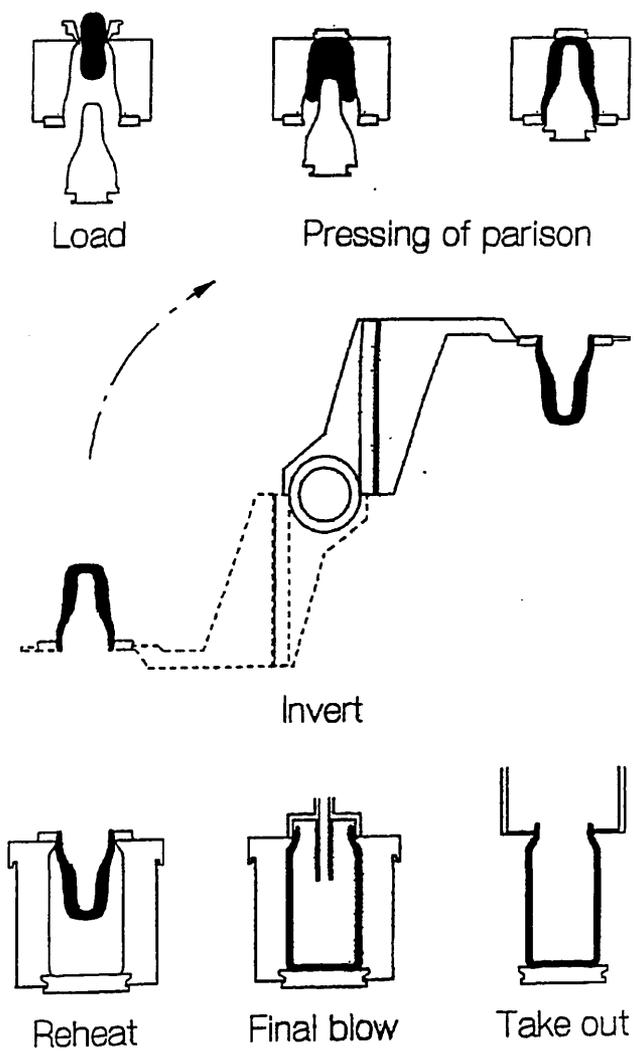


Figure 3 The press and blow process.

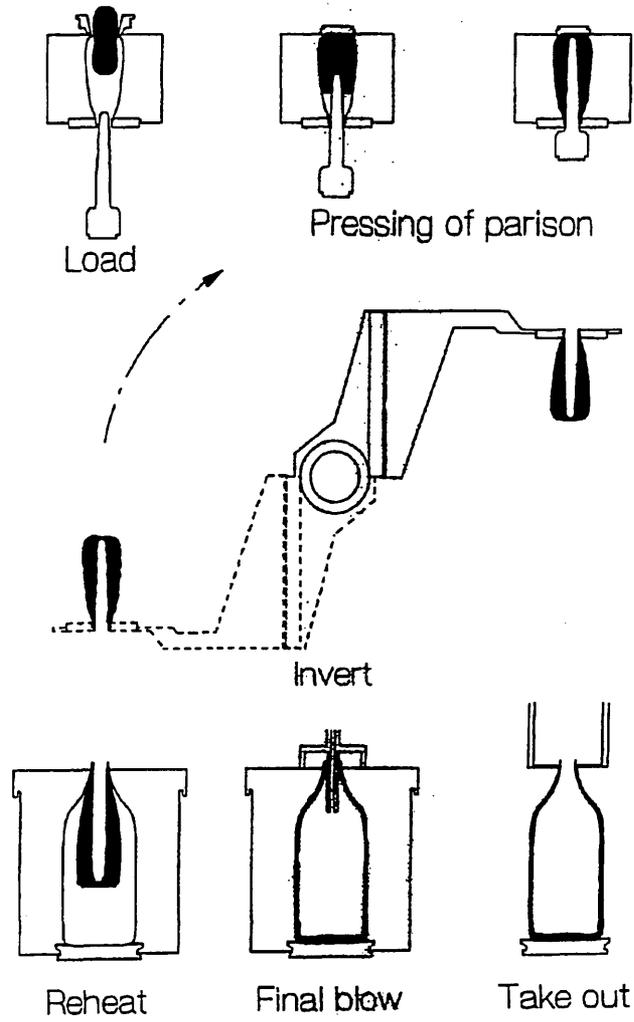


Figure 4. The narrow neck press and blow process.

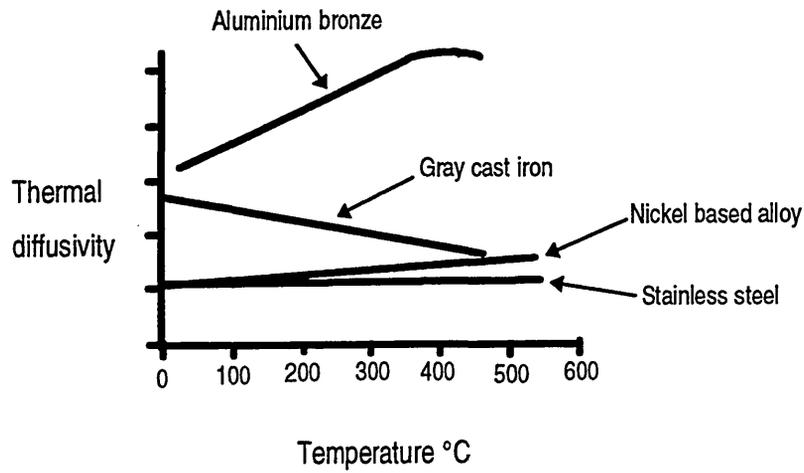


Figure 5. Relative thermal diffusivity.

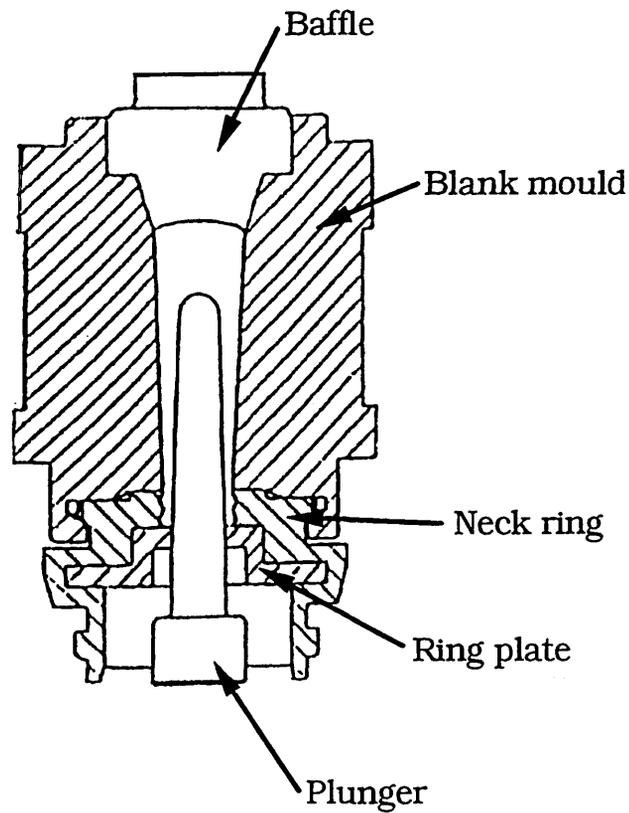


Figure 6 Blank mould tooling.

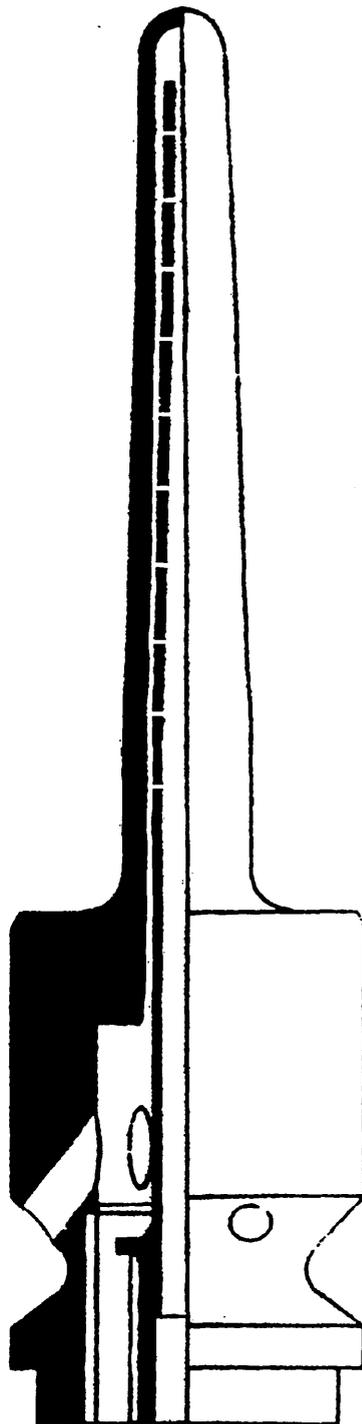


Figure 7 Typical narrow neck press and blow plunger  
and cooling tube

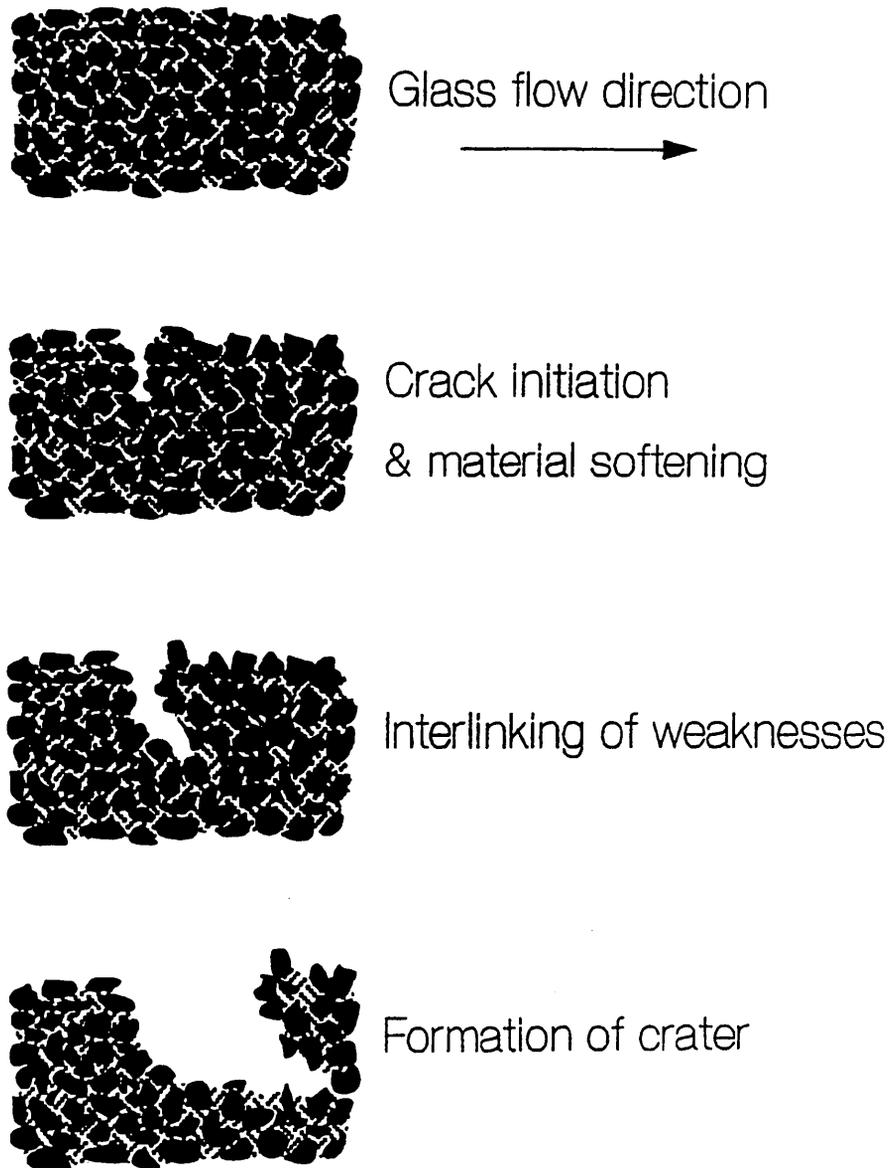


Figure 8 Interlinking of microcracking.

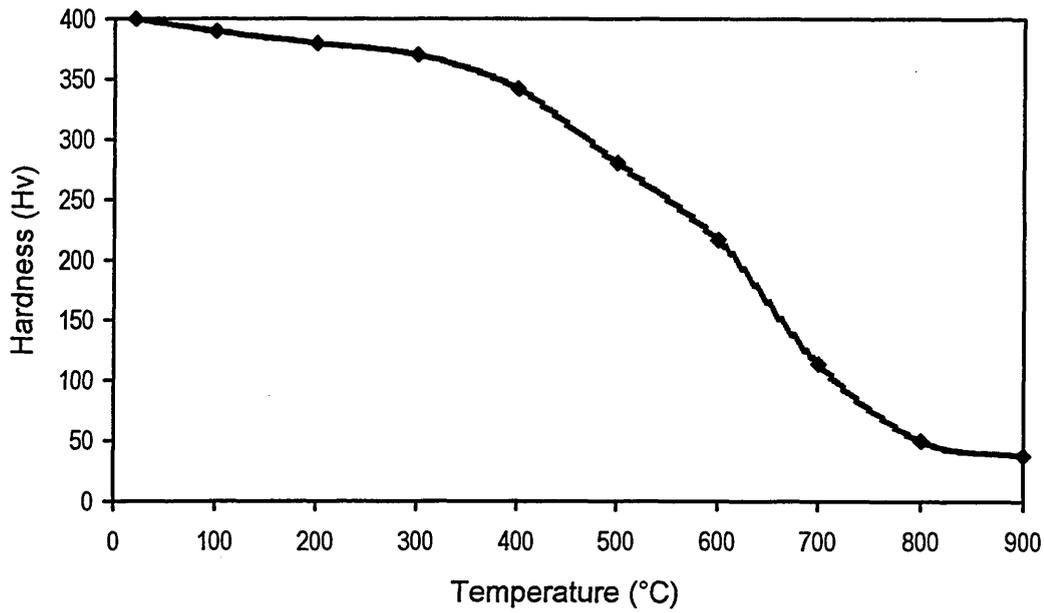


Figure 9 Graph of temperature vs. Hardness for Deloro Stellite SF40s (from Manufactures data).

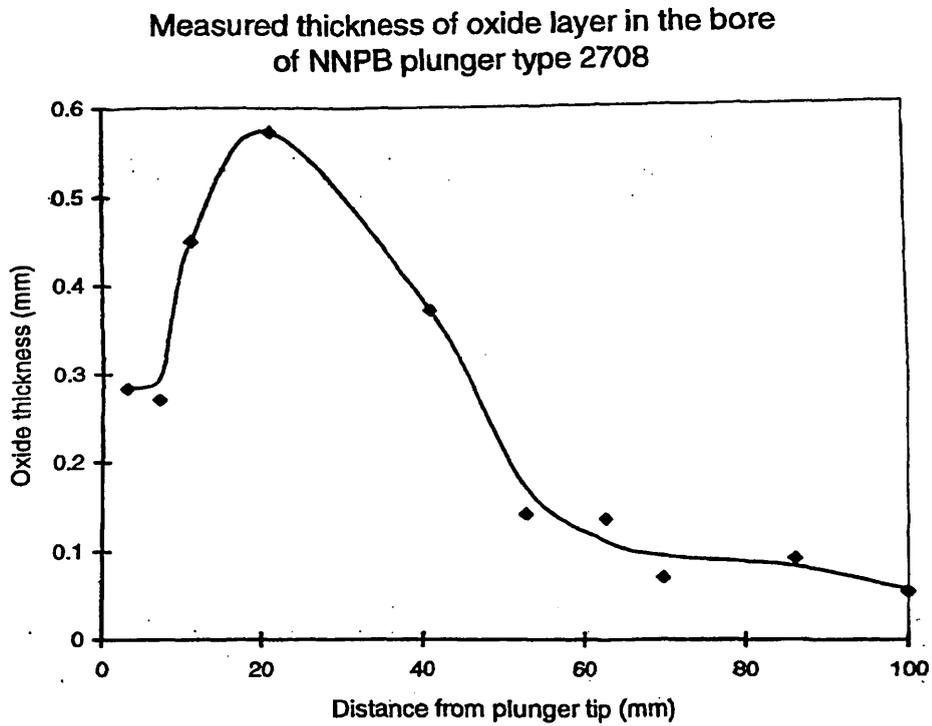


Figure 10 Distribution of Oxide layer within plunger bore.

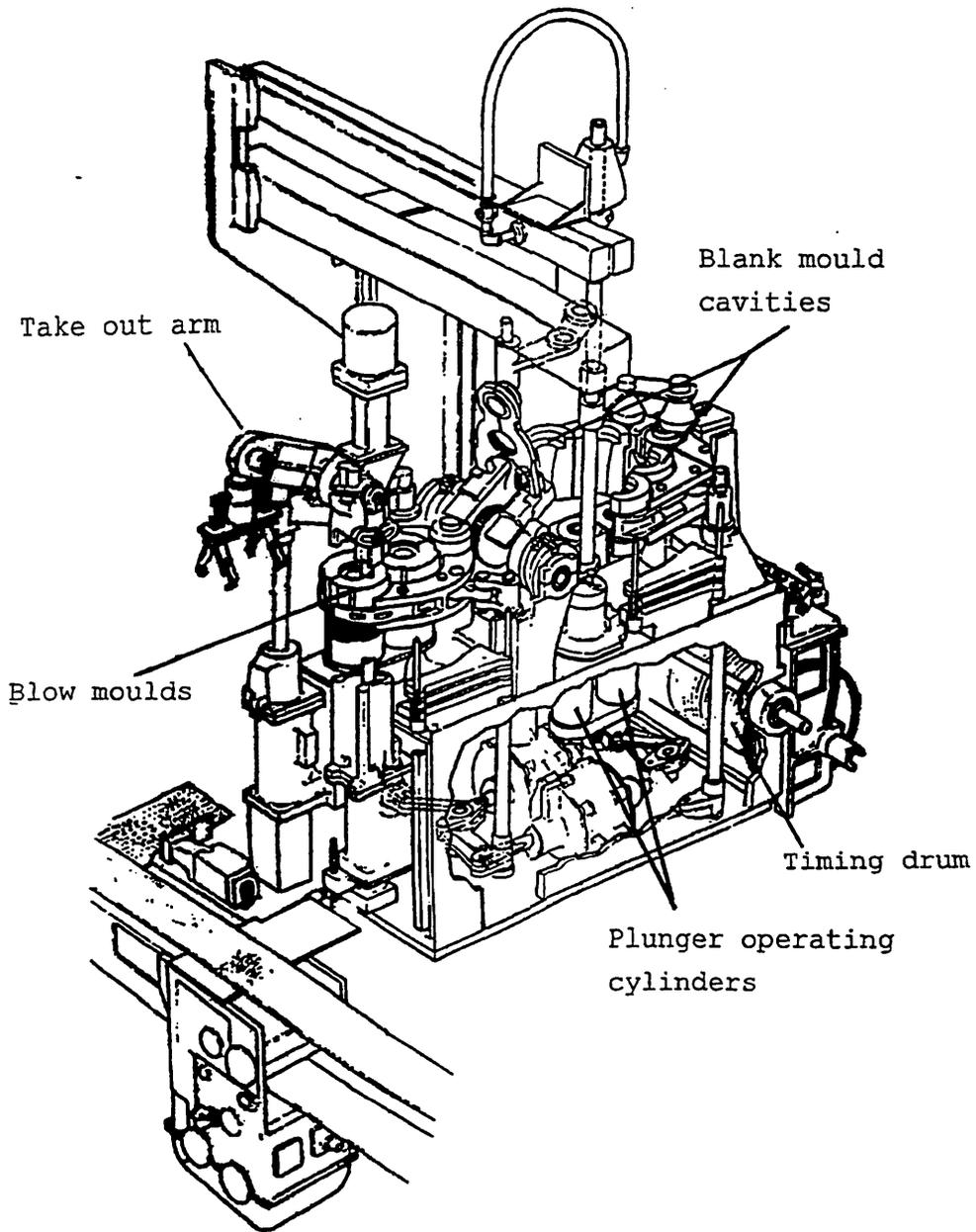


Figure 11 Cutaway view of one section of an IS container forming machine

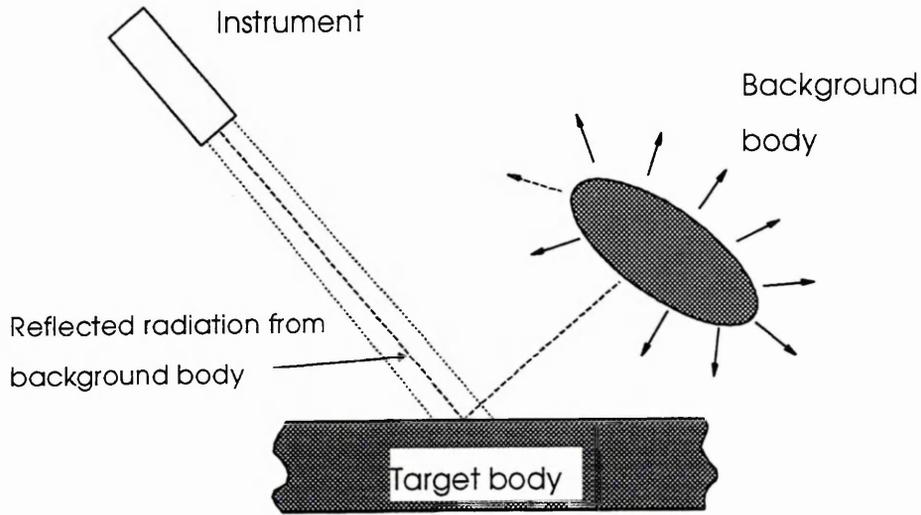


Figure 12 Reflected radiation.

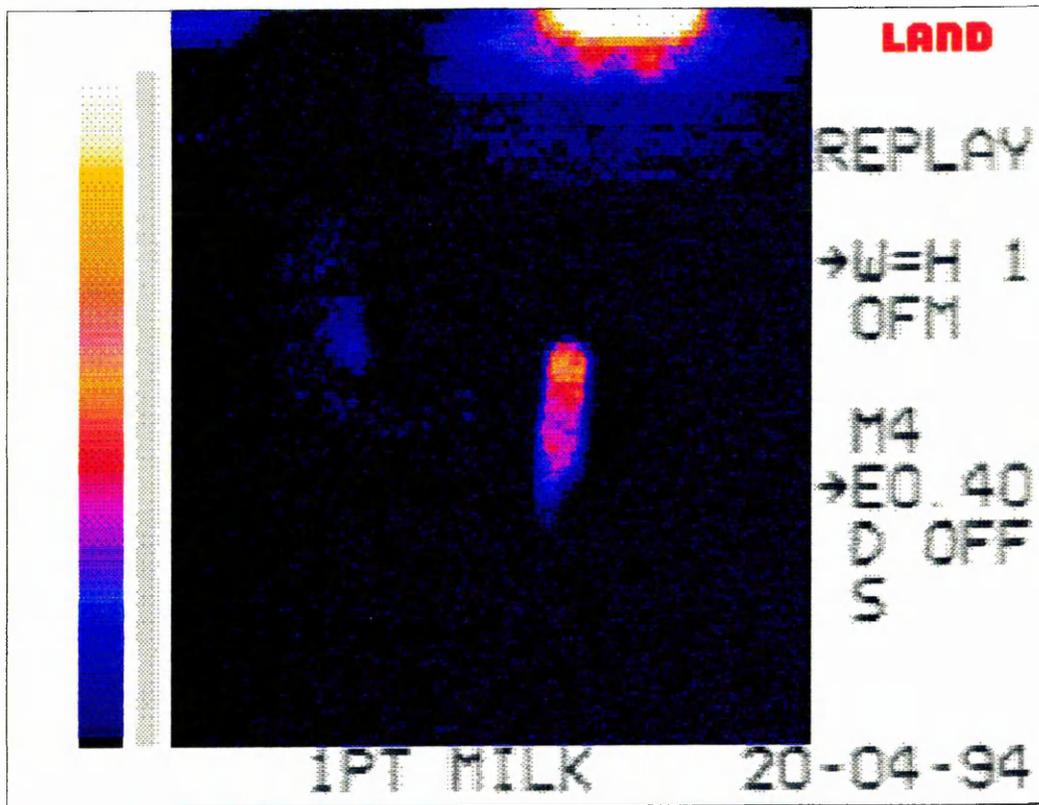


Figure 13 A typical thermal image 'as gathered' by the LAND TI 35sm (original in colour)

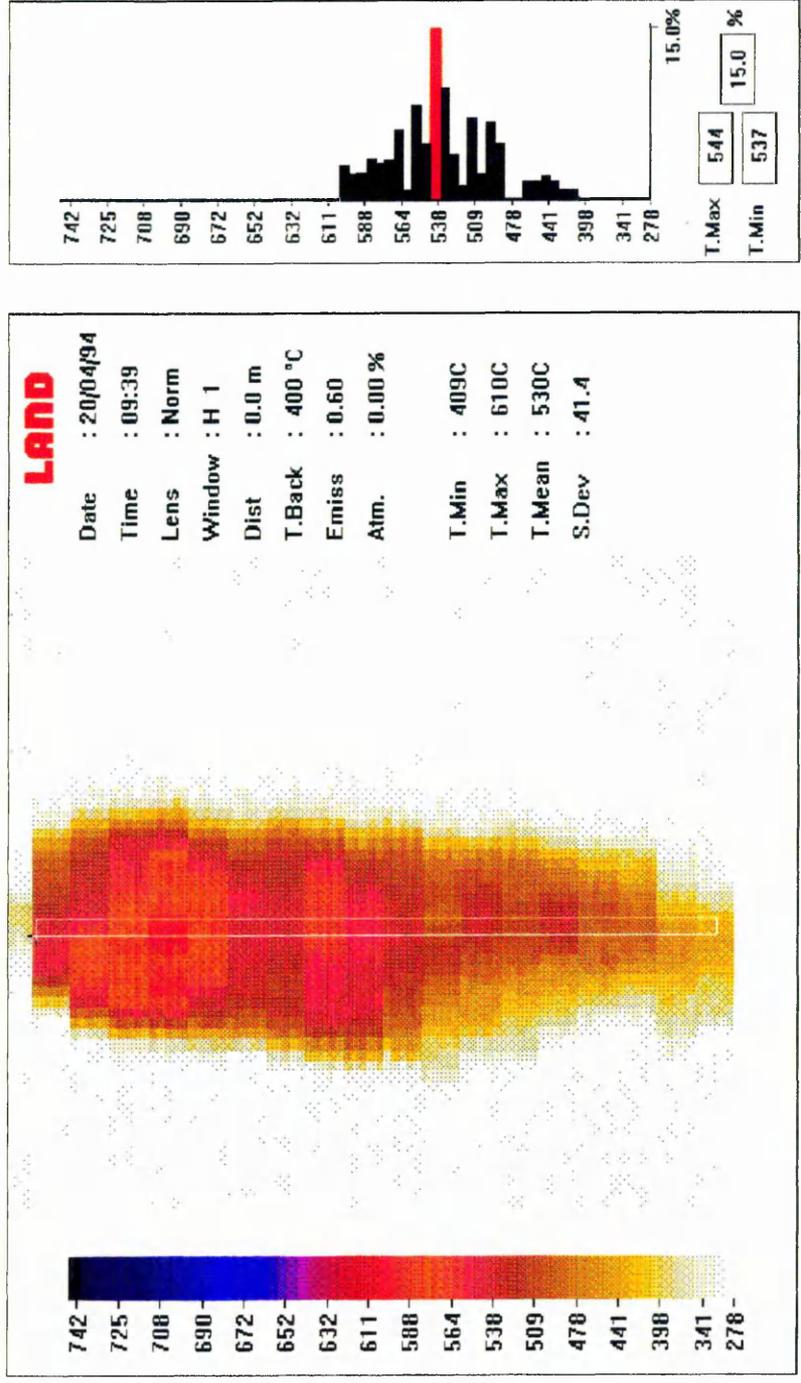


Figure 14 Temperature distribution histogram for a plunger with no oxide layer time = 0.08  
 (original in colour)

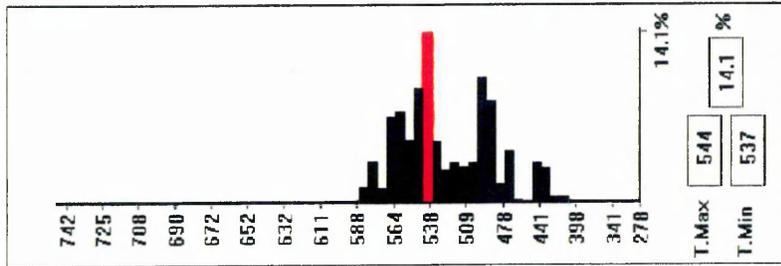
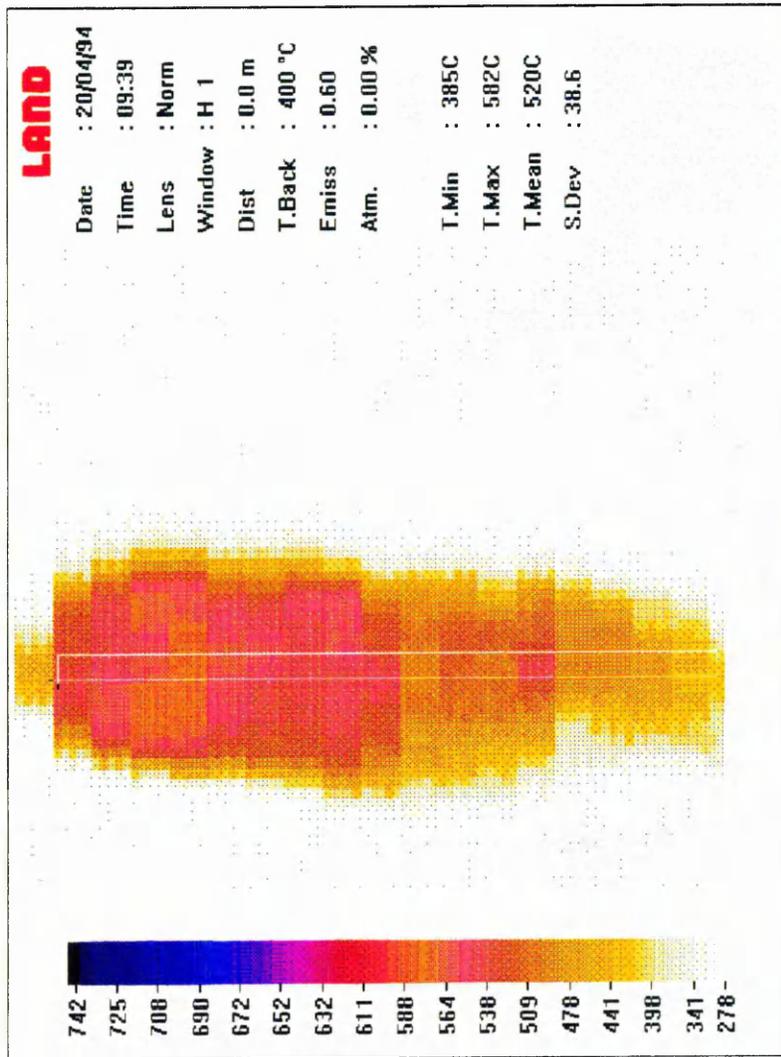


Figure 15 Temperature distribution histogram for a plunger with no oxide layer time = 0.16  
 (original in colour)

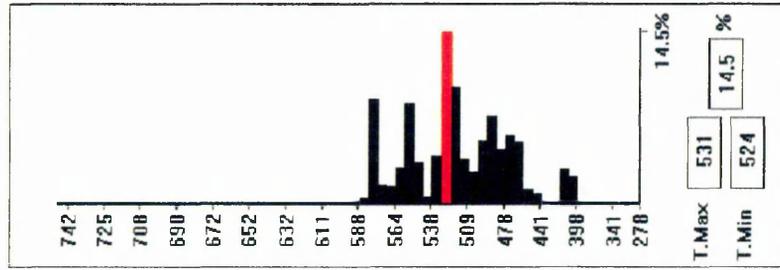
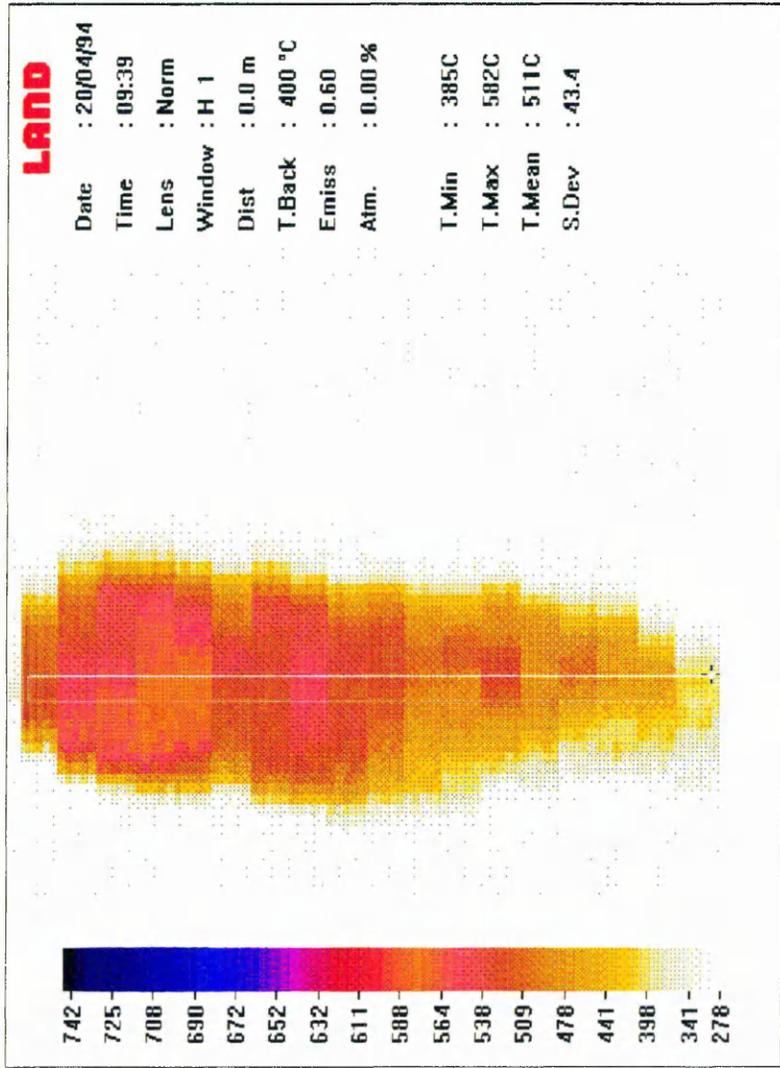


Figure 16 Temperature distribution histogram for a plunger with no oxide layer time = 0.24  
 (original in colour)

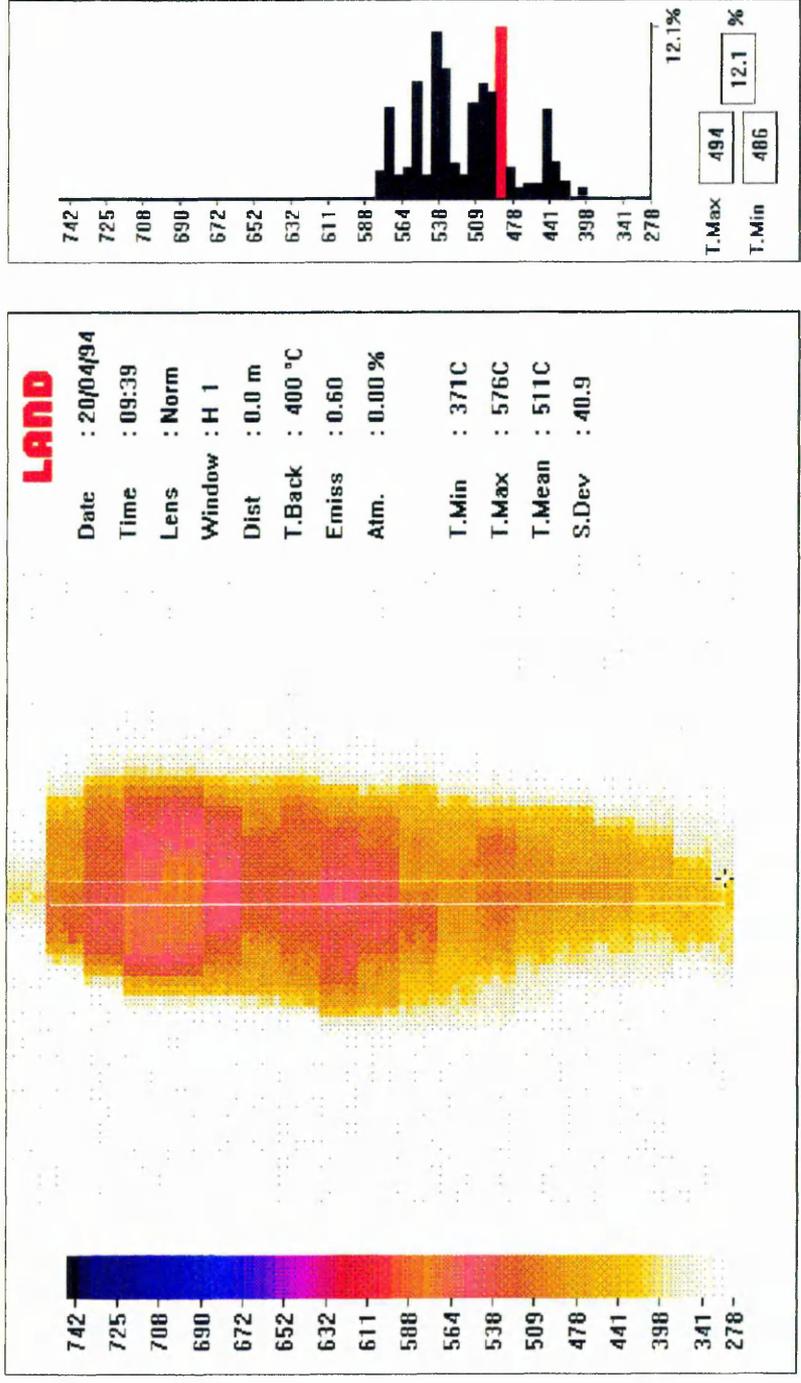


Figure 17 Temperature distribution histogram for a plunger with no oxide layer time = 0.32  
 (original in colour)

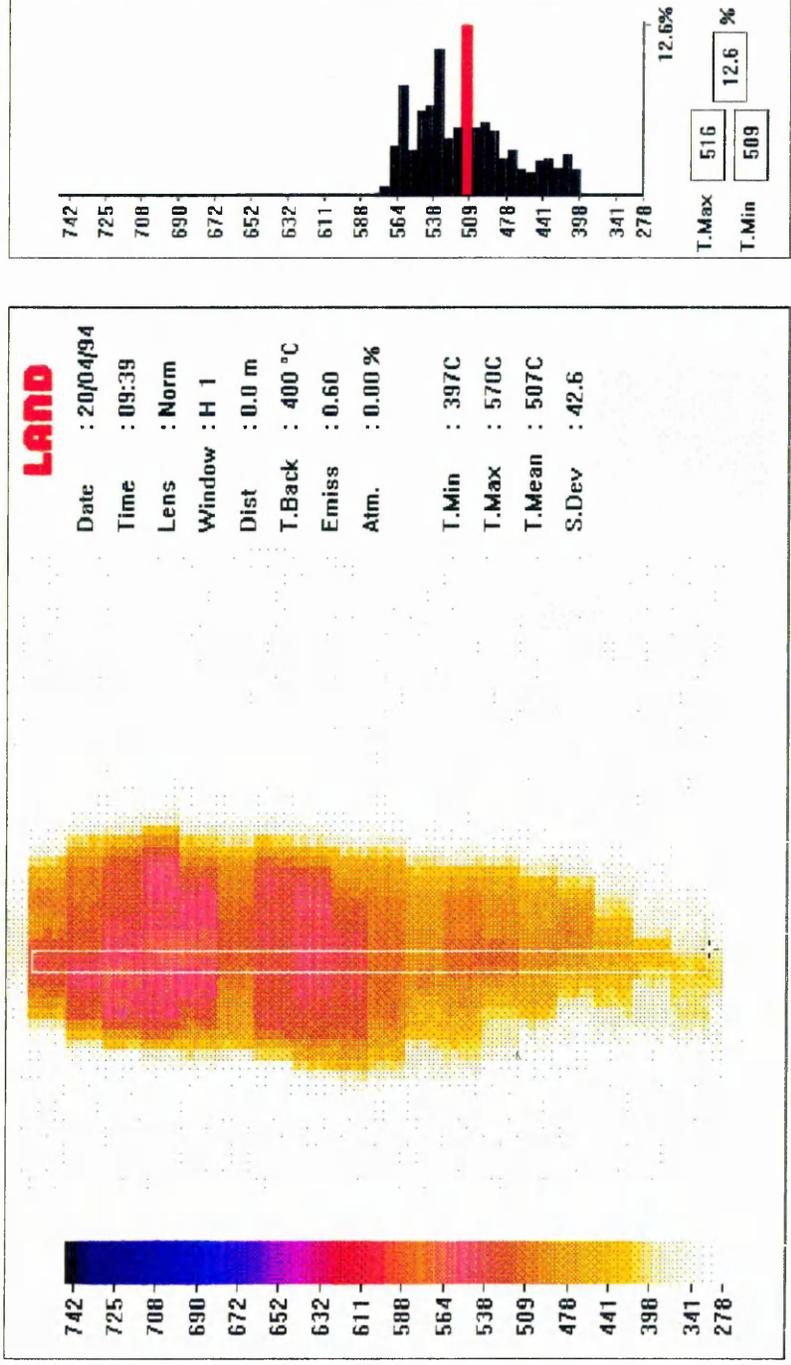


Figure 18 Temperature distribution histogram for a plunger with no oxide layer time = 0.40  
 (original in colour)

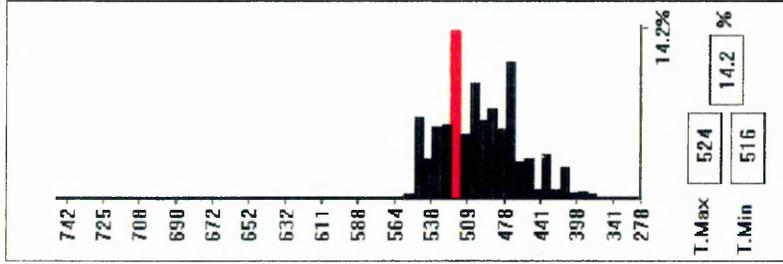
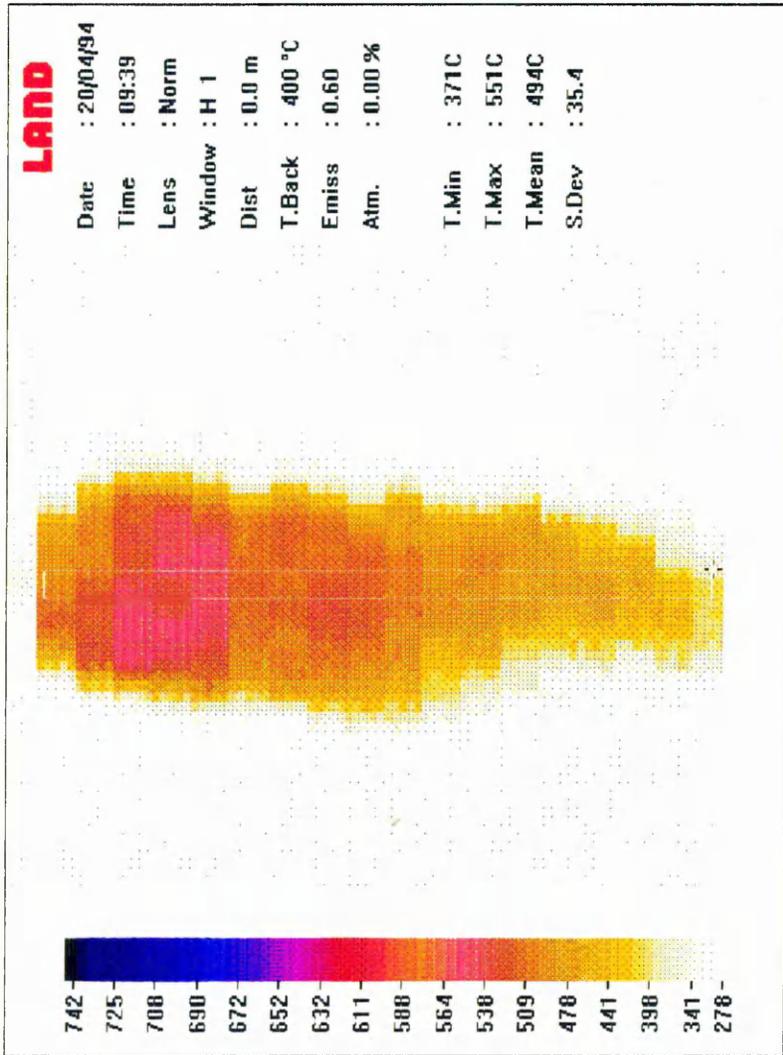


Figure 19 Temperature distribution histogram for a plunger with no oxide layer time = 0.80  
 (original in colour)

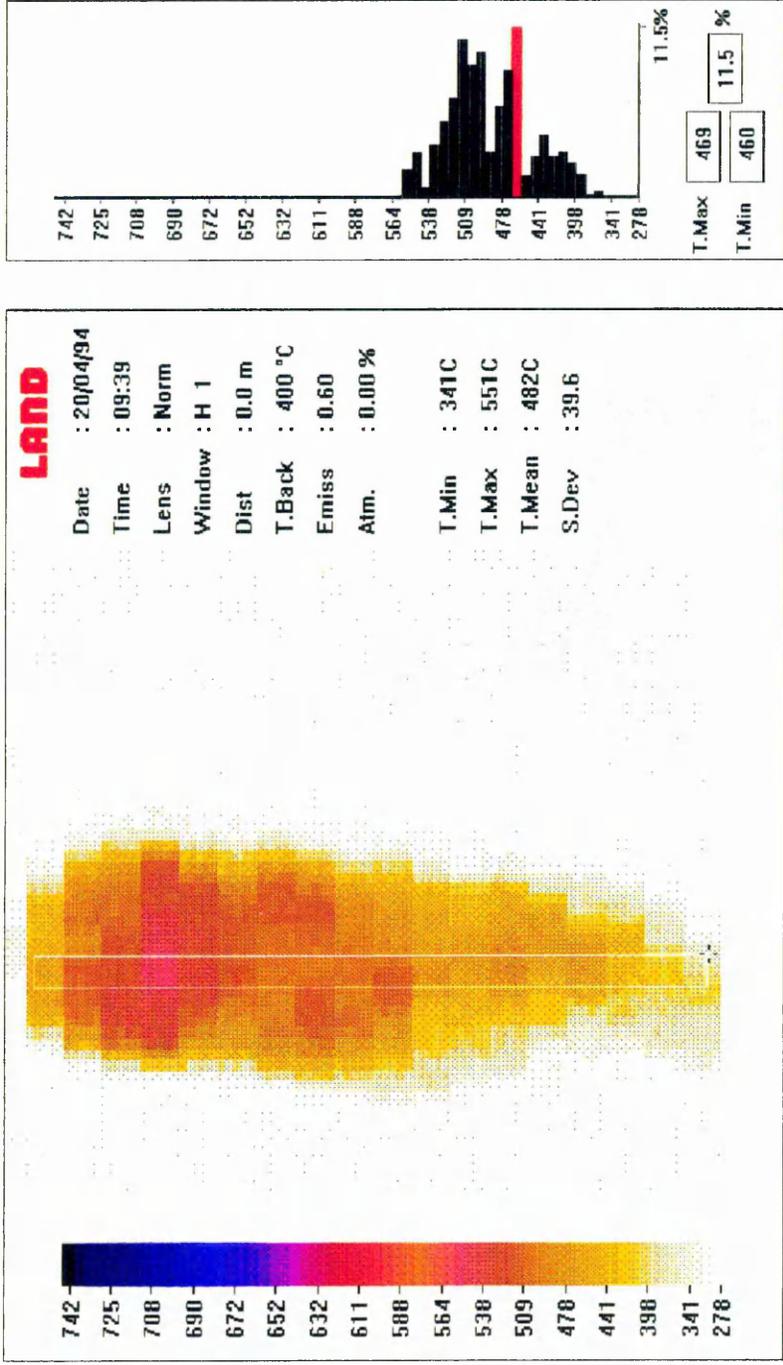


Figure 20 Temperature distribution histogram for a plunger with no oxide layer time = 1.20  
 (original in colour).

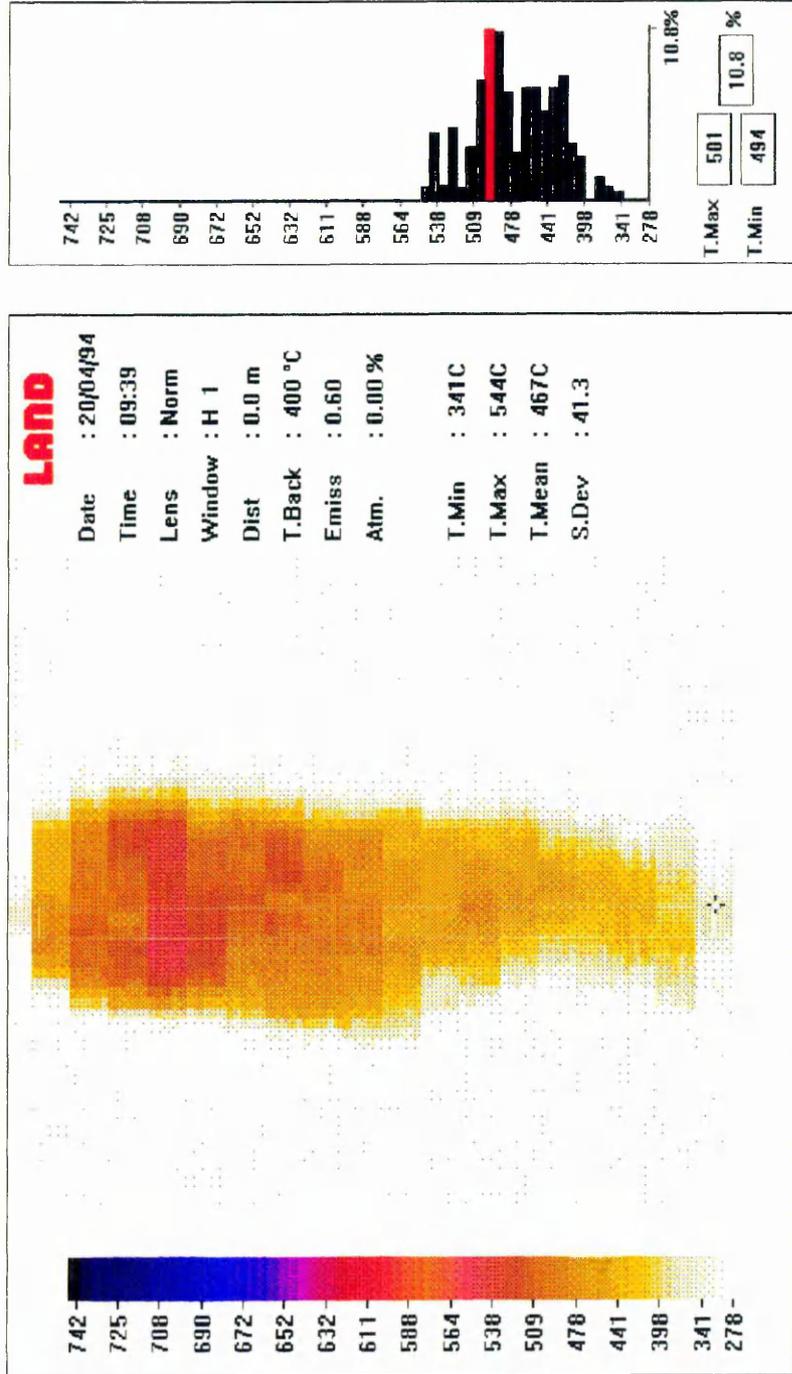


Figure 21 Temperature distribution histogram for a plunger with no oxide layer time = 1.44  
 (original in colour)

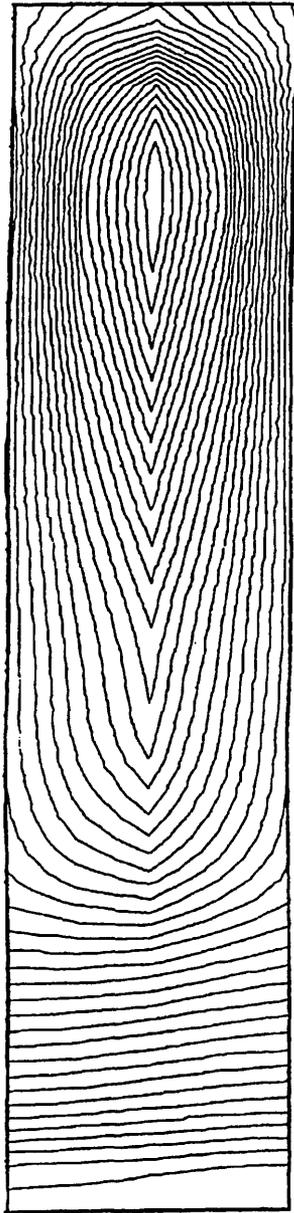


Figure 22 Typical temperature contours within the parison, from 'Glassflow' distribution prediction.

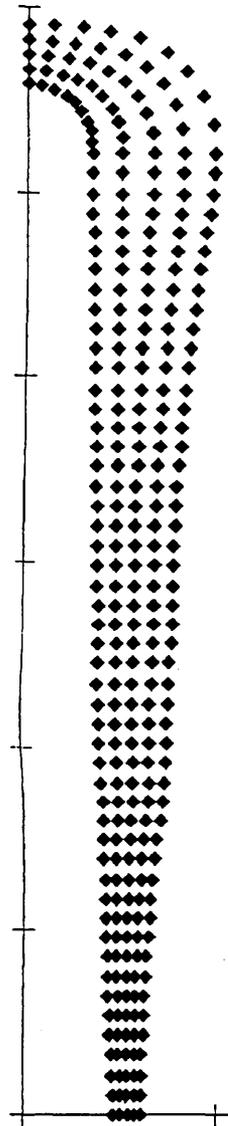


Figure 23 Typical glass distribution for a narrow neck container parison.

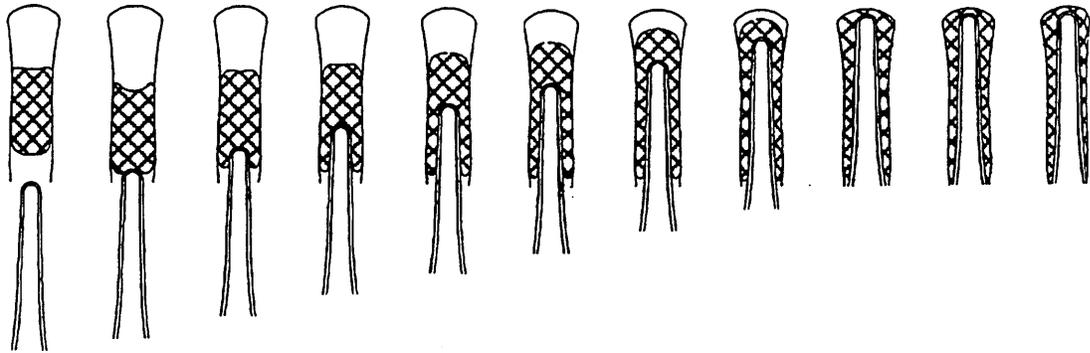


Figure 24 'Bottom up' glass redistribution.

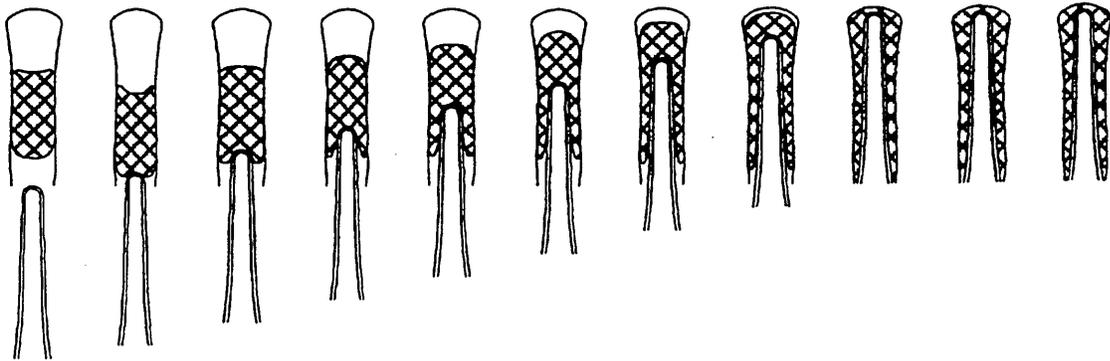


Figure 25 'Top down' glass redistribution.

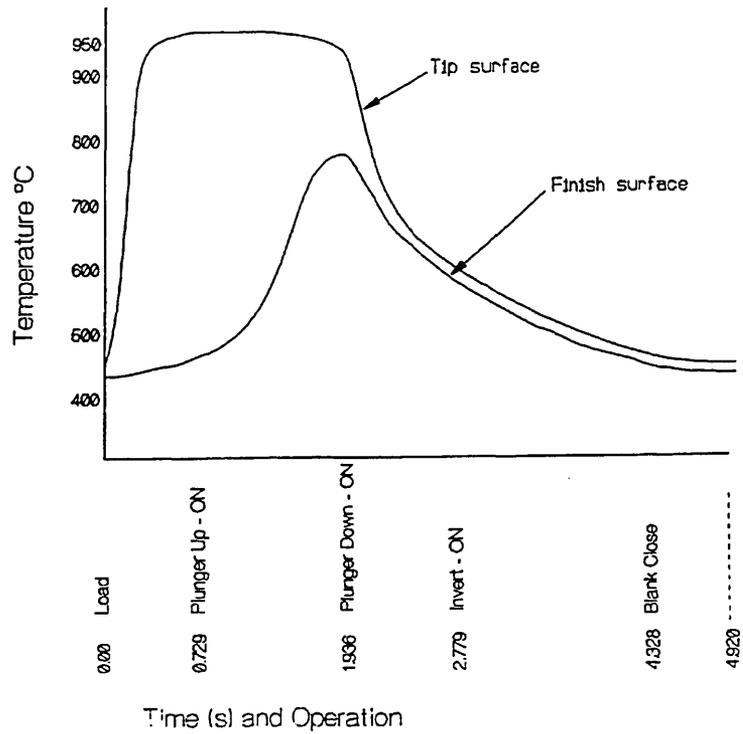


Figure 26 Predicted temperature profile for a NNPB plunger surface during the forming cycle

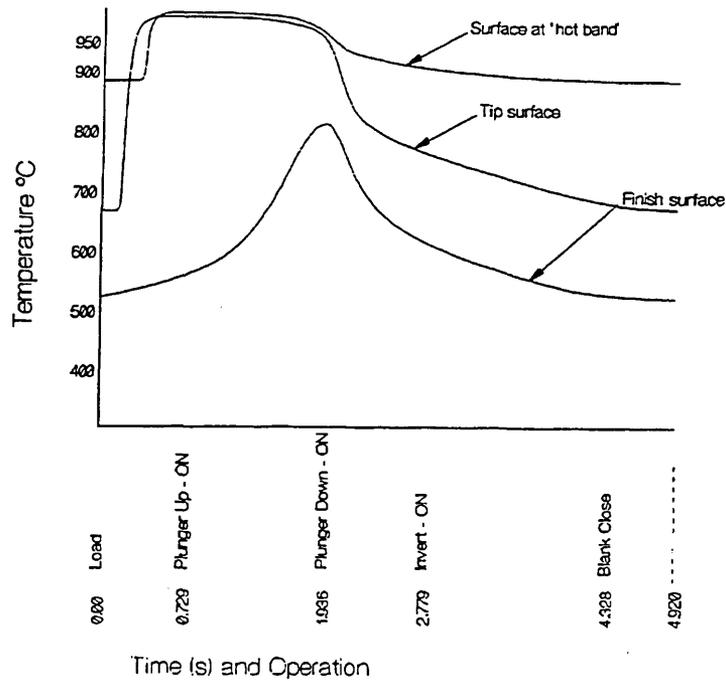


Figure 27 Predicted temperature profile for a NNPB plunger in poor operating condition.

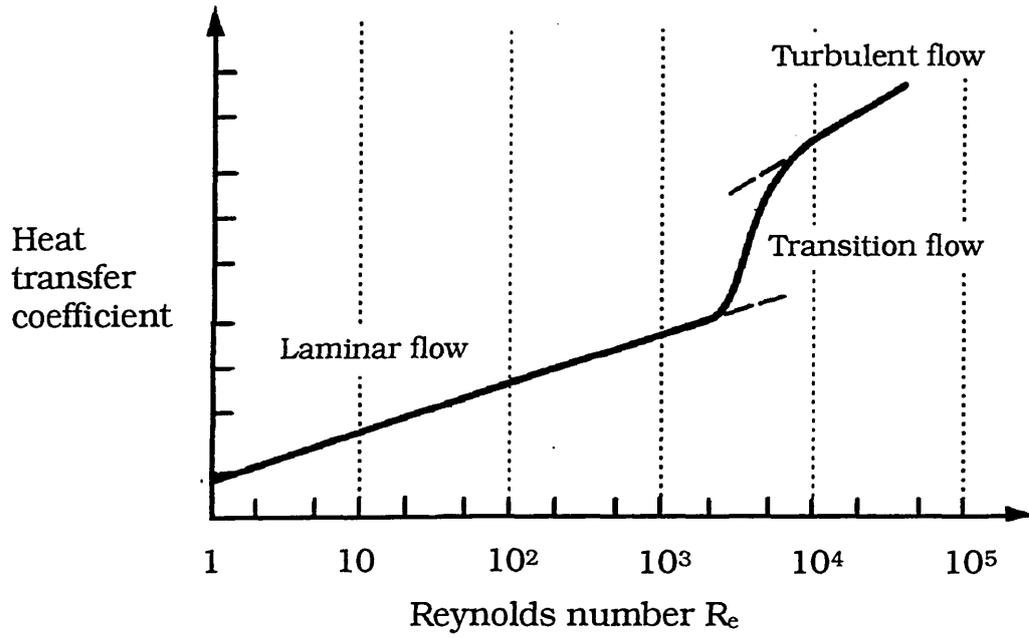


Figure 28 Heat transfer coefficient vs. Reynold number.

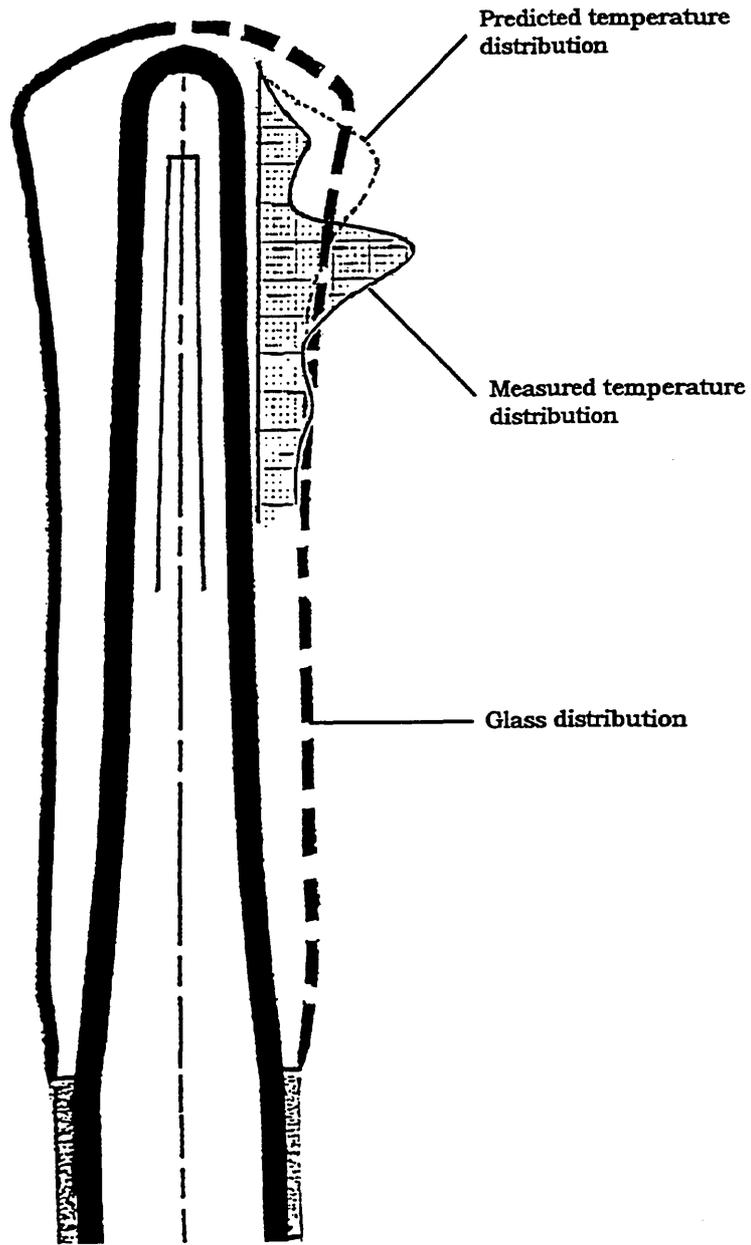


Figure 29 Theoretical and measured predictions of temperature distribution

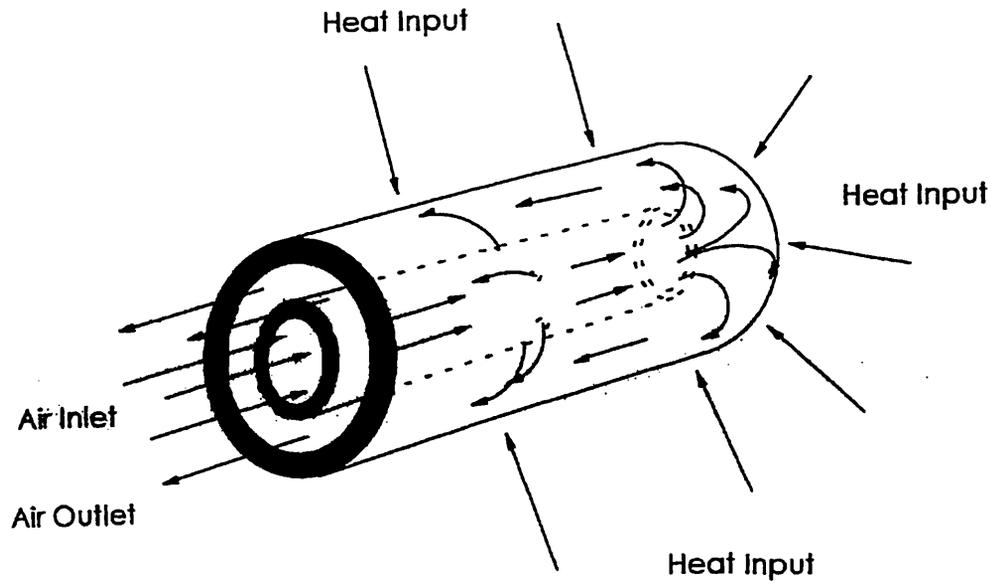


Figure 30 Schematic layout of NNPB plunger tip model

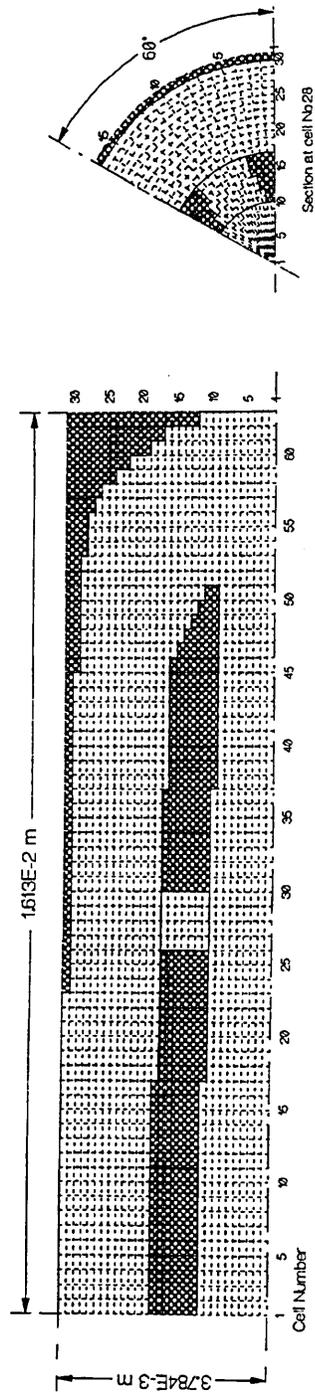


Figure 31 Geometrical layout of the internal form of the plunger and the cooling tube for the initial plunger tip model

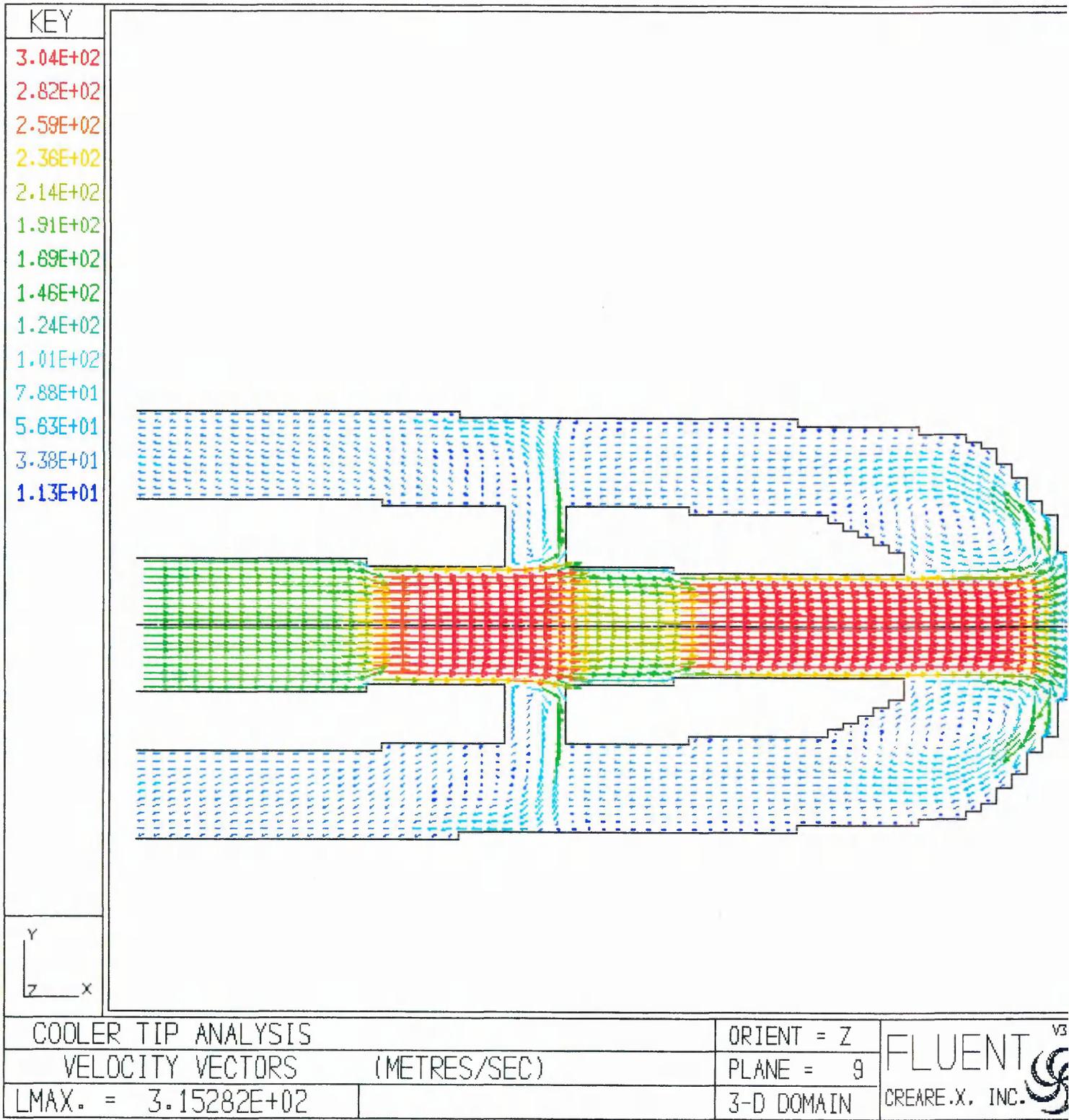


Figure 32 Flow field for initial plunger tip model, velocity magnitude vectors for each computational cell. (lower temperature condition). (original in colour)

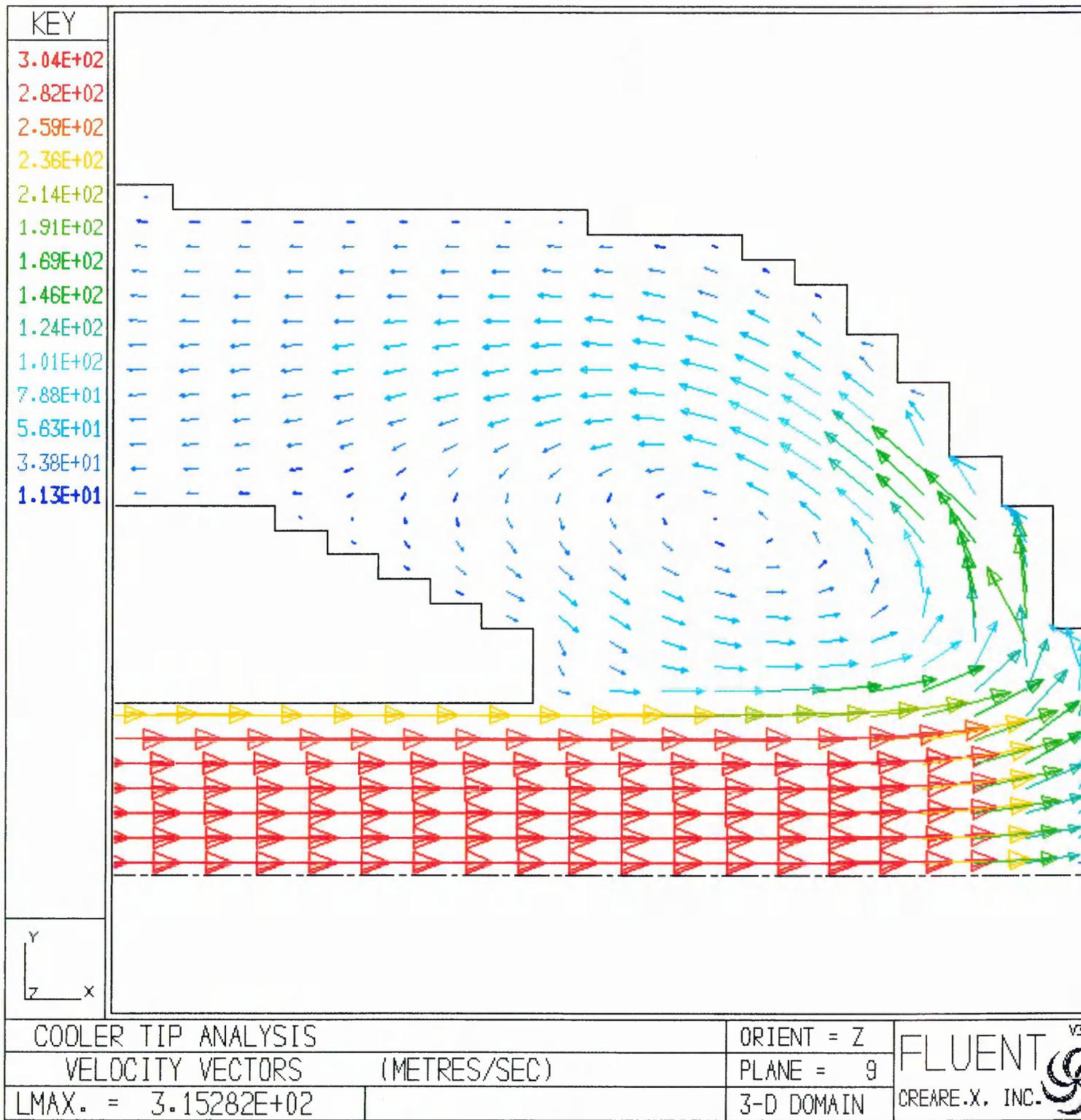


Figure 33 Detail of flow pattern at the tip.  
(lower temperature condition).  
(original in colour)

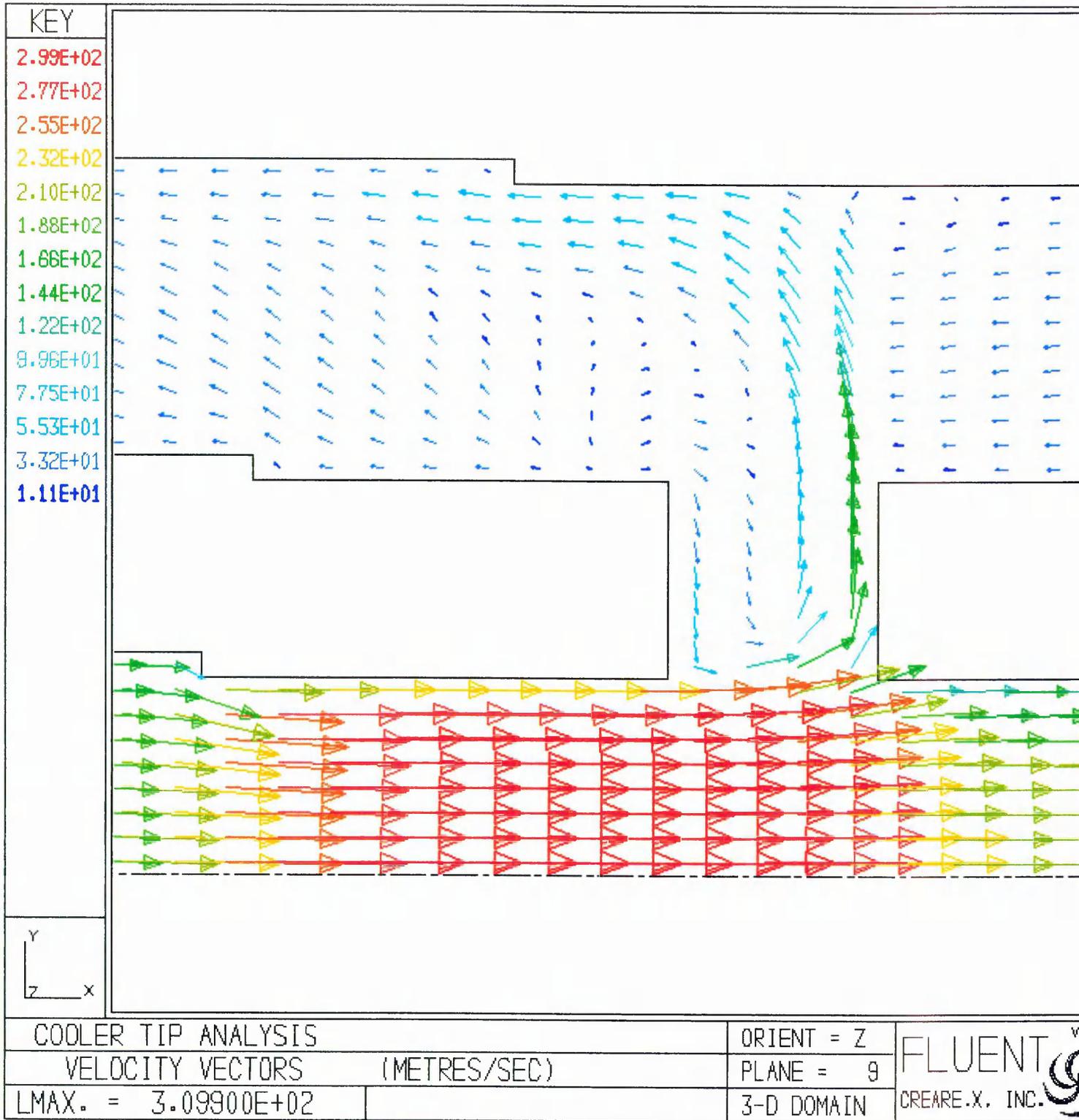


Figure 34 Detail of flow pattern at radial hole  
in the cooling tube (longitudinal section).  
(lower temperature condition).  
(original in colour)

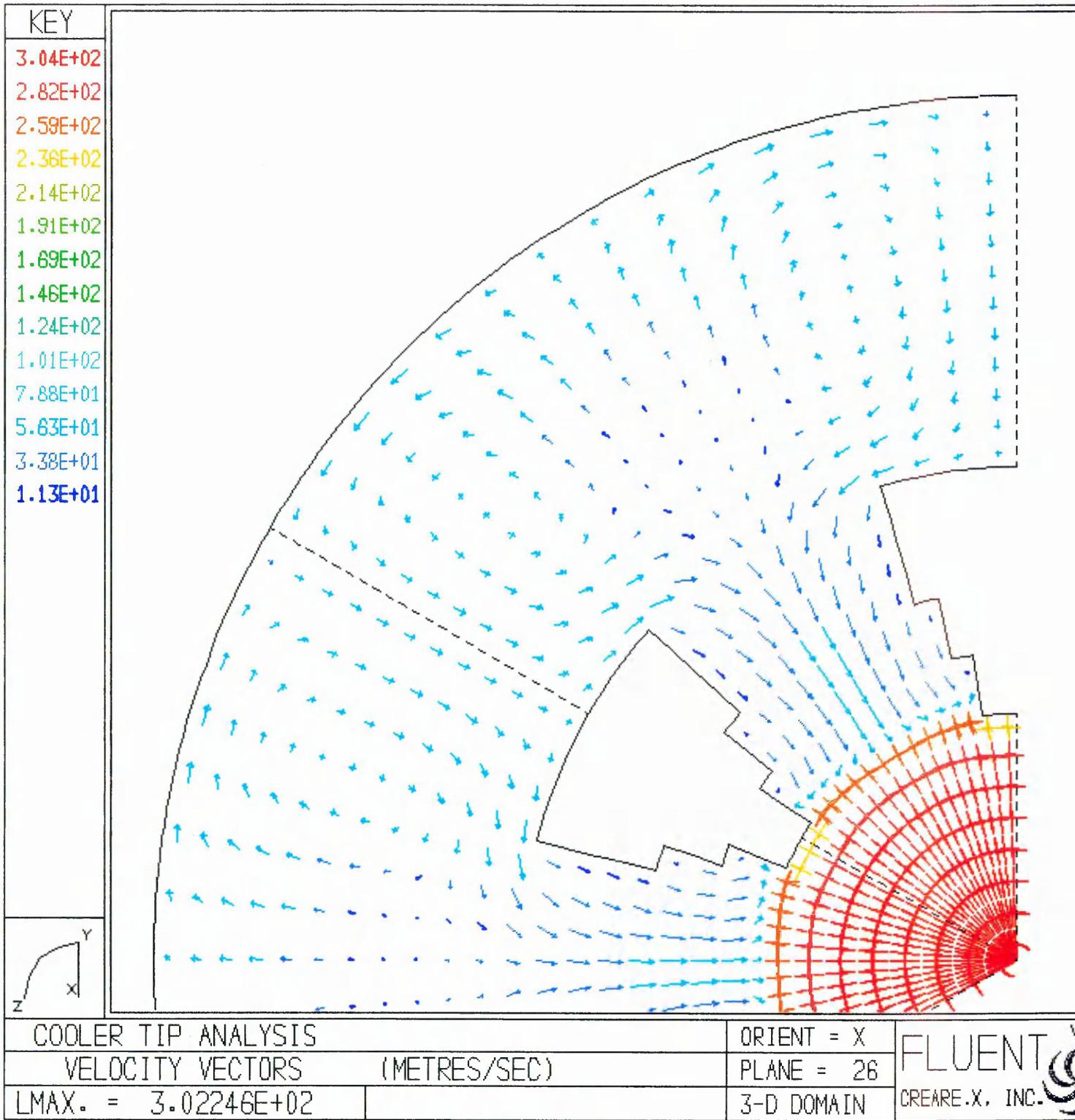


Figure 35 Flow pattern at radial hole  
in cooling tube - at cell I = 26.  
(lower temperature condition).  
(original in colour)

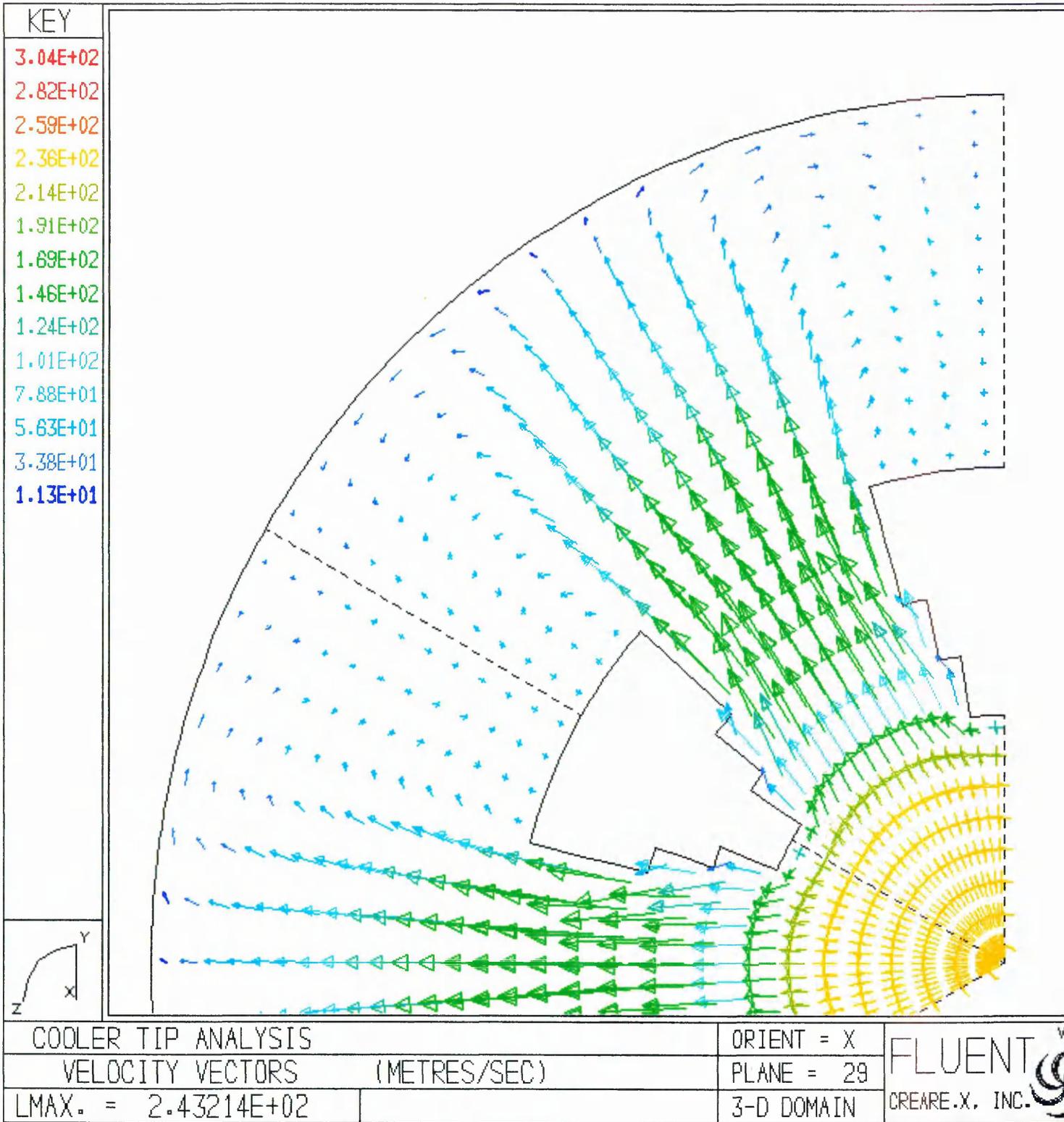


Figure 36 Flow pattern at radial hole  
in cooling tube - at cell I = 29.  
(lower temperature condition).  
(original in colour)

### Cross Sectional Area of Fluid Path for Plunger 0145 - H13

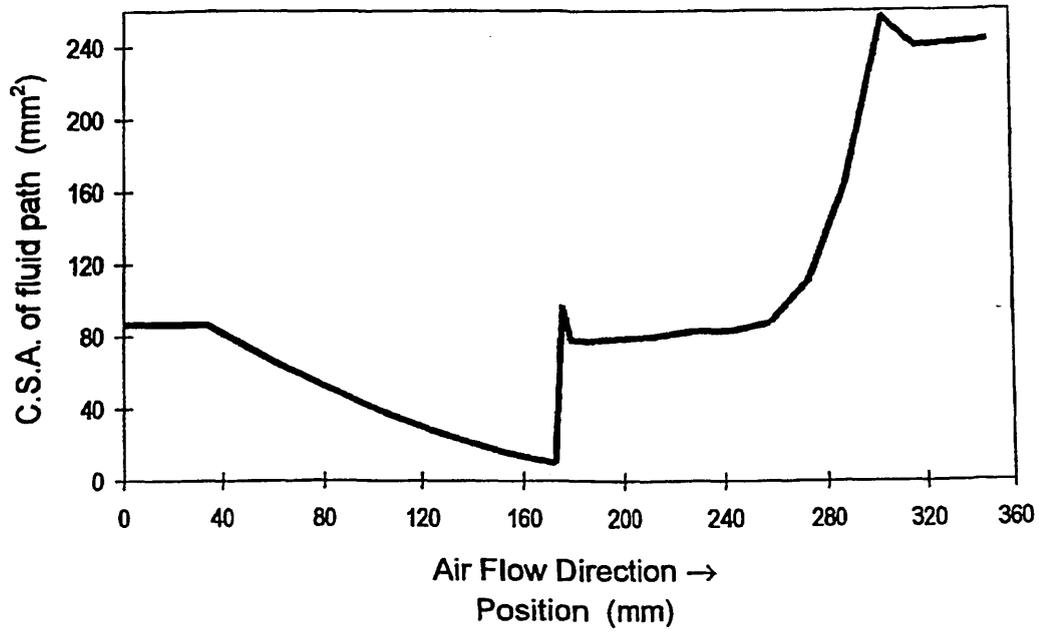


Figure 37 Cross sectional area of flow path  
for a typical NNPB plunger

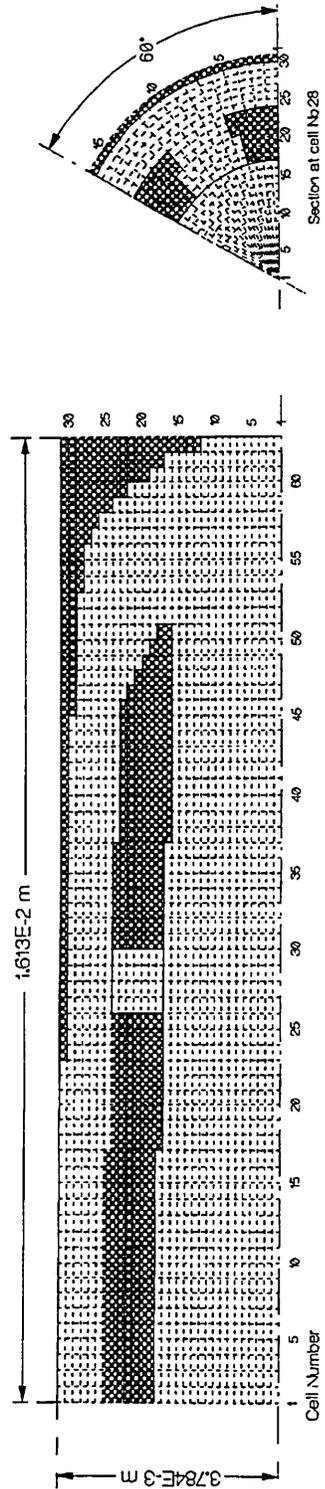


Figure 38 Geometry of modified cooling tube

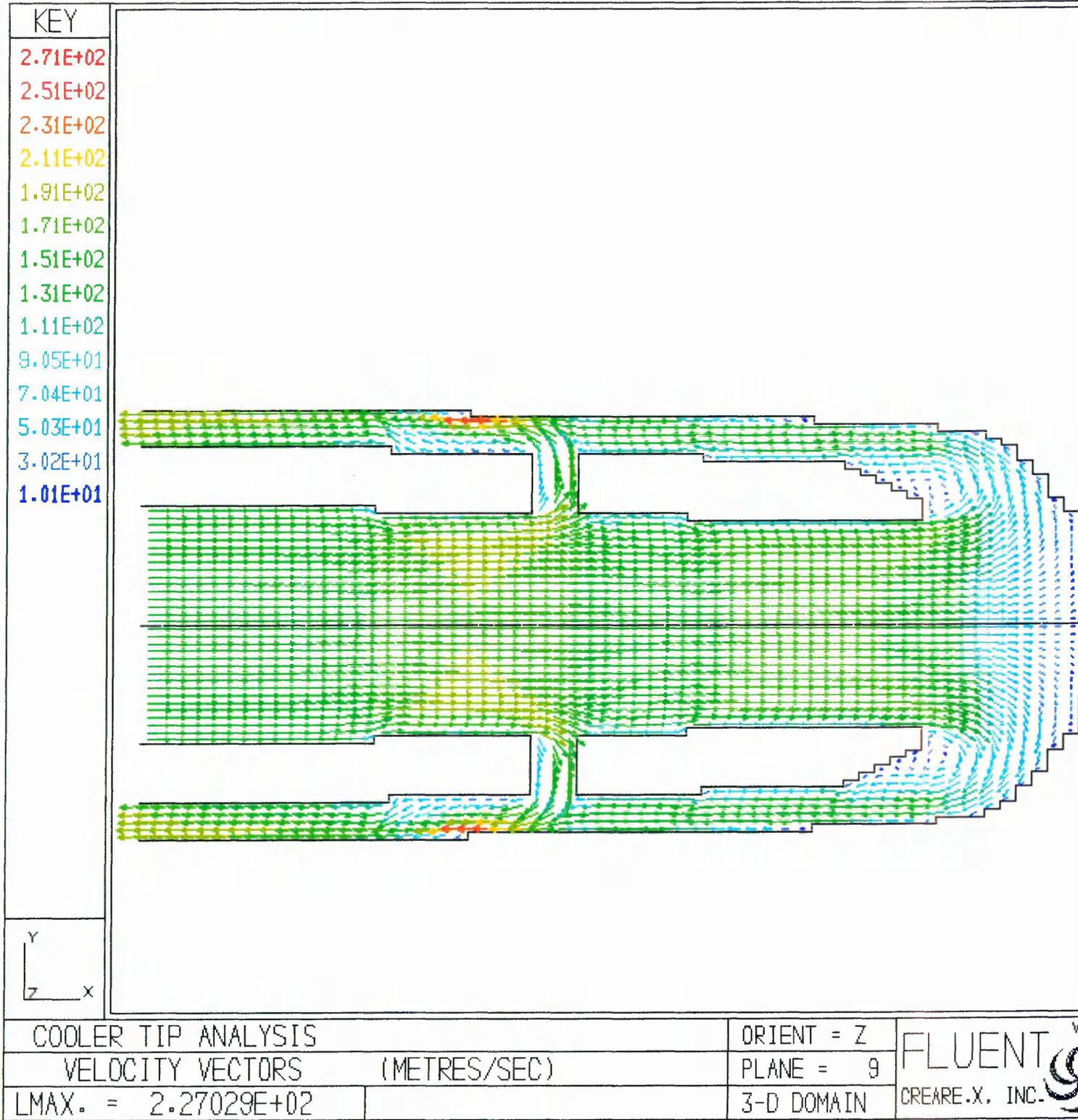


Figure 39 Flow field for modified plunger tip model,  
velocity magnitude vectors for each computational cell.  
(lower temperature condition).  
(original in colour)

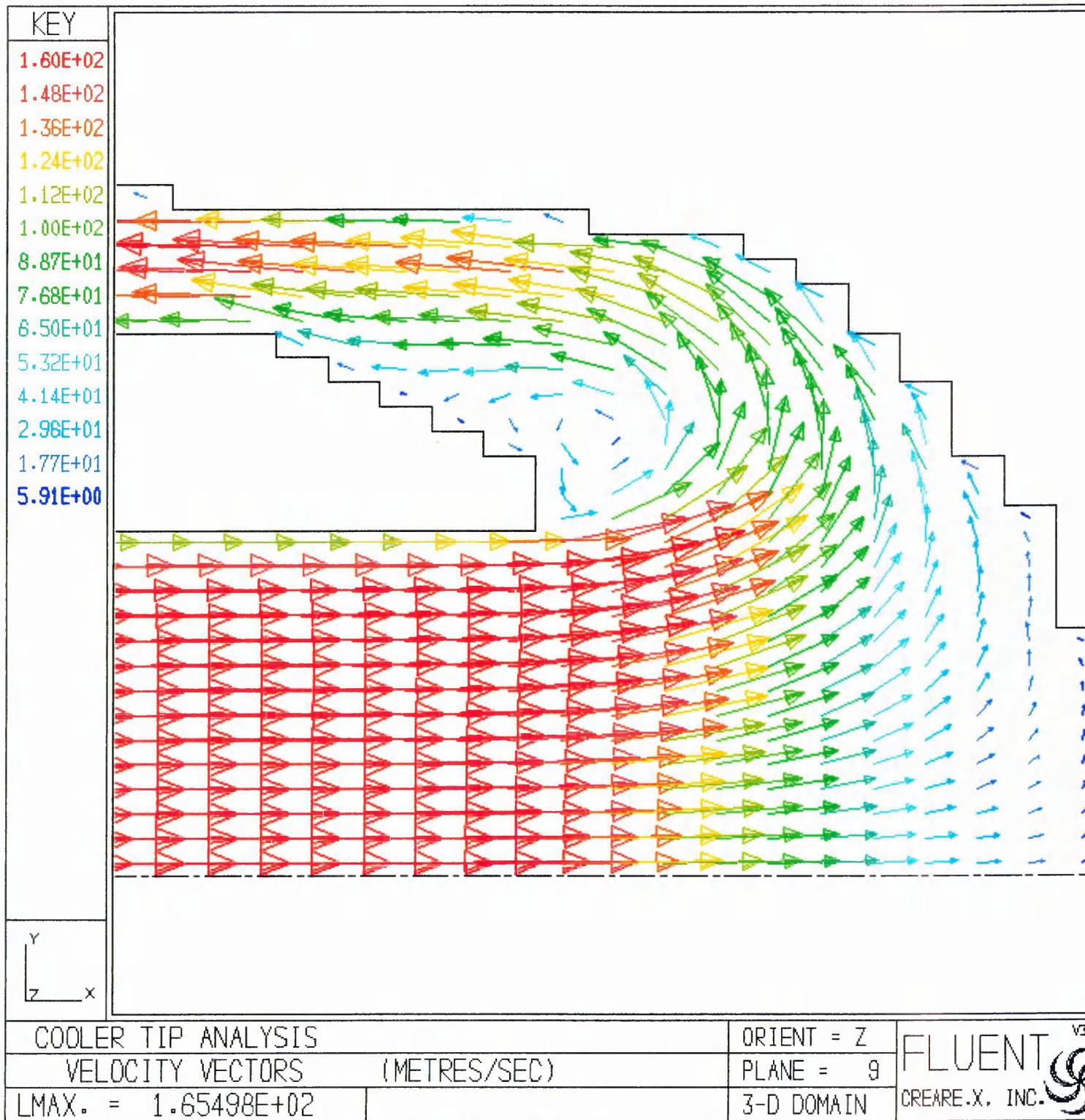


Figure 40 Detail of flow pattern at the tip.  
 (lower temperature condition).  
 (original in colour)

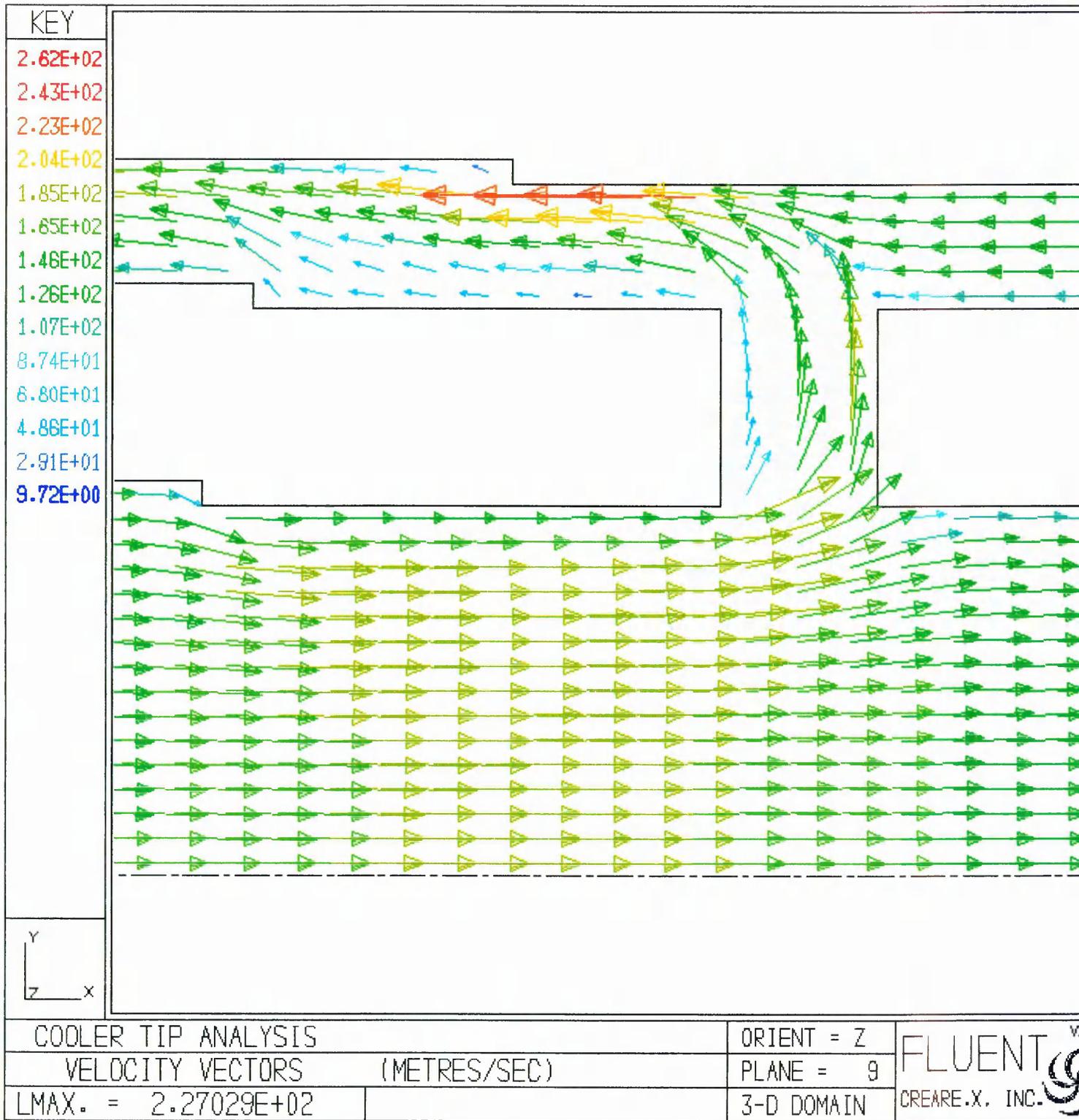


Figure 41 Detail of flow pattern at radial hole  
in the cooling tube (longitudinal section).  
(lower temperature condition).  
(original in colour)

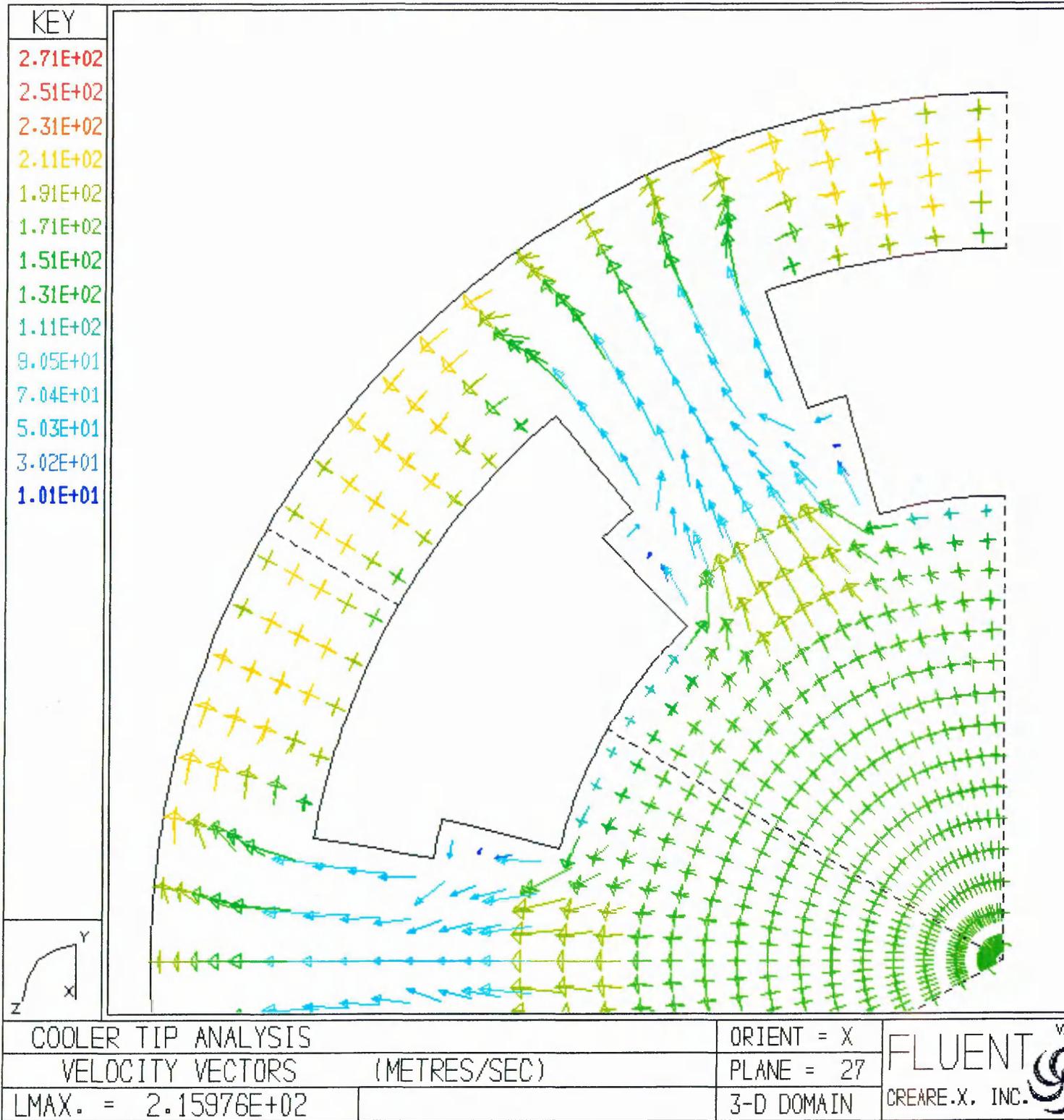


Figure 42 Flow pattern at radial hole  
in cooling tube - at cell I = 27.  
(lower temperature condition).  
(original in colour)

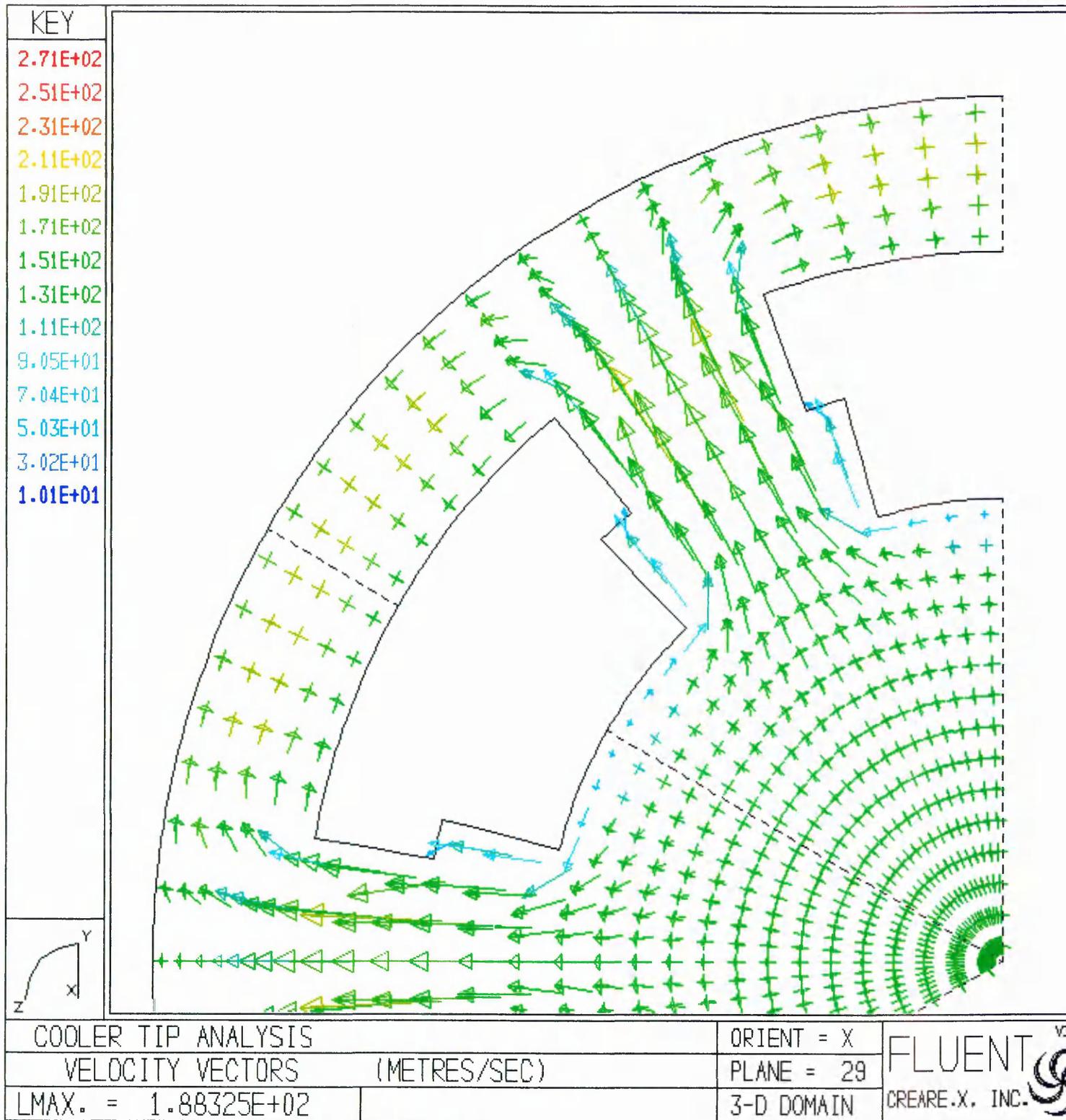


Figure 43 Flow pattern at radial hole  
in cooling tube - at cell I = 29.  
(lower temperature condition).  
(original in colour)

## Chapter 9 PLATES

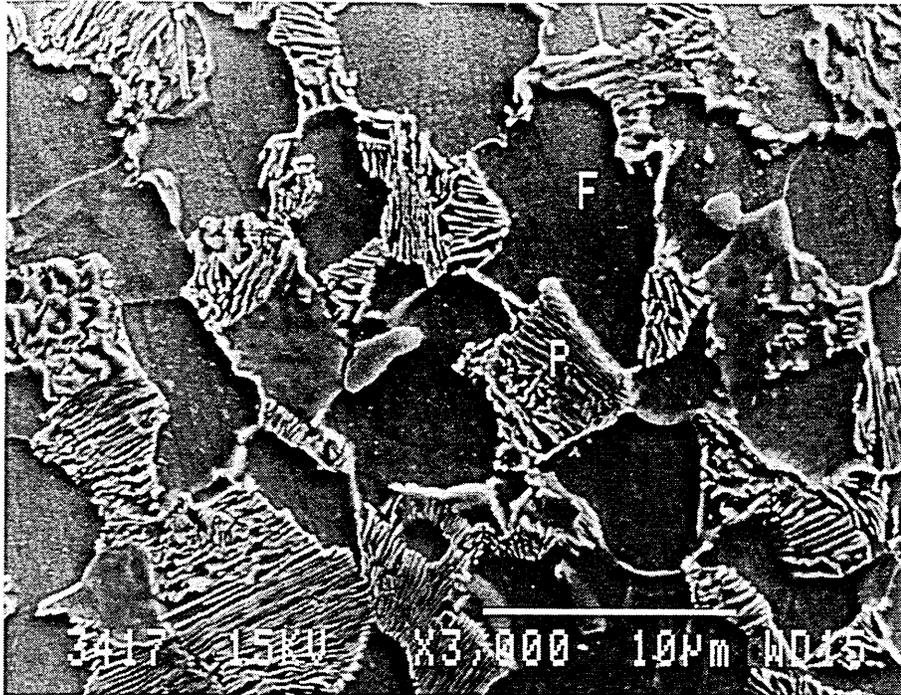


Plate 1. Typical normalised microstructure,  
(F) ferrite, (P) pearlite (mag x3000)

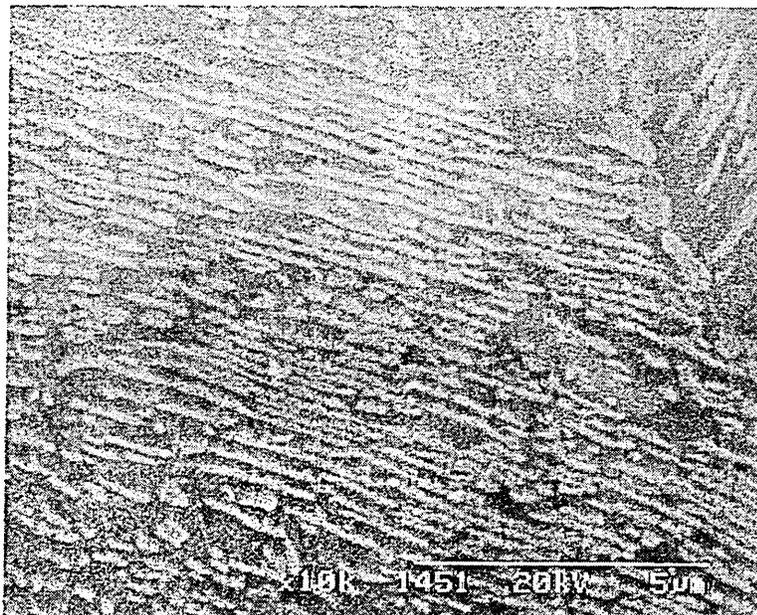


Plate 2 Partially spheroidised pearlite.  
(mag x10000)

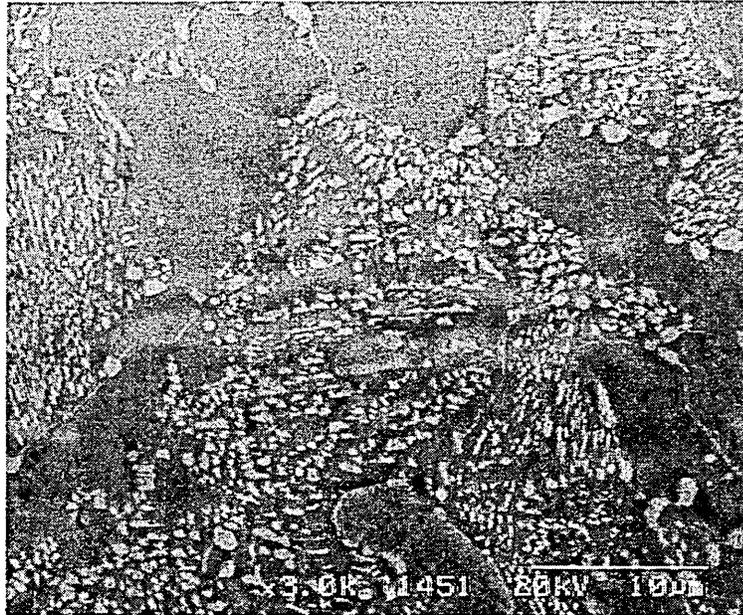


Plate 3 Complete spheroidisation of pearlite.  
(mag x3000)

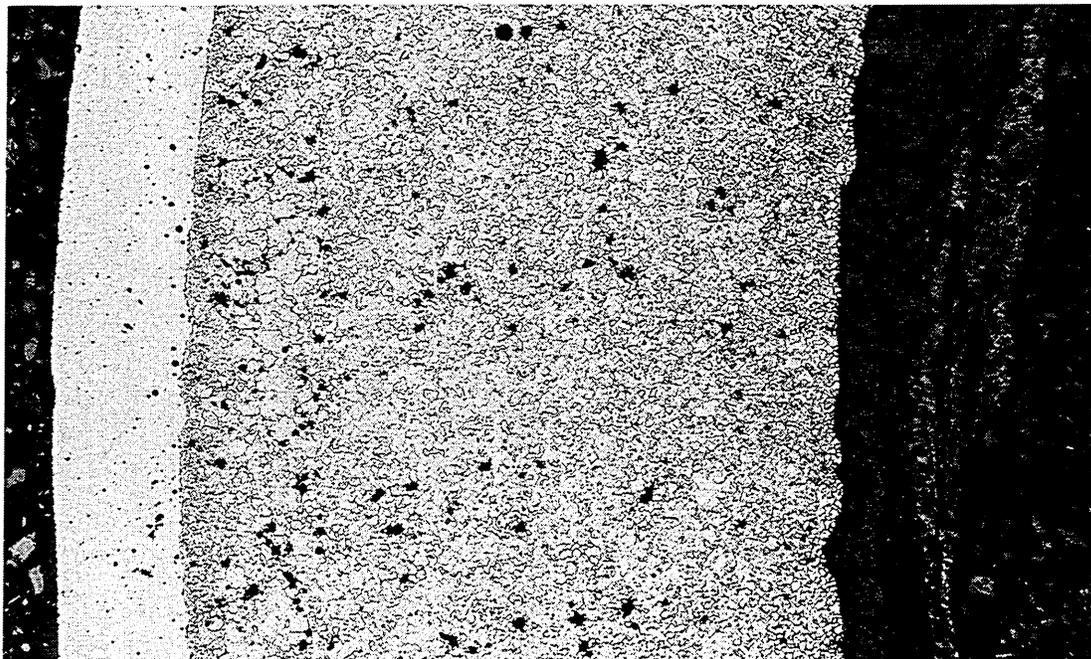


Plate 4 Grain growth and graphitisation.  
(mag x125)

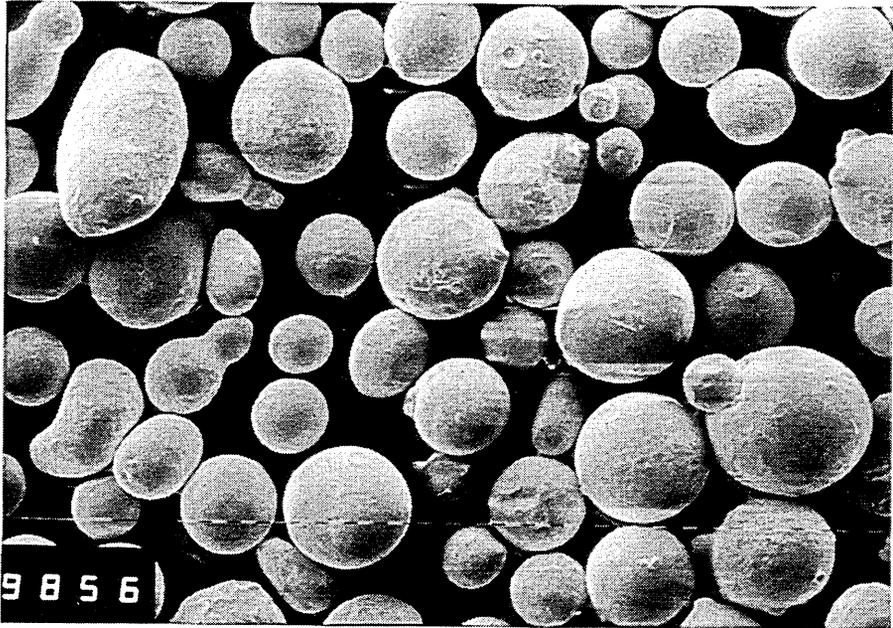


Plate 5 Typical powder particles.  
(mag x170)

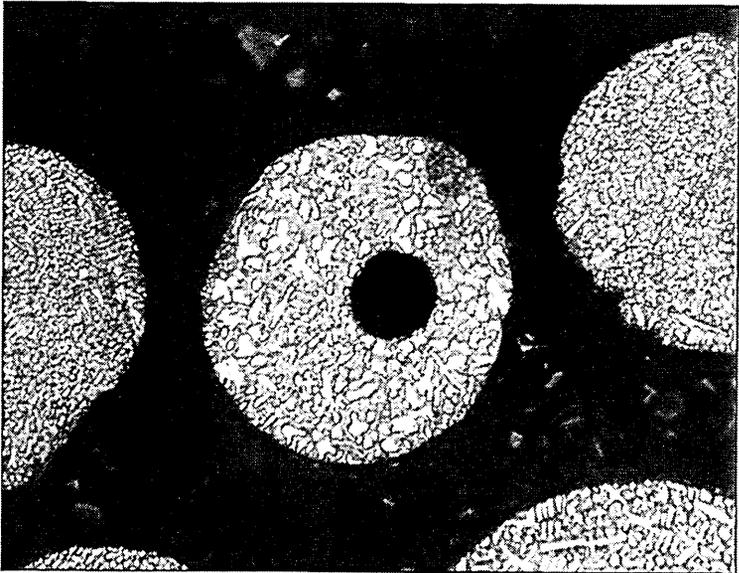


Plate 6 Structure of a powder  
particle.  
(mag x920)

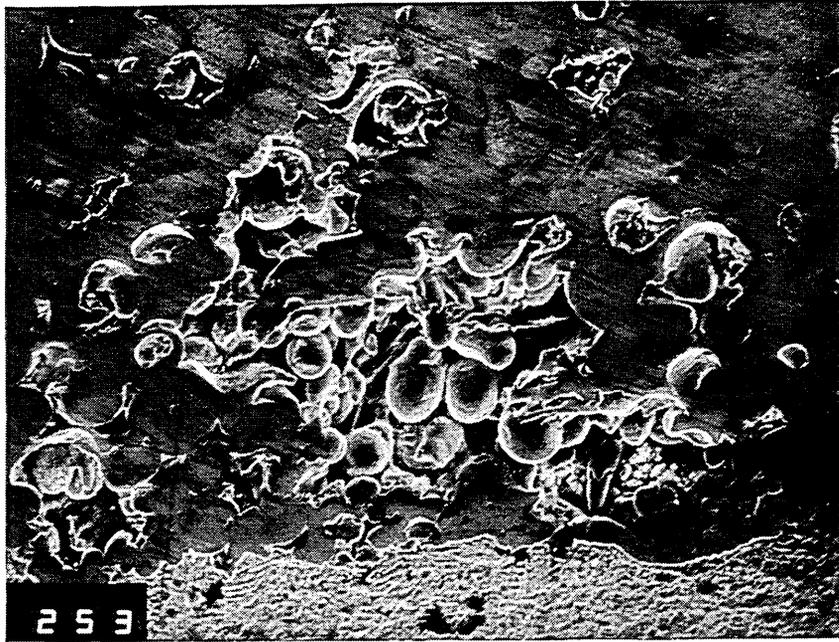


Plate 7 Unfused coating deposit.  
(mag x150)

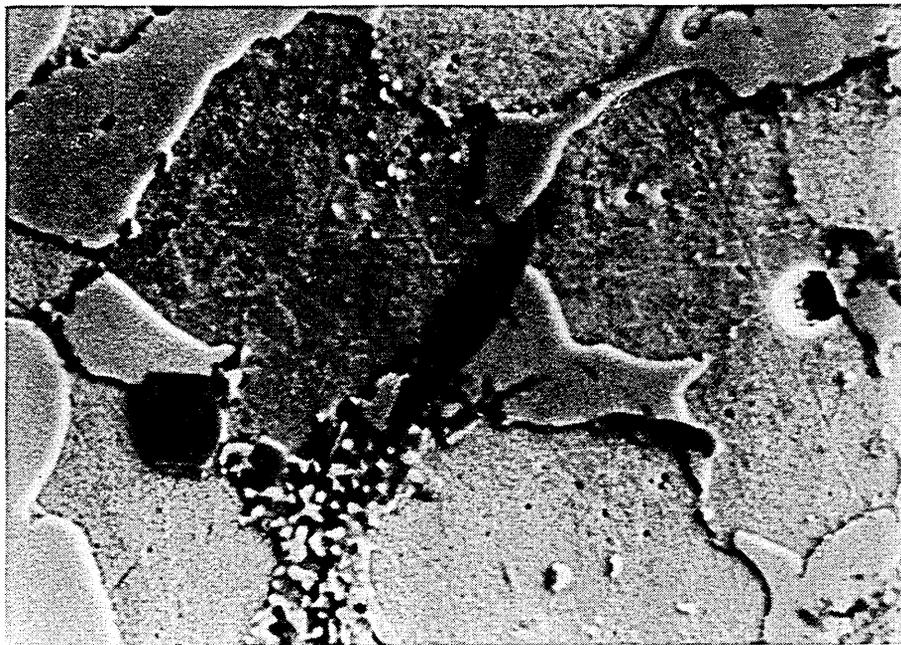


Plate 8 Coating microstructure.  
(mag x3000)

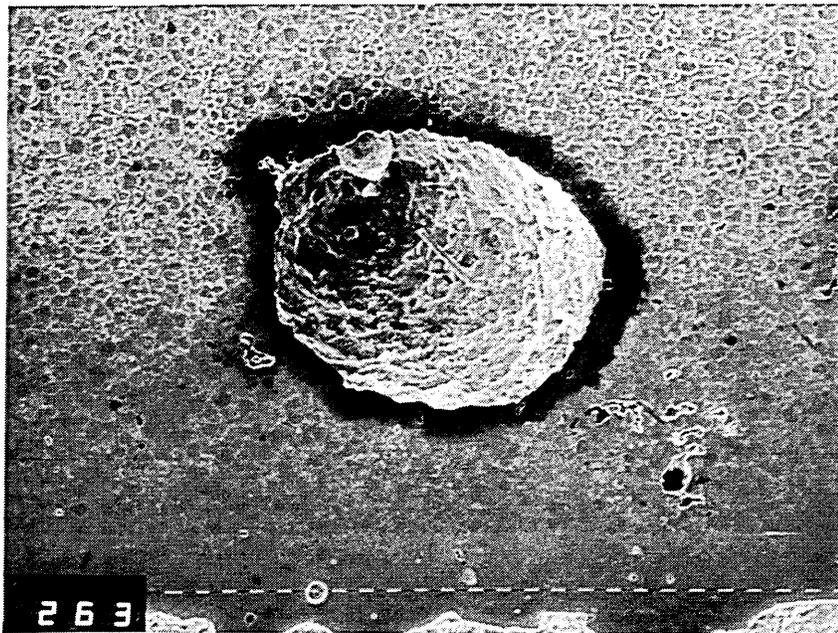


Plate 9 Entrapped gas porosity.  
(mag x203)

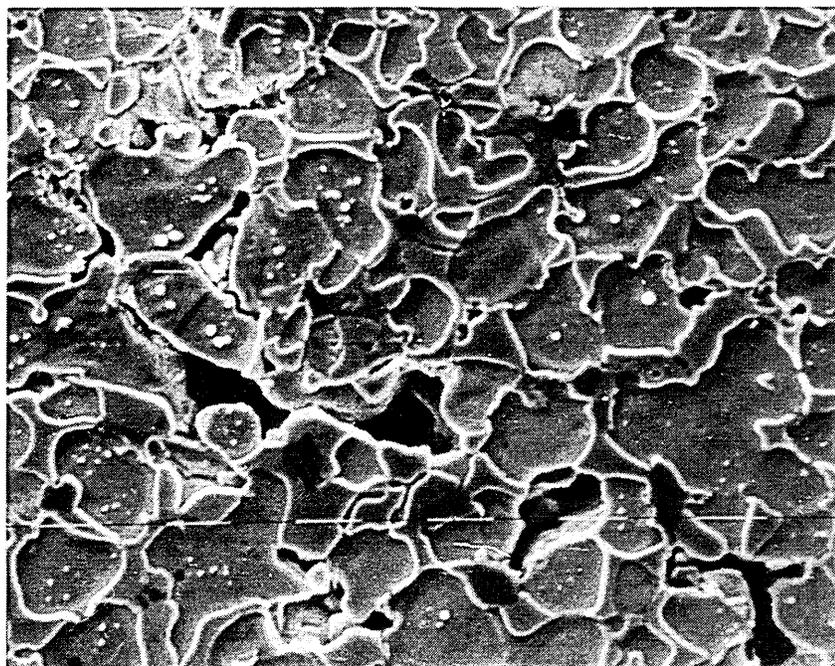


Plate 10 Intergranular porosity.  
(mag x640)

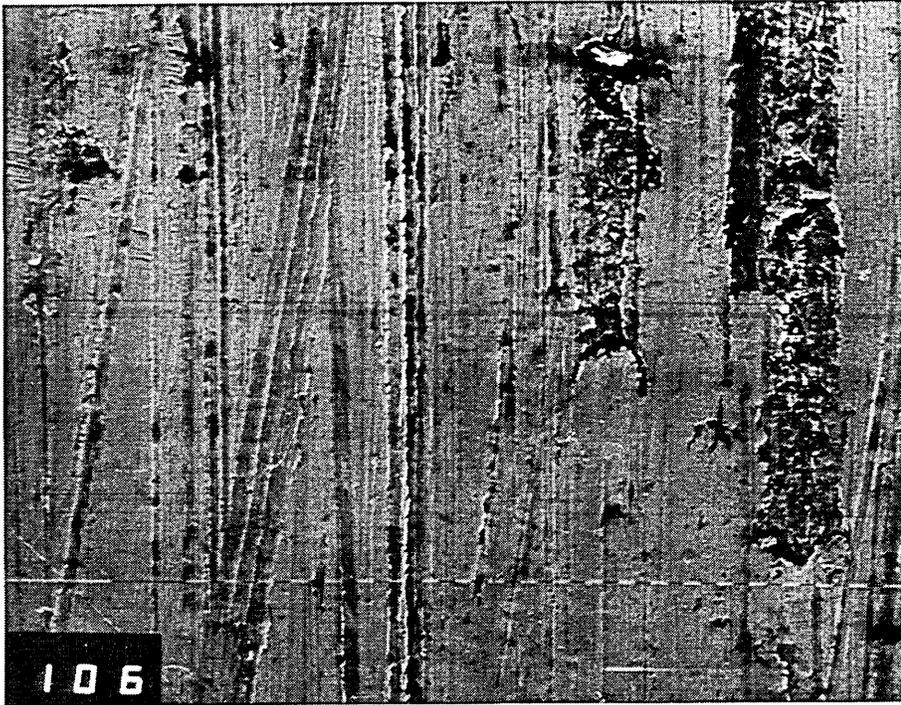


Plate 11 Machined surface detail, sub-surface weakness.  
(mag x520)



Plate 12 Machined surface detail, smearing.  
(mag x424)

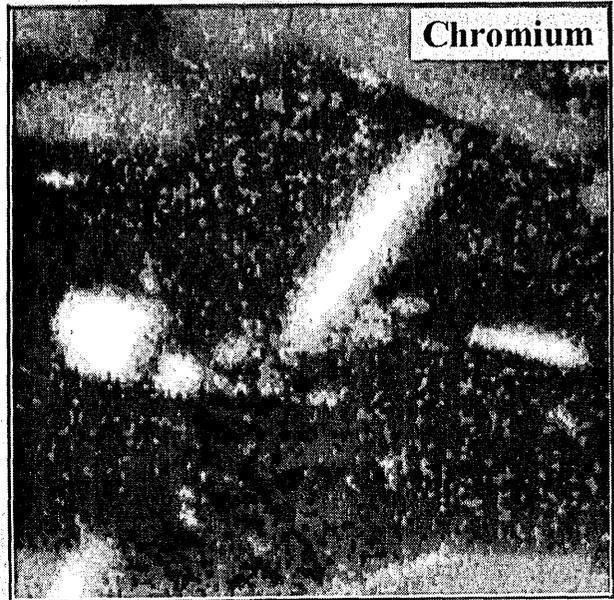
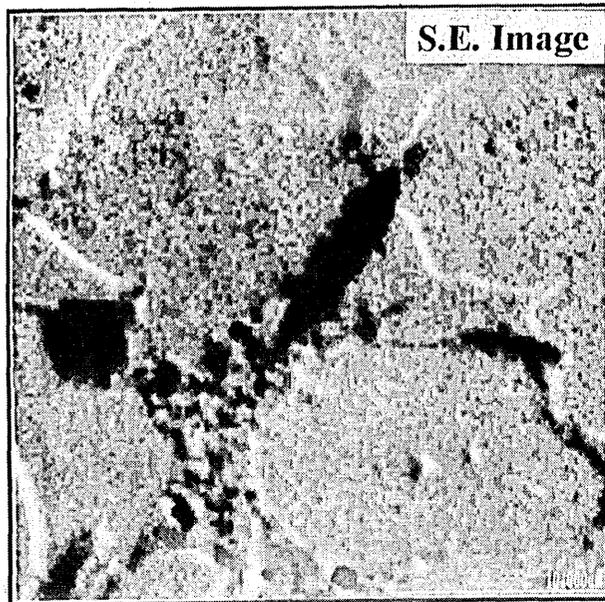
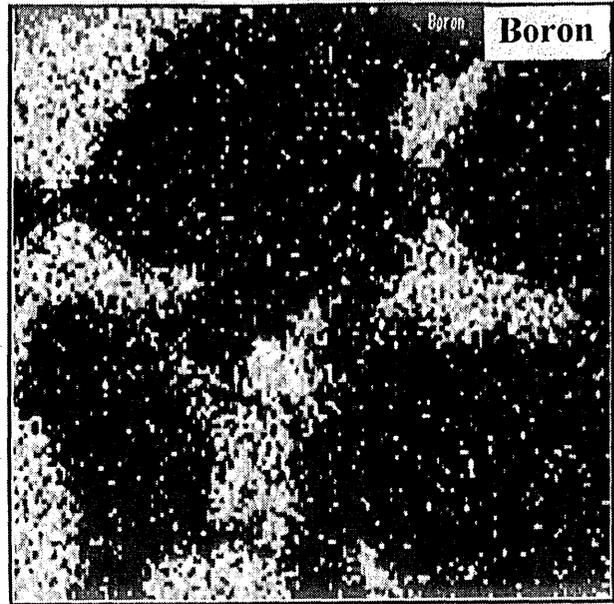
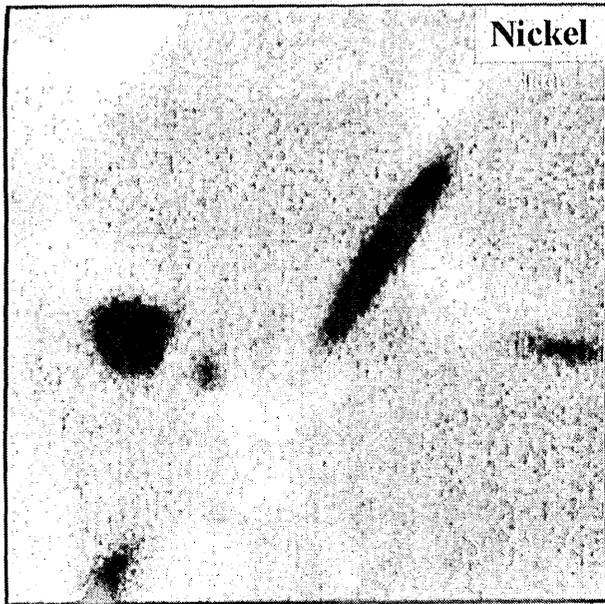


Plate 13 Distribution of elements within the microstructure of the coating.



Plate 14 Typical 'comet tail' wear scar.  
(mag x150)

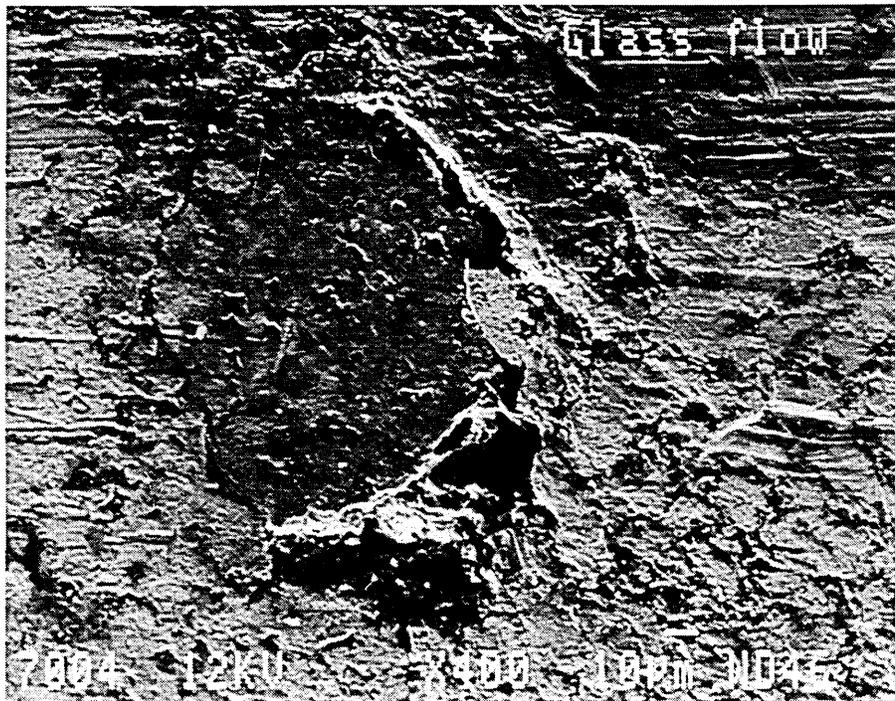


Plate 15 Initiation of wear scar.  
(mag x400)

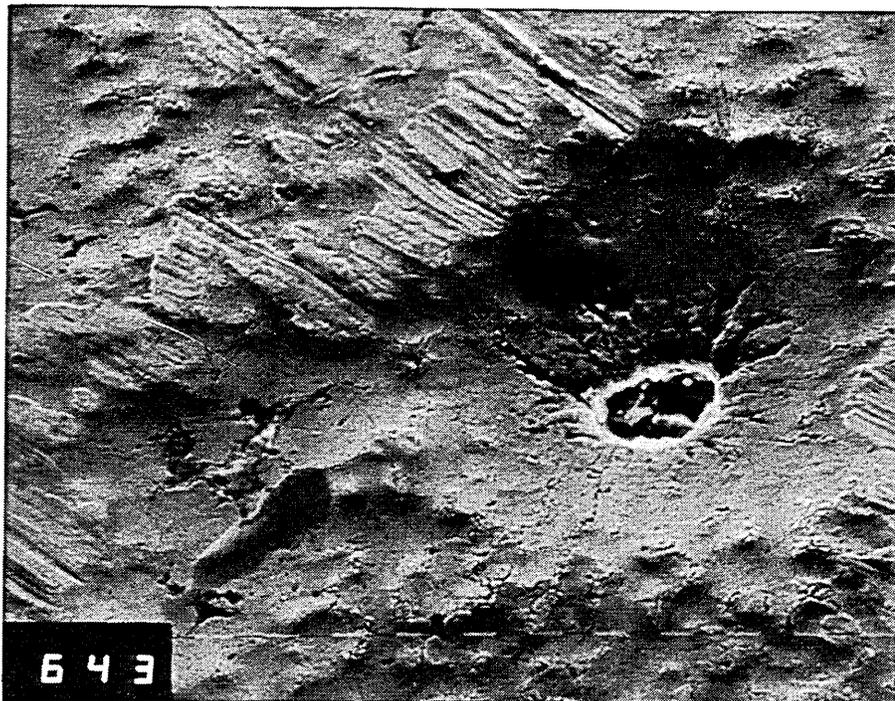


Plate 16 Tip wear, deformation and microcracking.  
(mag x480)



Plate 17 Plunger tip responsible for pulling spikes.  
(mag x160)



Plate 18 Oxide layer within plunger bore.

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Data file for the initial model - high temperature condition	lxxvii
Data file for the modified cooling tube model low temperature condition	c
Data file for the modified cooling tube model high temperature condition	cxxv





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31 WWWWWWWWWWWWWWWWW 31
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29 WWWWWWWWWWWWWWWWW 29
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5 WWWWWWWWWWWWWWWWW 5
4 WWWWWWWWWWWWWWWWW 4
3 WWWWWWWWWWWWWWWWW 3
2 WWWWWWWWWWWWWWWWW 2
1 WWWWWWWWWWWWWWWWW 1
J I = 58 60 62 = I

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K = 3
J I = 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52 54 56 = I
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30 WWWWWWWWWWWWWWWWW 30
29 WWWWWWWWWWWWWWWWW 29
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27 WWWWWWWWWWWWWWWWW 27
26 WWWWWWWWWWWWWWWWW 26
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4 WWWWWWWWWWWWWWWWW 4
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2 WWWWWWWWWWWWWWWWW 2
1 WWWWWWWWWWWWWWWWW 1
J I = 58 60 62 = I

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J I = 58 60 62 = I
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26 WWWWWWWWWWWWWWWWW 26

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11 .W1WWWWW 11
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7 .W1WWWWW 7
6 .W1WWWWW 6
5 .W1WWWWW 5
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3 .W1WWWWW 3
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J I = 58 60 62 = I J
K = 5

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30 WWWWWWWW 1 WWWWWWWW 9 WWWWWWWW 17 WWWWWWWW 25 WWWWWWWW 33 WWWWWWWW 41 WWWWWWWW 49 WWWWWWWW 57 WWWWWWWW
29 WWWWWWWW 2 WWWWWWWW 10 WWWWWWWW 18 WWWWWWWW 26 WWWWWWWW 34 WWWWWWWW 42 WWWWWWWW 50 WWWWWWWW 58 WWWWWWWW
28 WWWWWWWW 3 WWWWWWWW 11 WWWWWWWW 19 WWWWWWWW 27 WWWWWWWW 35 WWWWWWWW 43 WWWWWWWW 51 WWWWWWWW 59 WWWWWWWW
27 WWWWWWWW 4 WWWWWWWW 12 WWWWWWWW 20 WWWWWWWW 28 WWWWWWWW 36 WWWWWWWW 44 WWWWWWWW 52 WWWWWWWW 60 WWWWWWWW
26 WWWWWWWW 5 WWWWWWWW 13 WWWWWWWW 21 WWWWWWWW 29 WWWWWWWW 37 WWWWWWWW 45 WWWWWWWW 53 WWWWWWWW 61 WWWWWWWW
25 WWWWWWWW 6 WWWWWWWW 14 WWWWWWWW 22 WWWWWWWW 30 WWWWWWWW 38 WWWWWWWW 46 WWWWWWWW 54 WWWWWWWW 62 WWWWWWWW
24 WWWWWWWW 7 WWWWWWWW 15 WWWWWWWW 23 WWWWWWWW 31 WWWWWWWW 39 WWWWWWWW 47 WWWWWWWW 55 WWWWWWWW 63 WWWWWWWW
23 WWWWWWWW 8 WWWWWWWW 16 WWWWWWWW 24 WWWWWWWW 32 WWWWWWWW 40 WWWWWWWW 48 WWWWWWWW 56 WWWWWWWW 64 WWWWWWWW
22 WWWWWWWW 9 WWWWWWWW 17 WWWWWWWW 25 WWWWWWWW 33 WWWWWWWW 41 WWWWWWWW 49 WWWWWWWW 57 WWWWWWWW 65 WWWWWWWW
21 WWWWWWWW 10 WWWWWWWW 18 WWWWWWWW 26 WWWWWWWW 34 WWWWWWWW 42 WWWWWWWW 50 WWWWWWWW 58 WWWWWWWW 66 WWWWWWWW
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7 WWWWWWWW 7
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3 WWWWWWWW 3
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1 WWWWWWWW 1
J I = 58 60 62 = I J

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J 24 . . . . . W1 6
J 23 . . . . . W1 5
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J 20 . . . . . W1 2
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J 7 . . . . . SWW 1
J 6 . . . . . SWW 1
J 5 . . . . . SWW 1
J 4 . . . . . SWW 1
J 3 . . . . . SWW 1
J 2 . . . . . SWW 1
J 1 . . . . . SWW 1

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J 25 . . . . . W1 7
J 24 . . . . . W1 6
J 23 . . . . . W1 5
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J 21 . . . . . W1 3
J 20 . . . . . W1 2
J 19 . . . . . W1 1
J 18 . . . . . SWW 1
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J 2 . . . . . SWW 1
J 1 . . . . . SWW 1

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MOLECULAR WEIGHT = 2.8000E+01

. VISCOSITY DEFINITION .

TEMP	VISCOSITY
2.5000E+02	1.345E-05
3.5000E+02	1.0718E-05
4.5000E+02	2.2670E-05
5.5000E+02	2.2587E-05
6.5000E+02	2.8488E-05
7.5000E+02	3.0238E-05
8.5000E+02	3.1771E-05
9.5000E+02	3.3324E-05
1.0000E+03	3.4812E-05
1.1000E+03	3.6289E-05
1.2000E+03	3.7681E-05
1.3000E+03	3.9025E-05
1.4000E+03	4.0250E-05
1.5000E+03	4.1466E-05
1.6000E+03	4.265E-05
1.7000E+03	4.3825E-05
1.8000E+03	4.499E-05
1.9000E+03	4.6145E-05
2.0000E+03	4.729E-05
2.1000E+03	4.8425E-05
2.2000E+03	4.955E-05
2.3000E+03	5.0675E-05
2.4000E+03	5.179E-05
2.5000E+03	5.2905E-05
2.6000E+03	5.402E-05
2.7000E+03	5.5135E-05
2.8000E+03	5.625E-05
2.9000E+03	5.7365E-05
3.0000E+03	5.848E-05
3.1000E+03	5.9595E-05
3.2000E+03	6.071E-05
3.3000E+03	6.1825E-05
3.4000E+03	6.294E-05
3.5000E+03	6.4055E-05
3.6000E+03	6.517E-05
3.7000E+03	6.6285E-05
3.8000E+03	6.74E-05
3.9000E+03	6.8515E-05
4.0000E+03	6.963E-05
4.1000E+03	7.0745E-05
4.2000E+03	7.186E-05
4.3000E+03	7.2975E-05
4.4000E+03	7.409E-05
4.5000E+03	7.5205E-05
4.6000E+03	7.632E-05
4.7000E+03	7.7435E-05
4.8000E+03	7.855E-05
4.9000E+03	7.9665E-05
5.0000E+03	8.078E-05
5.1000E+03	8.1895E-05
5.2000E+03	8.301E-05
5.3000E+03	8.4125E-05
5.4000E+03	8.524E-05
5.5000E+03	8.6355E-05
5.6000E+03	8.747E-05
5.7000E+03	8.8585E-05
5.8000E+03	8.97E-05
5.9000E+03	9.0815E-05
6.0000E+03	9.193E-05
6.1000E+03	9.3045E-05
6.2000E+03	9.416E-05
6.3000E+03	9.5275E-05
6.4000E+03	9.639E-05
6.5000E+03	9.7505E-05
6.6000E+03	9.862E-05
6.7000E+03	9.9735E-05
6.8000E+03	1.0085E-04
6.9000E+03	1.01965E-04
7.0000E+03	1.0308E-04
7.1000E+03	1.04195E-04
7.2000E+03	1.0531E-04
7.3000E+03	1.06425E-04
7.4000E+03	1.0754E-04
7.5000E+03	1.08655E-04
7.6000E+03	1.0977E-04
7.7000E+03	1.10885E-04
7.8000E+03	1.12E-04
7.9000E+03	1.13115E-04
8.0000E+03	1.1423E-04
8.1000E+03	1.15345E-04
8.2000E+03	1.1646E-04
8.3000E+03	1.17575E-04
8.4000E+03	1.1869E-04
8.5000E+03	1.19805E-04
8.6000E+03	1.2092E-04
8.7000E+03	1.22035E-04
8.8000E+03	1.2315E-04
8.9000E+03	1.24265E-04
9.0000E+03	1.2538E-04
9.1000E+03	1.26495E-04
9.2000E+03	1.2761E-04
9.3000E+03	1.28725E-04
9.4000E+03	1.2984E-04
9.5000E+03	1.30955E-04
9.6000E+03	1.3207E-04
9.7000E+03	1.33185E-04
9.8000E+03	1.343E-04
9.9000E+03	1.35415E-04
10.0000E+03	1.3653E-04

. SPECIFIC HEAT DEFINITION .

TEMP	CP
2.5000E+02	1.0037E+03
3.5000E+02	1.0037E+03
4.5000E+02	1.0037E+03
5.5000E+02	1.0037E+03
6.5000E+02	1.0037E+03
7.5000E+02	1.0037E+03
8.5000E+02	1.0037E+03
9.5000E+02	1.0037E+03
1.0000E+03	1.0037E+03
1.1000E+03	1.0037E+03
1.2000E+03	1.0037E+03
1.3000E+03	1.0037E+03
1.4000E+03	1.0037E+03
1.5000E+03	1.0037E+03
1.6000E+03	1.0037E+03
1.7000E+03	1.0037E+03
1.8000E+03	1.0037E+03
1.9000E+03	1.0037E+03
2.0000E+03	1.0037E+03
2.1000E+03	1.0037E+03
2.2000E+03	1.0037E+03
2.3000E+03	1.0037E+03
2.4000E+03	1.0037E+03
2.5000E+03	1.0037E+03
2.6000E+03	1.0037E+03
2.7000E+03	1.0037E+03
2.8000E+03	1.0037E+03
2.9000E+03	1.0037E+03
3.0000E+03	1.0037E+03
3.1000E+03	1.0037E+03
3.2000E+03	1.0037E+03
3.3000E+03	1.0037E+03
3.4000E+03	1.0037E+03
3.5000E+03	1.0037E+03
3.6000E+03	1.0037E+03
3.7000E+03	1.0037E+03
3.8000E+03	1.0037E+03
3.9000E+03	1.0037E+03
4.0000E+03	1.0037E+03
4.1000E+03	1.0037E+03
4.2000E+03	1.0037E+03
4.3000E+03	1.0037E+03
4.4000E+03	1.0037E+03
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5.6000E+03	1.0037E+03
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6.1000E+03	1.0037E+03
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6.4000E+03	1.0037E+03
6.5000E+03	1.0037E+03
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6.9000E+03	1.0037E+03
7.0000E+03	1.0037E+03
7.1000E+03	1.0037E+03
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10.0000E+03	1.0037E+03

ENTHALPY REFERENCE TEMPERATURE = 2.7300E+02

. THERMAL CONDUCTIVITY DEFINITION .

TEMP	K
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3.5000E+02	2.6240E-02
4.5000E+02	3.0030E-02
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1.8000E+03	6.9200E-02
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2.6000E+03	8.5200E-02
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2.9000E+03	9.1200E-02
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3.1000E+03	9.5200E-02
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9.8000E+03	22.9200E-02
9.9000E+03	23.1200E-02
10.0000E+03	23.3200E-02

SOLUTION CONTROL PARAMETERS

SOLVER MARCHING DIR. . . . . Z-DIRECTION
SWEEP DIR. . . . . Z-DIRECTION
ALTERNATE SWEEP DIR. . . . . YES
SOLVER ACCUMULATED SWEEP FACTOR . . . . . 1.00
SOLUTION METHOD . . . . . SIMPLE
PATCH OPTION . . . . . NO
CONVERG/DIVERG CHECK . . . . . YES
NORMALIZE RESIDS . . . . . YES
CONTINUITY CHECK . . . . . YES
RESET OPTION . . . . . NO
REYNOLDS STRESS MODEL . . . . . NO
MONITOR SOLVER . . . . . YES
COMPRESSIBLE FLOW . . . . . YES
COMP. TVAR. VIS. TERMS . . . . . NO
VISCOSUS DISSIPATION . . . . . NO
BLOCK CORRECTION . . . . . NO

SECOND RELAXATION FACTORS ON AFTER 32000 ITERATIONS

DIFFERENCING SCHEME . . . . . POWER LAW
FIXED PRESSURE BOUNDARIES ARE ACTIVE

ZERO PRESSURE GRADIENT CYCLIC CELLS SPECIFIED

Table with columns: VARIABLE, SOLVED, NO. SWEEPS, UNDERRELAX 1, UNDERRELAX 2, RESIDUAL AT 23405 ITERATIONS. Rows include PRESSURE, U-VELOCITY, V-VELOCITY, W-TURB. V. COEFF., KENTHALDLY, BLOCKCOR., PROPERTIES, VISCOSITY, TEMPERATURE.

FLOW FIELD AFTER 23405 ITERATIONS..

K = 2 FOR U-VELOCITY (STAGGERED) (UNITS = METRES/SEC)

Large data table with columns J= (1-5) and rows for U-VELOCITY, V-VELOCITY, W-VELOCITY, KENTHALDLY, BLOCKCOR., PROPERTIES, VISCOSITY, TEMPERATURE. Each cell contains a value in scientific notation (e.g., 0.00E+00, 1.80E+02).







































































































J	1	2	3	4	5	6	7	8	9	10	11	12
21	2.70E+02											
20	2.70E+02											
19	2.70E+02											
18	2.70E+02											
17	2.70E+02											
16	2.70E+02											
15	2.70E+02											
14	2.70E+02											
13	2.70E+02											
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8	2.70E+02											
7	2.70E+02											
6	2.70E+02											
5	2.70E+02											
4	2.70E+02											
3	2.70E+02											
2	2.70E+02											
1	2.70E+02											

K = 5 FOR TEMPERATURE (UNITS = KELVIN)



























Data file for initial model; high temperature condition



























```

NNNNNN
+00000
WWWEE
77777
...
22222

```

```

NNNNNN
+++++
WWWEE
44444
...
88888

```

```

NNNNNN
+00000
WWWEE
40040
...
44444

```

```

654321
11111

```

Data file modified cooling tube; high temperature condition













































## APPENDIX 2

### Published material

Penlington, R. Sarwar, M. Marshall, G.W. Cockerham, G.  
Lewis, D.B.

Material Requirements for Narrow Neck Press and Blow Plungers  
Within the Glass Container Industry.

Key Engineering Materials 86-87 1993 pp55-60

Penlington, R. Sarwar, M. Marshall, G.W. Lewis, D.B.  
Cockerham, G.

Wear Mechanisms in Narrow Neck Press and Blow Plungers

Proceedings of the Second Conference of the European Society  
of Glass Science and Technology. 'Fundamentals of Glass  
Science and Technology' Venice, Italy, 21-24 June 1993  
pp279-284

Penlington, R. Marshall, G.W. Lewis, D.B. Sarwar, M.

The Wear of Coatings Used on Glass Manufacturing Equipment.

EAST-Report 1993 'New Materials and Technologies in Surface  
Finishing For Better Corrosion and Tribology Properties'  
pp86-90

IRISH MATERIALS FORUM CONFERENCE - IMF 8

ENGINEERED MATERIALS

**MATERIAL REQUIREMENTS FOR NARROW NECK  
PRESS & BLOW PLUNGERS WITHIN THE GLASS  
CONTAINER INDUSTRY**

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# **MATERIAL REQUIREMENTS FOR NARROW NECK PRESS & BLOW PLUNGERS WITHIN THE GLASS CONTAINER INDUSTRY**

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M Sarwar  
G W Marshall  
G Cockerham  
School of Engineering  
D B Lewis  
Materials Research Institute  
Sheffield Hallam University

## **ABSTRACT**

Plain carbon steel plungers hardfaced with a nickel based powder alloy are used for the narrow neck press and blow process in the glass container industry. This process has become significant as advances in 'lightweighting' and reductions in production cycle times have allowed glass containers to remain competitive with other container materials and technologies.

The plunger operates in an aggressive environment involving temperature cycling and sliding contact with hot abrasive glass, resulting in high wear rates.

This paper outlines the properties required of narrow neck press and blow plungers. Typical characteristics of those materials most commonly used are discussed, and identifying wear modes unique within the container forming equipment are discussed. The potential for improvement in plunger performance to reduce: ware defects, machine downtime, plunger maintenance and their associated costs is highlighted.

## **INTRODUCTION**

The press and blow, and its more recent derivative the narrow neck press and blow (NNPB) processes are methods commonly used for the production of glass containers. Their advantage over the traditional blow and blow process is that as a plunger, rather than an air bubble, forms the internal cavity during the blank forming stage, this assures the accurate distribution of the glass within the mould cavity. This allows containers to be designed to tighter tolerances, the mass of glass in each container to be reduced, and production speeds to be increased.

In this process the hot glass enters the blank mould cavity at a temperature of c1200° C. The mould cavity is closed and the plunger is forced by a low pressure pneumatic cylinder upwards into the molten glass, this forces the glass into all the features of the blank mould cavity, thus forming the parison. The plunger is withdrawn when the mould equipment has removed sufficient heat from the surface of the glass to lower its viscosity, forming a surface skin, which will support the form of the parison as it is inverted for the second stage of the forming process. It is essential that no reaction occurs at the metal/glass interface which will cause adhesion.

As the plunger enters the glass there is rapid heat transfer from the glass to the plunger surface, and heat is then transferred through the plunger wall and removed by cooling air passing through the internal bore. Heat transfer is required at the base of the plunger as this forms the neck of the ware which is fully formed at this stage, but is only required towards the tip of the plunger to prevent overheating and the tendency of the glass to adhere to the plunger causing defects known as spikes in the finished ware.

As the NNPB plunger is withdrawn from the glass there is considerable sliding contact between the hot surface of the plunger and the skin formed on the glass. This is due to the shallow taper  $c1-1.5^\circ$  along the length of NNPB plungers.

## CHARACTERISATION

NNPB plungers, figure 1, are produced by turning and profiling plain carbon steel bar which is then given a wear and corrosion resistant surface coating, which will be in contact with the hot glass, before final machining to size.

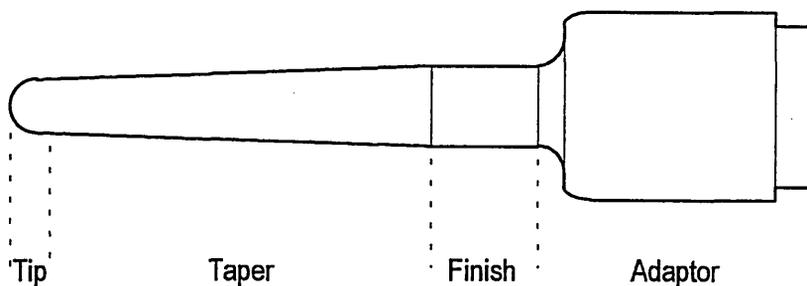
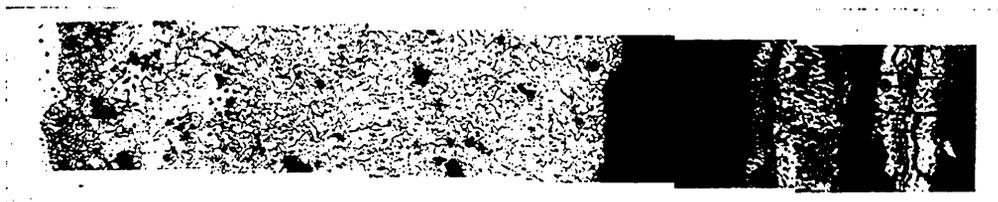


Figure 1 NNPB plunger

The steel substrate (B.S. 970: 080-A40) has a composition as follows:

element	C	Si	Mn	S	P	Fe
mass %	0.36-0.44	0.05-0.35	0.60-1.00	0.060 max	0.060 max	Balance

The microstructure shows evidence of grain growth and spheroidation in the region where most wear occurs, figure 2. This micro structure suggests that the substrate is operating at temperatures just below the  $\alpha/\gamma$  phase transformation temperature.



(a)

(b)

Figure 2 micrograph of (a) substrate grain structure and (b) oxide layer

The hard faced coating is obtained by spraying suitable Ni based powders onto the substrate which are then fused to produce the desired coating. The specification of the powder used in this process differs from that used to produce similar coatings on the other mould equipment and is given below;

element	C	Si	B	Fe	Cr	Ni
mass %	0.2-0.3	3.2-3.8	1.5-1.8	1.8-3.2	6.9-8.2	Balance

The particle size distribution is within the range 38 - 106mm and the particles are spherical in form. figure 3.

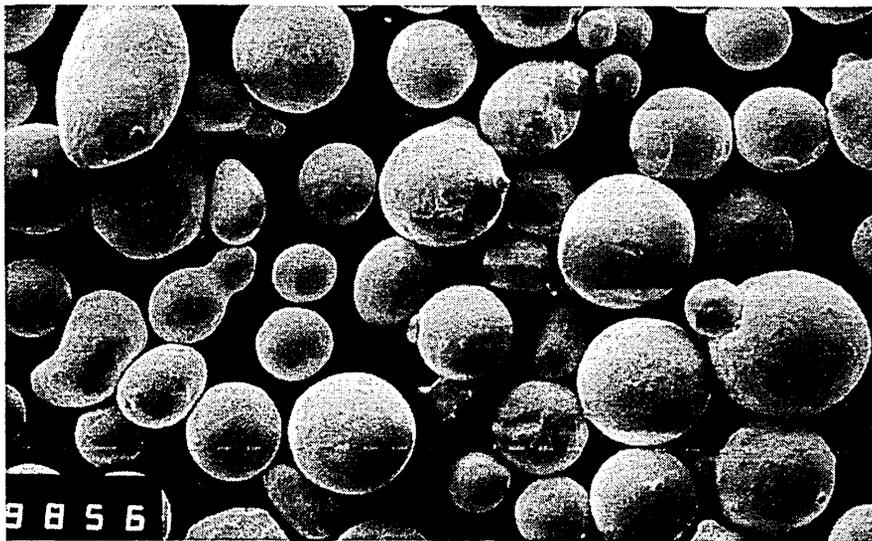


Figure 3 Ni-Cr-B-Si powder particles

The powders are applied to the steel substrate carried by an aspirating gas from an oxyacetylene thermo- spray gun. The required coating thickness builds up as a semi-molten deposit as shown in figure 4. This is then fused in a secondary and separate stage using a second oxyacetylene torch.

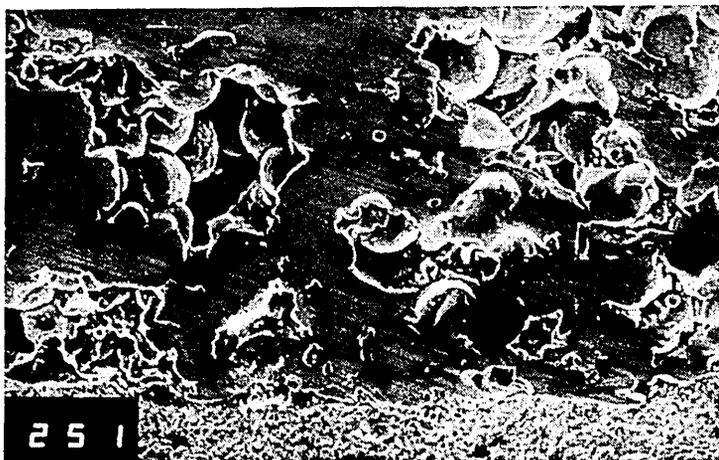


Figure 4 unfused coating deposit

These alloys are based upon a Ni-Cr-Si-B system which upon fusing form boride compounds in a nickel matrix. The borides increase the hardness of the deposit but lower the melting point of the alloy to allow fusing of the coating to take place at around 1100°C. The Si is present to form SiO<sub>2</sub>, upon contact with the substrate, which aids coalescence and bonding. The nickel and chromium provide good oxidation resistance up to 950°C and good low stress abrasion (sliding wear without impact) resistance at low temperatures.

Porosity is present in these coatings. This defect is caused by a number of factors and is exceedingly detrimental to the coating's performance. The application of the powder material and its subsequent fusion are critical factors in the formation of porosity. During the initial laying down of the alloy the packing of the particles and their size distribution may inhibit full fusion and densification of the deposit. This may be the cause of the inter-granular porosity observed, figure 5. The control of the fusion of the deposits is also a major factor in the resultant levels of porosity. Sufficient energy must be applied for the material to flow into the spaces between the powder particles and to allow any changes of state required to form a solid film. Owing to the geometry of the plungers any material flow must take place on a micro scale allowing densification and not on a macro scale which would tend to cause runs in the coating, since such runs give rise to variations in coating thickness. During fusing there may also be gas evolution from the substrate or entrapped combustion products from the fusion flame. The voids resulting from such a process can be seen in figure 6. Following the fusion process the plungers are allowed to cool at room temperature prior to finish machining to the required profile.

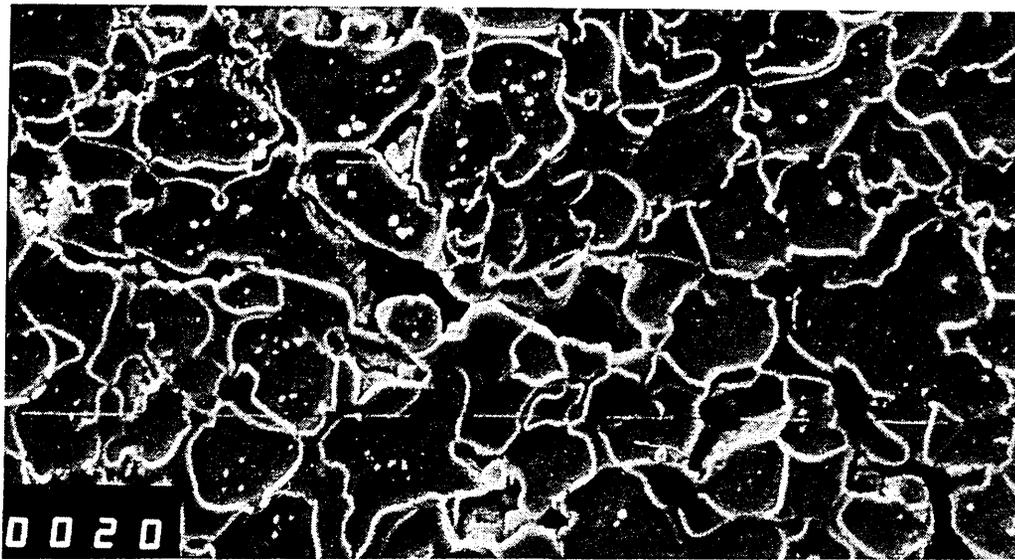


Figure 5 intergranular porosity in coating

The main deficiencies in current NNPB plunger performance are; high wear rates, plunger material being released into the glass and plunger distortion.

From this study it has been found that these deficiencies are interrelated, and to some extent can all be linked to the heat transfer performance and geometry of the NNPB plunger. The ideal material for this application would transfer heat rapidly enough to

prevent temperature build up but not so rapid so as to cause excessive chilling of the glass surface.

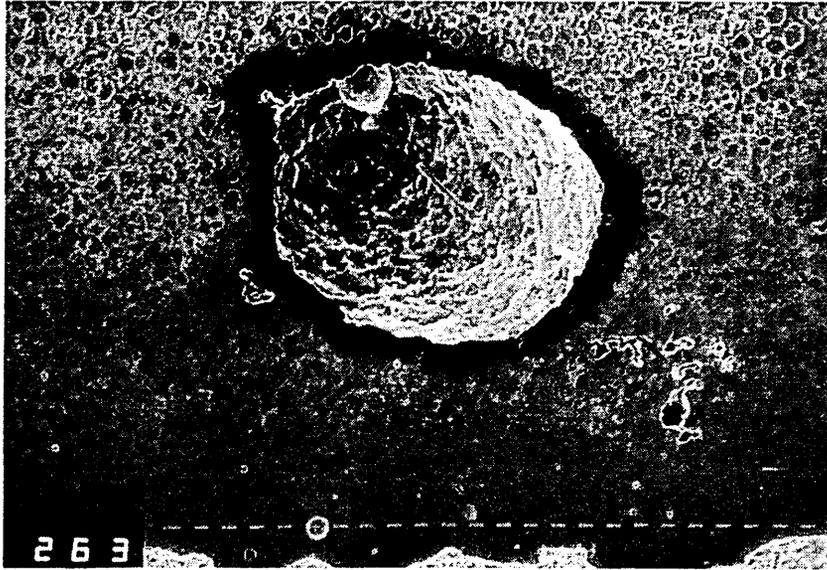


Figure 6 entrapped gas porosity

There are four recognisable factors affecting the rate of heat transfer through the plunger wall and into the cooling medium:

- i. The thermal conductivity of the plunger materials, and heat transfer coefficients at their interfaces.
- ii. Efficiency of the internal cooling system,
- iii. Plunger wall thickness,
- iv. Material inconsistencies which form a thermal barrier, this may be porosity in the coating or corrosion of the internal bore.

The first of these factors is a function of the condition of the materials used and is only one factor in the overall material properties required to satisfy this application.

The internal cooling system consists of a perforated narrow bore tube inserted into the full length of the plunger bore through which air is passed over the internal surface of the plunger. The air is only applied for a portion of the container forming cycle to prevent inadvertent chilling of the glass surface. The efficiency of this cooling process is dependent upon the volume flow rate of the air, the cross sectional area of the cooling tube and the plunger, the direction of the flow, any disturbance to the flow, and the initial temperature of the air. Little is known about the local surface temperature conditions during the forming of the parison due to the location and motion of the NNPB plunger.

NNPB plunger wall thickness is derived from a requirement for sufficient distortion resistance whilst allowing maximum heat transfer, and current practice is for a combined wall thicknesses of 2.5-3.5 mm. The plunger is screw mounted onto its operating cylinder vertically below the blank forming side of the IS. machine. During the operation of the machine there is some tendency for play to develop at the point of

attachment and for the plunger to distort due to the subsequent uneven loading, illustrated by wear to the neck ring. It may also be the case that misalignment of the cooling tube, which is easily bent during its installation, may cause a temperature imbalance around the circumference of the plunger leading to a tendency to bend due to the differential expansion in the longitudinal direction. Another, although possibly avoidable, problem with distortion occurs during the machining of the plunger, the bore and external profile must be concentric for even heat transfer but distortion caused by the cutting forces may prevent this from occurring.

The most serious factors affecting heat transfer are material features which form small thermal barriers. These appear in the form of voids in the coating and as cracks between the substrate and the oxide layer which forms on the internal bore, This can be seen in figure 2, There is no protection against the moisture inherent within the cooling air. The oxide layer is at its thickest at the hot spots, where due to its effect of reducing heat transfer it may cause an increase in the temperature differential between these areas and the rest of the NNPB plunger.

Wear damage on NNPB plungers appears as longitudinal gouges initiated at hemispherical cavities. These are most heavily concentrated in the upper third of the plunger's length. All wear damage indicates that the removal of the plunger from the glass is the most critical part of the forming cycle, as material flow is unidirectional and low wear rates are experienced on the tip of the plunger. Figure 7 shows the wear on the length of the plunger and figure 8 the wear on the tip of the plunger.



Figure 10 tip: matrix deformation

From examination of the wear pattern of NNPB plungers it has become evident that the wear is very dependent upon the temperature of the coating and substrate. The plunger temperature reaches a maximum at a point a little way below the tip and just before it is withdrawn from the glass, at which time the glass is also at its least viscous. The temperature at this time appears to far exceed published values<sup>[1,2]</sup> of 500-580°C. A value in the order of 800-900°C is expected to be reached at the glass contact surface and a temperature exceeding 700°C at the bore. The high rates of wear occur

because the coating material does not retain its hardness at these temperatures Figure 9. There appears to be a softening of the matrix allowing groups of the harder borides to be plucked from the surface. This may occur at areas weakened by subsurface porosity or areas showing poor fusion. When a cavity has been formed subsequent machine cycles will force hot glass into the cavity which will then become less viscous and gouge a channel in the coating as the plunger is withdrawn. Figures 10 & 11.

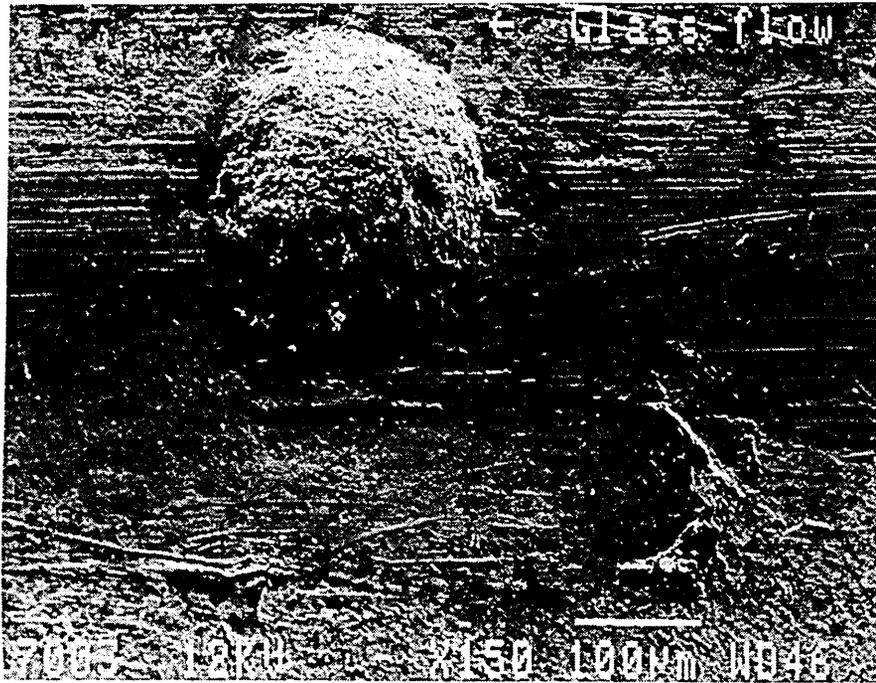


Figure 11 taper section: scoring and cratering

Examination of the machined surface of the plunger coating prior to use shows some similar features to those of a worn surface. The surface shows the nickel smeared rather than cut with identifiable cavities, subsurface weaknesses and displaced hard particles causing a torn surface. These surfaces visually appear to have a high polish but examination by scanning electron microscopy shows the poor integrity of the surface, figures 10 & 11. These surface features allow the initiation of wear despite their apparently smooth optical appearance. The surface roughness measurements obtained are Ra  $0.7\mu\text{m}$ , Rt  $6.5\mu\text{m}$ , measured parallel to glass flow. Worn plunger surfaces give results of Ra  $0.6\text{--}4.2\mu\text{m}$  and Rt  $8\text{--}75\mu\text{m}$ .

The deterioration of the NNPB plunger coating has a serious effect upon the ware produced, a recognise quality defect called black speck. Flakes of coating material with dimensions of  $0.01\text{--}0.5\text{mm}$ [3] act as stress raisers on the internal surface of the container reducing resistance to bursting and side impact.

Other materials are used for NNPB plungers, cast iron as a substrate, cobalt based powder alloys and tungsten carbide as a constituent of spray and fuse coatings. With these materials costs are increased but, although reduced, the same wear conditions exist. Solid cast plungers of Ni-Cr-B-Si alloys are available, these are expensive, avoid the problems of porosity and internal oxidation but cooling, sliding contact with the hot glass and material softening problems still exist.

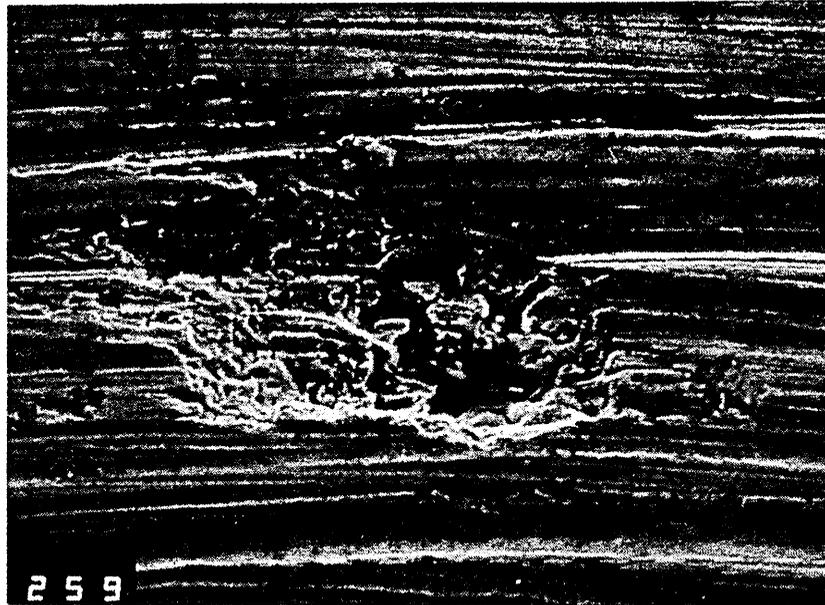


Figure 12 machined surface smearing

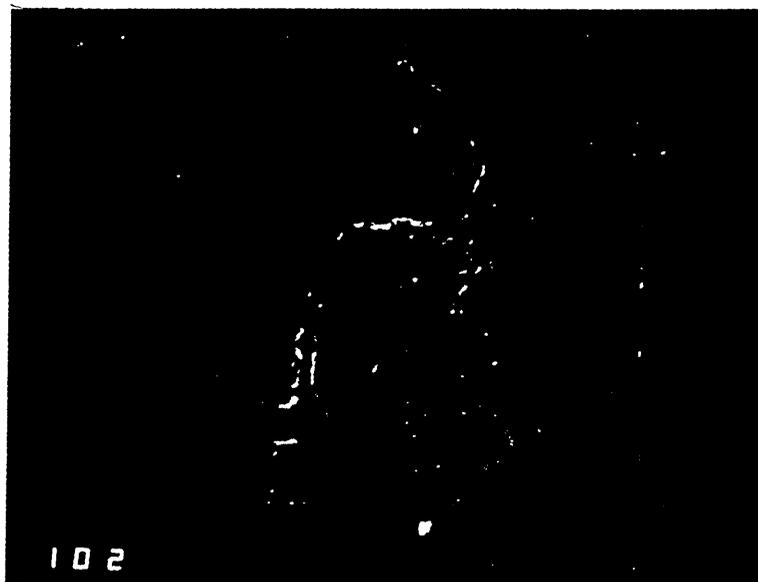


Figure 13 subsurface defects

This examination has shown that there exist some considerable deficiencies in the performance of NNPB plungers. These have occurred because the working environment of this tooling is not fully understood. Examination of the thermal, atmospheric and material contact conditions with respect to NNPB plungers within the NNPB forming process must be carried out to allow a re-evaluation of material selection criteria. This will enable satisfactory NNPB plunger performance to be obtained as existing technology in glass mould tooling cannot be transferred to the more extreme environment of the narrow neck press and blow process.

## **ACKNOWLEDGEMENTS**

The authors would like to thank the Science and Engineering Research Council, Mr A Armitage & Mr S Baker of PLM Redfearn, and the School of Engineering Sheffield Hallam University for their assistance in the preparation of this paper.

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2. Kent, R. Mould temperature and heat flux measurement and the control of heat transfer during the production of glass containers. IEEE. Transactions on Industry Applications, Vol.1A-12. 4, July/August 1976,
3. Wasylyk, J.S. AGRAPSIP Targets container-performance-limiting factors Glass Industry, April 1991

**EUROPEAN SOCIETY OF GLASS SCIENCE AND  
TECHNOLOGY**

**2<sup>ND</sup> International Conference on Fundamentals of Glass  
Science and Technology**

**WEAR MECHANISMS IN NARROW NECK  
PRESS AND BLOW PLUNGERS**

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# WEAR MECHANISMS IN NARROW NECK PRESS AND BLOW PLUNGERS

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## INTRODUCTION

The narrow neck press and blow (NNPB) plunger utilising a plain carbon steel substrate coated with a Ni-Cr-Si-B powder alloy is standard tooling for the production of thin-walled narrow neck containers within the glass industry.

Following the historic use of these coatings with plungers for wide mouth containers and for other glass contact surfaces. These materials continue to be employed owing to their ease of manufacture.

With increasing production speeds and reductions in container weight the demands in performance upon the NNPB plunger have increased. With corresponding increases in wear rates experienced a fundamental reappraisal of the NNPB plunger is required.

This paper outlines the wear modes evident in NNPB plungers, and shows their relationship to plunger materials and operating conditions.

## PLUNGER MATERIALS

Substrate:

The NNPB plungers examined during this study employ a plain carbon steel substrate (BS. 970:080 - A40) with the following specified nominal composition.

element	C	Si	Mn	S	P	Fe
mass%	0.36-0.44	0.05-0.35	0.60-1.00	0.060 max	0.060 max	Balance

The microstructure of the unused plunger shows a ferrite/pearlite microstructure typical of a normalised steel. This material is used on account of its machinability and because a better coating adhesion and integrity is obtainable compared to the cast iron substrates previously employed.

## COATING

The coating system currently used for NNPB plungers is a powder alloy weld coating based upon nickel alloys. The Ni-Cr-Si-B powder alloy has a nominal composition as shown below.

element	C	Si	B	Fe	Cr	Ni
mass %	0.2-0.3	3.2-3.8	1.5-1.8	1.8-3.2	6.9-8.2	Balance

The metallurgical study of these coatings by Knotek<sup>(1,2,3)</sup> and others<sup>(4)</sup> highlighted some of the benefits of these coatings, resistance to wetting by hot glass, ease of application and ability to hand finish, and resistance to the effects of corrosion and abrasion by hot glass.

The composition and elemental distribution within these coatings and their characteristics under laboratory conditions have been reported by Knotek<sup>(3)</sup> and are confirmed by this study.

The additions of boron and silicon to the nickel alloy lower the melting point and allow fusion by oxyacetylene torch. The nickel and boron form a Ni - Ni<sub>3</sub>B eutectic at 1083°C, and the addition of silicon further lowers the eutectic temperature by combining with the surface oxides on powders to form borosilicates. The presence of Ni<sub>3</sub>B has been confirmed, in the current work, by X-ray diffraction. Examination of the coating by Scanning Electron Microscopy showed the presence of fine particles within the eutectic regions. Electron Probe Microanalysis showed these were rich in the elements boron and silicon thus indicating the presence of borosilicates within the eutectic. As the solubility of boron in nickel is low (c0.1 wt%), the abrasion resistance of these alloys is a function of the hard borides (nickel borides) and carbides (chromium carbide) present.

## WEAR MODES

The NNPB plunger operates in an environment of cycling temperatures and sliding contact with hot abrasive glass. Because of this, wear rates can be high and rise significantly as machine speeds increase.

A study of characteristics of the failure modes exhibited by NNPB plungers has identified three differing wear situations.

1. Wear at the tip of the plunger showed heat affected deformation of the coating material with the matrix deforming around the harder borides and carbides.
2. The shallow tapered portion of the plunger is subject to high rates of wear.
3. A previously unreported contribution to the above wear modes is the formation of an oxide layer on the internal bore of the NNPB plunger. This oxide layer exacerbates the thermal properties of the plunger.

## TIP WEAR

The surface of a worn plunger tip is characterised by areas of as machined surface surrounded by areas of deformed coating exposing the hard particles. The failure mode associated with plunger tips is the pulling of spikes in the base of a container. Spikes are caused by glass adhering to the plunger and their being lifted during the extraction of the plunger. It was thought that spikes were caused by plungers exceeding the temperature at which glass 'wets' the surface but estimates of plunger surface temperatures obtained from analysis of Infrared images suggests that the tip operates at a lower temperature than some areas on the taper. Examination of the surfaces by Scanning Electron Microscopy have shown glass adhered to the plunger tip but not as expected in the cavities (Plate 1). Knotek & Steine<sup>(3)</sup> reported the temperature related elemental distribution at the coating surface. They reported an enrichment of silicon at the tip operating temperatures estimated from the infrared analysis. Furthermore in the current work energy dispersive X-ray analysis indicated a surface richer than expected in silicon and oxygen in areas adjacent to the adhered glass. This suggests that the wetting of the surface is a chemical and not mechanical or temperature-related phenomenon, and occurs in this region because low material removal rates allow the redistribution of constituent elements which give rise to areas having high concentrations of these elements.

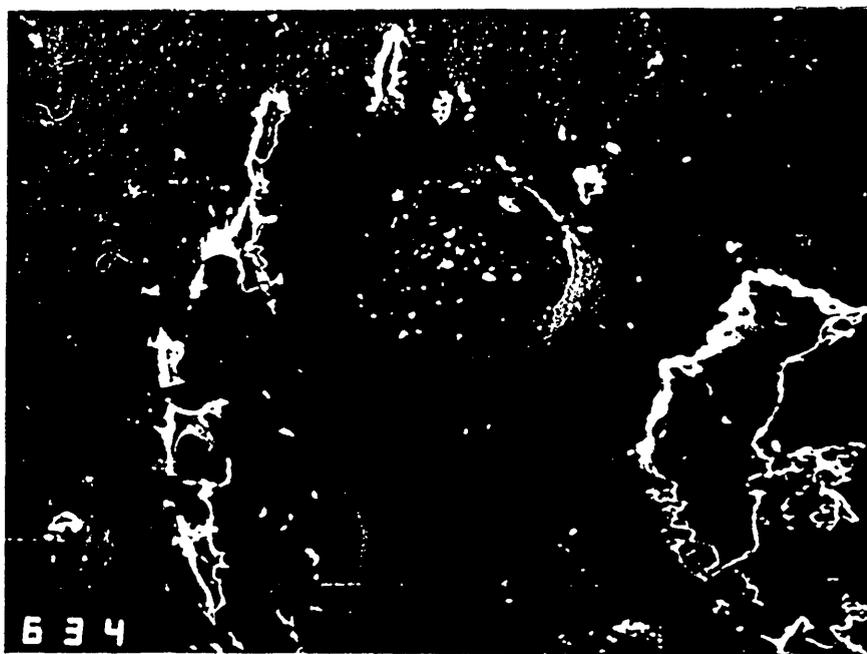


Plate 1

## TAPER WEAR

Taper wear is the primary form of material removal from the plunger surface. The classic wear feature is known as 'Comet tail', a characteristic abrasive wear scar, although there is also some evidence of surface micro cracking.

The worn surface as described above has two distinctive features:

- 'Comet tails', craters and abrasive wear scars, showing considerable material removal as the plunger is withdrawn from the glass.
- Surface micro cracking. The areas of surface micro cracking which tend to exist around the craters and particularly opposite the abrasive wear scar take on the form and dimensions of the particle distribution within the coating.

Thermal analysis of NNPB plungers during the forming cycle has shown that previously reported<sup>(6,7)</sup> operating temperatures of 500 - 550°C are far from correct. Using Infrared image analysis surface temperatures have been shown to range from around 600°C to above 800°C. This is supported by Knotek<sup>(8)</sup> who noted the absence of an oxide layer at 800°C. This can be observed on the operating NNPB plunger as a bright radiating band with a glazed and molten appearance.

With a more representative knowledge of NNPB plunger operating temperatures the nature of the plunger wear pattern is easier to understand.

By consideration of the hot hardness graph, Figure 1. with previously reported<sup>(6,7)</sup> and predicted temperature distribution of the NNPB plunger it can be seen that the expected hardness of the coating is in the order of 250 - 280 HV whereas the actual hardness will be within the range 39 to 200 HV.

The effect of material softening can be seen with the initiation of cracks around a clump of hard particles. Evidence suggests that such clumps of the hard particles are pulled from the surface by the cooled inner surface of the parison and then, held in this viscous skin, are dragged along the softened plunger surface as it is withdrawn from the glass. Coating material is removed from the surface of the plunger in sufficient quantity to cause a stress concentrating defect in

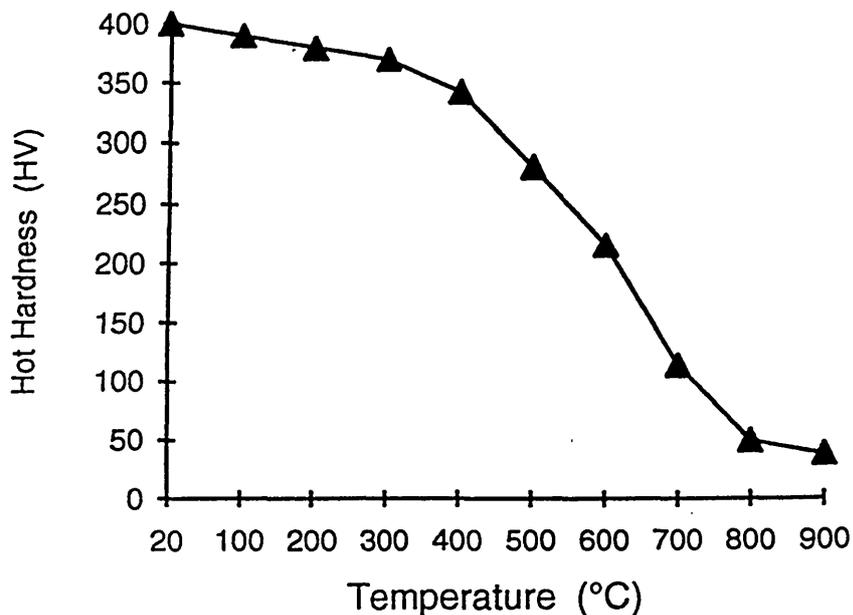


Figure 1

containers known as 'black speck'<sup>(5,6,7)</sup>. This is a small (0.01 - 0.5mm) particle of plunger material found on the inside of containers.

This explains why this wear mode does not exist in wide mouth press and blow plungers which operate at slightly lower temperatures and are heavily tapered which causes the glass to be released from the surface rather than being drawn along it.

#### INTERNAL OXIDE

The formation of oxide on the surface of the internal bore of the plunger (Plate 2) is not in itself a failure mode until it is sufficiently thick as to damage the cooling tube or prevent cooling air flow. Prior to reaching these proportions it will act as a thermal barrier, preventing heat flow from the plunger body to the cooling air. This causes the temperature of the plunger to rise towards that of the glass surface, c1000°C. At these temperatures the material removal rate from the external surface of the plunger will be very high resulting in such frequent repairs that the plunger is removed from service.



substrate

oxide

Plate 2

#### CONCLUSION

This study has identified the primary wear modes in NNPB plungers. These have highlighted deficiencies in the material properties particularly in relation to the operating temperature at the glass contact surface. Wear may be reduced by the use of an oxidation resistant coating within the bore of the plunger but to achieve a substantial reduction in wear rates a coating/substrate system must be employed which retains its coherent properties at the temperatures encountered at the glass contact surface. A full understanding of the thermal requirements at the NNPB plunger would allow a proficient selection of plunger materials.

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**New Materials and Technologies in Surface Finishing for Better  
Corrosion and Tribology Properties**

**The Wear of Coatings Used on Glass  
Manufacturing Equipment**

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# THE WEAR OF COATINGS USED ON GLASS MANUFACTURING EQUIPMENT

## ABSTRACT

The introduction of the narrow neck press and blow (NNPB) process in the glass container industry to produce lighter products has led to severe wear problems. These problems are associated with wear on the outer surface of the plunger where it comes into contact with the molten glass. Attempts to solve this problem have been made on an 'ad hoc' basis. This paper analyses the factors giving rise to surface wear under cyclic temperature changes under the fast heat transfer condition brought about by the forced air cooling of the plunger's inner surface. Potentially suitable wear resistant coatings are discussed for use on carbon steel plungers. The results of detailed studies of wear in flame sprayed nickel-chromium-silicon-boron coatings are presented. These show that the wear temperature is greater than previously thought and that this may be due to the occurrence of oxidation of the inner surface of the plungers. The use of electroless coatings on the inner surface to prevent this corrosion in order to reduce the wear temperature and hence the wear of the coating on the outer surface is discussed.

## INTRODUCTION

The requirements for glass containers having thin walls and closer dimensional tolerances led to the introduction of the narrow neck press and blow process in the late sixties. The steps involved in the process are shown in Figure 1. A gob of glass drops into the top end of a two piece split mould onto the tip of a plunger before a baffle closes the open end of the mould.

The plunger is then raised into the mould forming the glass gob into a suitably shaped and proportioned parison as it does so. Cold compressed air passed through a tube into the hollow plunger to maintain a suitable working temperature. The plunger is then withdrawn and the mould inverted. The glass parison is then forced to take up the desired profile of the container in the blow mould by air passed under pressure into the cavity made by the plunger.

Figure 2 shows how press and blow plunger design has evolved from the wide mouth to narrow neck plunger. The economics of glass container production has led to developments being concentrated upon increasing production speeds and reducing material weight in containers of a given capacity (1,2). The narrow necked press and blow plunger (NNPB) employed today has a long slender form and has allowed container weight reductions of 15 to 30% and increased production speeds of 15 to 25% (3). As the cost of the glass accounts for 33% of container production costs the economic importance of the NNPB process can clearly be seen (4).

As container production speeds have increased and defect rates have been reduced the cost of mould equipment has risen. Ensor gave the latter as 2% of

production costs in 1960 rising to 5% in 1970 (5). Sidler considered this cost to have reached 9.7% by 1988 (4).

Traditionally glass container moulds were manufactured from grey cast iron on account of its low cost, reasonable machinability, thermal conductivity and wear properties. However the increased demands made upon the mould equipment materials as a result of higher production rates has led to a search for alternative materials or suitable surface coatings. Nickel and nickel alloys (6,7) aluminium bronze (8) and stainless steel (9) have all been considered as alternative materials for use in the manufacture of moulds and associated equipment.

Sugg (10) considered the advantages of the use of surface coatings for glass moulding equipment to be:

- i. better release properties between the mould and glass surfaces,
- ii. the reduction in container defects,
- iii. increased wear and corrosion resistance,
- iv. decrease in mould tooling costs.

Hard chromium plated coatings have been used to increase the life of moulds (and surface quality) of glass crystal products by a factor of 2 to 3 times (11). Klein has similarly reported upon the use of electroless nickel-boron coatings on glass moulding equipment (12). However the use of electroless coatings appears to have gone out of favour in recent times on account of their susceptibility to impact damage during the physical handling of the tooling production. The most widely applied coating to the glass moulds in the glass container forming industry are Ni-Cr-Si-B powder sprayed coatings and have been found to be particularly useful in reducing plunger wear (13). Coatings containing tungsten carbide particles coated onto stainless steel plungers have recently become available in the U.S.A and are now being introduced to Europe. A problem resulting from the hardness of these coatings is the difficulty of repolishing them once they have lost their initial finish due to surface wear during container production (14) and also loss of the hard particles into the glass causing low strength containers (7).

Plunger wear is one of the most significant forms of mould tooling wear in relation to the light weight glass container manufacturing process. It has been noted that NNPB plungers are subjected to significantly higher rates of wear than wide mouthed plungers. Where such high rates of wear are encountered production time is lost when the forming machine section is stopped to allow the worn plungers to be replaced and during the time taken for the equipment to regain its operating temperature. It is therefore surprising that this aspect is not in itself the subject of much information in the literature. Seidel has given a detailed account of the process but dealt neither with the thermal properties nor wear characteristics of NNPB plungers. Recent work has established that two modes of plunger wear occur relatively high rates on a portion of their tapered sections and at their tips associated with the simultaneous formation of spike defects on the inner surfaces of the glass containers as they are formed (16). Coating material lost through the wear of the taper portion of the plunger is adhered to the internal surface of the parison resulting in internal container defects. The significance of such surface imperfection in the glass surfaces in relation to the strength of the glass containers

has been emphasised by Winter and Schaeffer (17). Additional information is available concerning the properties of Ni-Cr-Si-B coatings. Knotek studied the surface concentrations of silicon and chromium following the oxidation of these coatings at temperatures between 600 and 800°C in the laboratories (18) whilst work has established the hot hardness of the coatings.

The object of the present work was to examine how the different factors known to affect wear related to the different types found in powder sprayed Ni-Cr-Si-B coatings on NNPB plungers with a view to establishing ways of reducing this wear.

## **Experimental Work and Results**

NNPB plungers examined were machined from plain carbon steel conforming to BS 970:080-A41. Nickel alloy coatings of nominal composition, 0.2-0.3 C, 3.2-3.8 Si, 1.5-1.8 B, 1.8-3.2 Fe, 6.9-8.2 Cr, with the balance being nickel were formed on the plungers using a two stage process. The coating material in a spherical powder form within the size range 38 - 106µm was sprayed onto freshly cleaned and grit blasted plungers using an oxyacetylene spray torch. The resulting coatings were densified using a multi-tipped oxyacetylene torch designed to spread its heat over a large area to prevent large local temperature differences and thus thermal stress. This caused the coatings formed in the first stage to fuse and on cooling produced a dense, adherent coating.

## **Temperature Measurements**

A thermal imaging system was used to study the in plant operating temperatures of the plungers. The results obtained and interpreted in conjunction with metallurgical structural information are shown in figure 3. which shows that the maximum temperature attained on different areas of the plungers varies considerably along the length of the plunger and are higher than previously reported findings (6,7).

## **Metallurgical Examination of Worn Plungers**

The surfaces and metallurgical cross-sections of plungers subjected to wear during manufacturing operations were examined using electron optical techniques.

Plungers removed from service due to their pulling spikes were examined. Traces of glass were found adhering to the tips and energy dispersive X-ray analysis (EDX) showed that the areas adjacent to these to be rich in silicon. It was not clear whether or not the latter emanated from the coating or the action of the glass on the surface. It is perhaps significant that the lumps of glass were not particularly associated with pits or pores in the metal surfaces which might been expected to have caused the glass to adhere to the surface by means of a mechanical keying effect. Clearly this was not the case.

The most significant wear was found on the tapered section of the plungers at distances between 1 and 7 centimetres from their tips. This heavy wear took the classical form of 'Comet tails' consisting of a crater associated with the abrasive scars running vertically from the craters in the direction of the plunger tips. (see

figure 4). Surface microcracking was also seen in this region, from which hard particles of material had been dragged out by the action of the glass.

The internal surface of the plungers were found to have oxidised significantly and were covered with a thick scale.

The variation in thickness of the oxide scale along the length of a plunger which showed catastrophic wear was from 0.05mm to >0.5mm. The oxide film was thickest where the plunger has worn through on the tapered section towards the tip.

Figure 5 is a composite of typical data for the variations of temperature, internal oxidation, and wear along the profile a plunger related to the operation of the glass parison and the estimated hot hardness of Ni-Cr-Si-B coating along the length of the plunger. The latter has been calculated using temperature data obtained in the present work together with that for the variation of hot hardness of Ni-Cr-Si-B coatings with temperature.

## **Discussion**

It has been recognised for some time that the plunger/glass interface temperature is fundamental to the wear mechanism operating during plunger operation since it has a major influence upon both the adhesion of glass to the metal surface and the hot hardness of the metallic surface.

The sticking of glass to the plunger is akin to physics-chemical processes by which vitreous enamels stick to metal surfaces. Thus oxidation of the metal surface results in the formation of oxide(s) which may or may not react with the glass melt depending upon the compatibility of the two. Generally the higher the temperature the greater the surface oxidation and the faster the oxidation rate the lower the temperature at which significant amounts of oxide can be formed which might then react with the glass. Whether or not, once formed, an oxide film will react with the glass melt depends upon their compositions and compatibility. Surface films rich in silicon tend to be compatible with glass - itself a silicate - and allow sticking whereas the presence of films rich in chromium oxide, incompatible with glass, tend to prevent sticking. Costa(19) took this concept further and suggested that the best way to avoiding sticking was to use either alloys with a high resistance to oxidation or non-metallic materials such as carbides and borides. The latter tend to both resist oxidation and are incompatible with glass.

The role of surface hardness in wear is well known and it is generally recognised that wear resistance is favoured by high hardness. However it must be remembered that the hot hardness value of the materials matrix may be considerably lower than that of any hard particles within the coating and also lower their value at normal temperatures.

Factors which affect the surface temperatures of plungers during their operation are the mass, temperature and distribution of the glass, its colour the speed of the container forming cycle, the heat transfer properties of the plunger materials and the effectiveness of the cooling system.

Consideration of the data in Figure 5 in the light of the above enables the mechanisms associated with the different wear modes encountered to be rationalised to a large extent.

Since the greatest mass of glass to surface area of the plunger, and hence the heat associated with it, is found around the plunger tip it might be expected that the highest temperature would be found at this point. This is clearly not the case and suggests that the plunger's cooling system is most effective in this region. The operating temperatures in this region correspond to those found to favour silicon on Ni-Cr-Si-B alloys coatings Knotek (20). Such surfaces would be expected to be compatible with glass melts and would explain the tendency of the plunger tips to stick to the parison giving rise to spikes in the inner surfaces of containers.

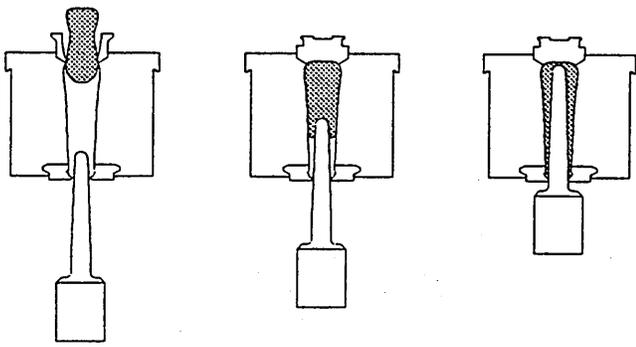
The region of the plunger showing the highest temperatures is that of the tapered section showing the highest wear rates. The mass of glass to surface area is only slightly less here than at the tip and might, as observed, be expected to lead to high surface temperatures. The high temperatures in this region clearly give rise to high rates of oxidation of the internal surface of the plungers at this point. This would be expected to further enhance the effects of the poor efficiency of the cooling system since the oxides have a lower thermal conductivity than that of the metal form from which they have been formed. It is probable that the rate of wear of plungers in this region increases with increased use and hence internal oxidation. Further work would be necessary to confirm this point. It must be assumed that the plunger's cooling system is less efficient in this section than in the region of the tip to allow the attainment of such high operating temperatures. These high temperatures cause the coating to soften with the result that hard boride and carbide particles are caught in the viscous glass melt and dragged out and along the surface of the coating causing further abrasive wear as the plunger is withdrawn. The material caught up in the parison is probably the source of the defect commonly called 'black speck' and seen on the inner surfaces of finished containers. These defects cause stress concentrations in the walls of the containers. Finally it is worth noting that the temperatures found in this region of high wear to correspond to those giving rise to chromium rich surfaces in Ni-Cr-Si-B coatings which would not encourage the glass to stick as in the case of the silicon rich surfaces found in the region of the plunger tips.

It would appear that the design and efficiency of the NNPB plunger cooling systems are of prime importance in relation to the operating temperatures attained at different points on the plunger and hence rate and wear modes associated with different areas. Clearly the cooling system needs to be redesigned to ensure a greater rate of cooling in that area presently subjected to high wear rates. A further improvement might be to prevent or reduce oxidation of the inner surface of the plungers by applying a suitable coating. The difficulty of applying such internal coatings suggests that only electroless nickel-boron coatings of the readily available commercial coatings might be suitable for this purpose and are under examination. Initial results from trials with these coatings are encouraging.

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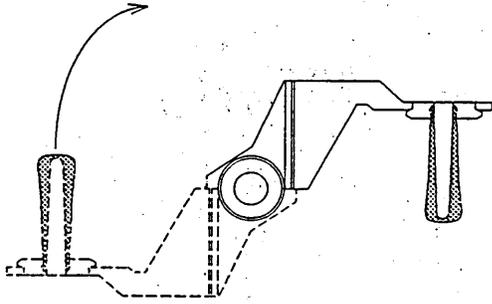
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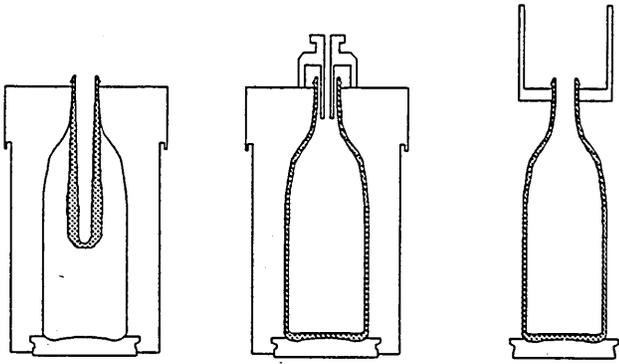


DELIVERY

PLUNGER PRESSING STROKE



PARISON INVERT



REHEAT

FINAL BLOW

TAKEOUT

Figure 1.  
The narrow neck press and blow process

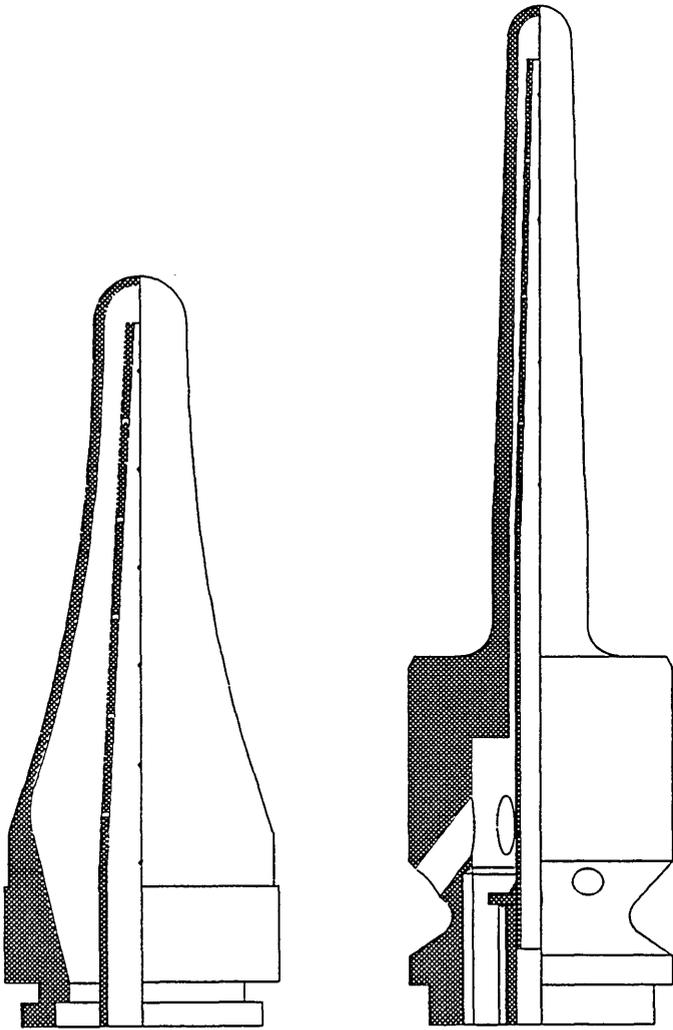


Figure 2.  
Wide mouth and narrow neck press & blow  
plungers showing cooling tube position.

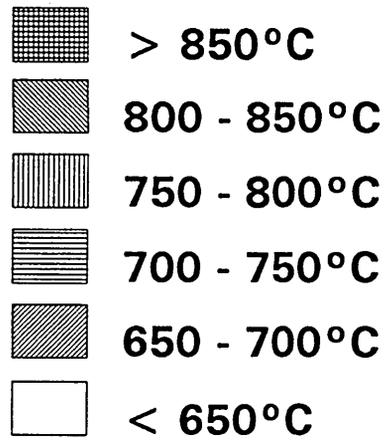
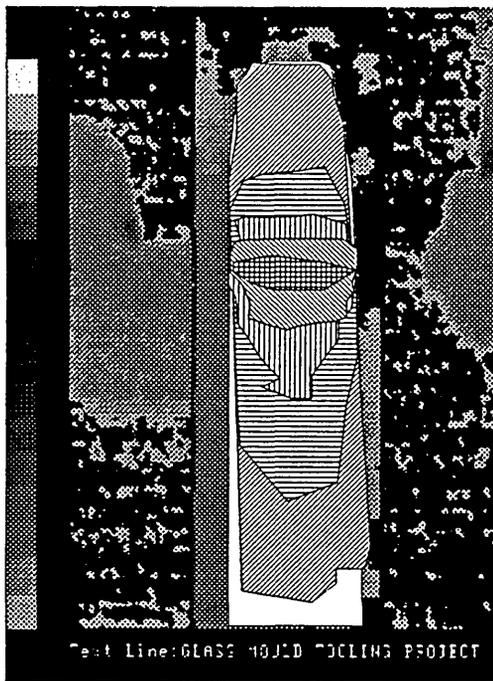


Figure 3.  
Temperature distribution for NNPB plunger with internal oxide.

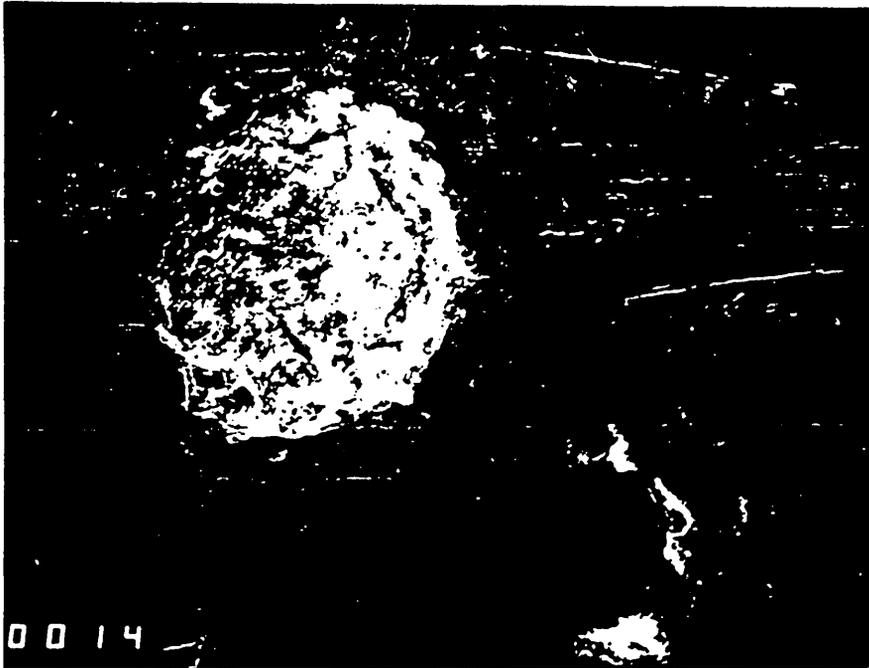


Figure 4.  
Typical worn plunger taper section.

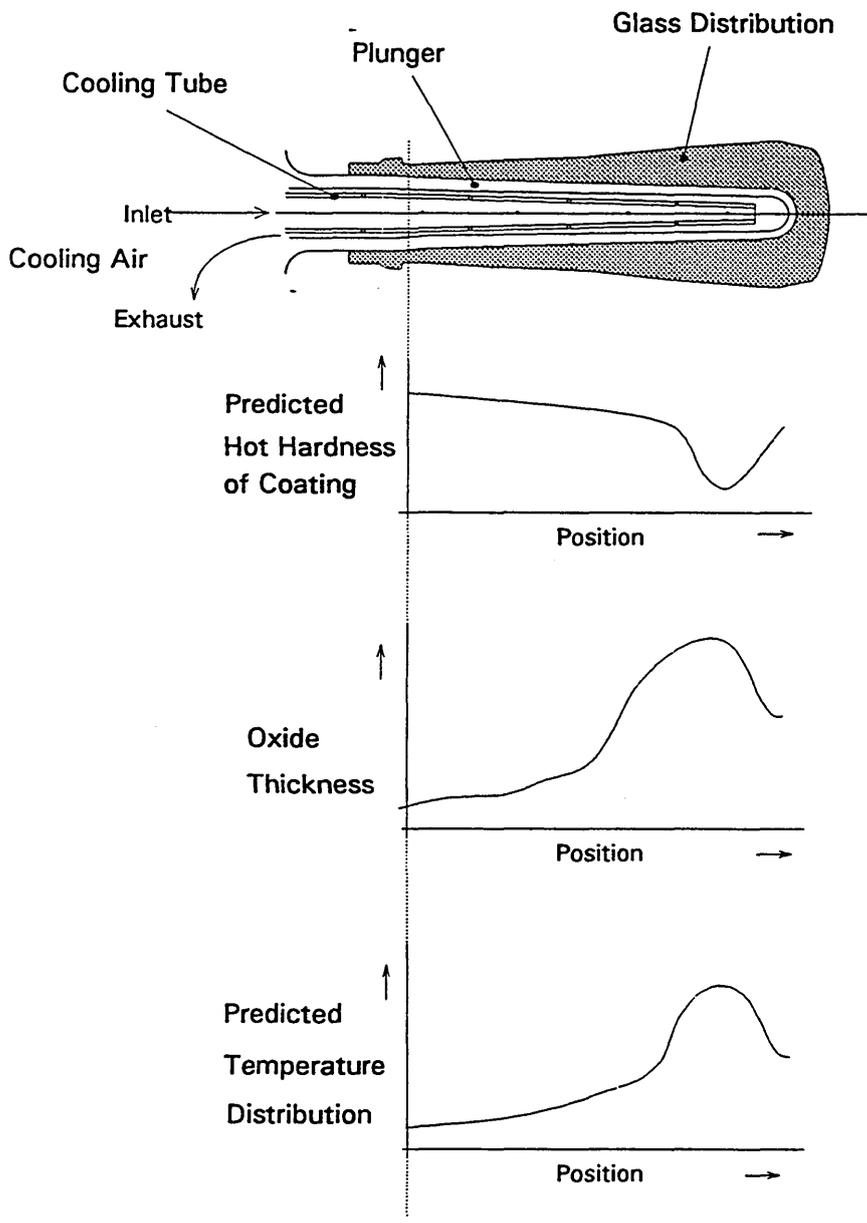


Figure 5.  
Results from the examination of worn plungers.