Flexible Polyurethane Foam
Slabstock Manual

Shell Chemicals

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FLEXIBLE FOAM SLABSTOCK MANUAL

This manual is intended to be a guide to the science of preparing flexible polyurethane foam blocks. It is hoped it will be a useful source of information to those with a peripheral interest in the subject, to prospective foamers and to those who have been producing for a relatively short time. It is a basic introduction to the subject and does not set out to be an exhaustive study. The manual should be read in conjunction with the Shell Chemicals technical bulletins, data sheets, safety data sheets, fact sheets and especially the modules designed to augment it. Shell Chemicals trade marks are CARADOL for polyols and CARADATE for di-isocyanates. It is strongly recommended that the latest guidelines from ISOPA (the European Isocyanate Producers Association) or the III (International Isocyanate Institute) or local industrial or governmental bodies on the safe handling, storage and use of di-isocyanates are followed.

Making foam blocks

A large proportion of flexible polyurethane foam is made in blocks, either discontinuously in simple boxes or in a continuous process known as slabstock foaming. In this process the raw materials, polyol, di-isocyanate, water, auxiliary blowing agents, catalysts, surfactant and other additives are metered continuously into an in-line mixer and the mixed reactants, still in liquid form, are poured into a continuous paper and/or polyethylene mould on a moving conveyor. In the paper mould, the liquids foam and expand to form a continuous block of foam. This block is cut into sections, stored for at least a day to cure and cool, and then cut in a variety of ways into the shapes required. The main uses for this foam are mattresses, furniture, automotive seating and textile laminating.

THE RAW MATERIALS AND THEIR FUNCTIONS

The essential components of a flexible foam formulation are:
Polyol
Di-isocyanate
Water
Auxiliary Blowing Agents (ABA's)
Catalysts: tertiary amines and tin salts
Silicone surfactants.

To these may be added optionally colours, fire retardants, combustion modifiers, fillers and other materials. The manufacture of the basic raw materials is discussed in the module *"Where do your raw materials come from?"*.

Taking each of the essential components in turn:

Polyol

Most flexible slabstock foam is made from polyether polyols as supplied under the Shell trade name CARADOL. These are essentially propylene oxide and ethylene oxide copolymers with a tri-functional initiator and are therefore triols. The CARADOL polyols for standard block foams have hydroxyl values in the range 46-56 mgKOH/g (nominal molecular weights of 3500 to 3000 respectively).

Di-isocyanate

The most common di-isocyanate for flexible foams is tolylene di-isocyanate, also called toluene di-isocyanate or simply TDI. Commercial grades of TDI are mixtures of the 2,4 and 2,6 isomers in controlled proportions. One grade is supplied under the Shell trade name CARADATE. CARADATE 80, which is the most frequently used for flexible polyurethane slabstock foams, consists of 80 parts of the 2,4 isomer and 20 parts of the 2,6 isomer.

Blowing agents

The primary blowing agent which causes the foam to expand is carbon dioxide, generated by the reaction between water and di-isocyanate. An auxiliary blowing agent may be used in combination with water to produce foams below 21 kg/m^3 density or to produce soft foams at all densities. These auxiliary blowing agents are low boiling point liquids and are discussed further in the *"Guidelines for foam formulations"* module.

Catalysts

Tertiary amines

These catalysts accelerate and control the rate of the water/di-isocyanate reaction.

Examples are:

di-methyl aminoethanol, often referred to as DMEA or DMAE (dimethylethanolamine)

tri-ethylene diamine, often referred to as TEDA or DABCO™, the original Houdry trade name; now marketed by Air Products and now most commonly supplied as DABCO™33LV – a 33% solution of TEDA in dipropylene glycol

bis (dimethylaminoethyl) ether 70% in di-propylene glycol; most commonly known as NIAX™ A1, the original trade name of Union Carbide Co; now marketed by Witco.

Tin salts

These catalysts are specific for the reaction between polyol and di-isocyanate. Almost universally used is stannous octoate (the tin II salt of 2-ethyl-hexoic acid), often referred to as tin catalyst, SnOct or T-9, the original trade name of M & T Chemicals Inc.; now marketed as DABCO™T-9 by Air Products.

To control accurately the small quantities required, the stannous octoate as supplied is normally diluted with polyol before use or can be purchased in an already diluted form. An alternative catalyst for use especially where polyol pre-blends (containing water, amines and silicone) are made is di-butyl tin dilaurate commonly known as DBTDL, DBTL or DABCO™T-12.

Silicone surfactant

A surfactant is essential to the control of the foaming process. In slabstock foams this is siloxane based and is commonly referred to as 'silicone'. It has two functions:

- To assist the mixing of the components to form a homogeneous liquid.

- To stabilise the bubbles in the foam during the expansion so preventing collapse before the liquid phase polymerises.

THE BASIC CHEMISTRY

A urethane is produced as a result of the reaction between a di-isocyanate group and a hydroxyl group.
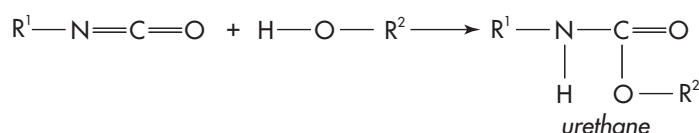
urethane

This reaction can be extended if the simple isocyanate is replaced by a di-isocyanate and the monoalcohol by a polyol.
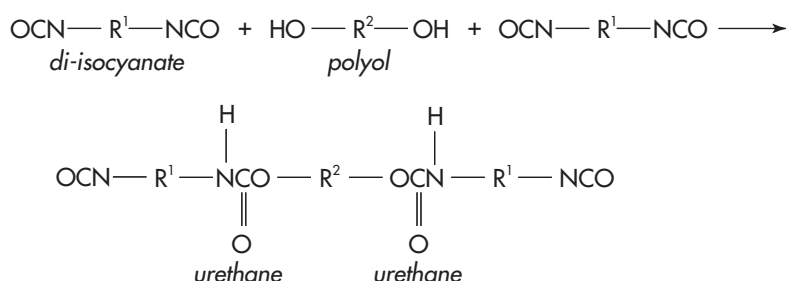
urethane   *urethane*

Or more generally, for a polyurethane:
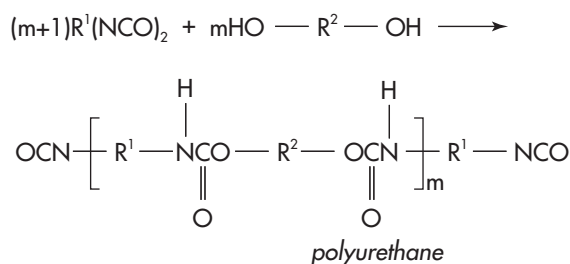
polyurethane

Di-isocyanates react with materials having active hydrogen atoms and in the production of a polyurethane foam a whole series of reactions of this type takes place. For simplicity, only one functional di-isocyanate group and the functional parts of the reaction products are illustrated.

1.

$$R^1 - NCO + H_2O \longrightarrow \left[R^1 - \overset{\overset{H}{|}}{N} - C \overset{O}{\underset{OH}{<}} \right] \longrightarrow R^1 - NH_2 + CO_2 \uparrow$$

water — unstable carbamic acid — amine   carbon dioxide

2.

$$R^1 - NCO + R^1 - NH_2 \longrightarrow R^1 - \overset{\overset{H}{|}}{N}\overset{\overset{H}{|}}{C}N - R^1$$

amine — urea

(with $\overset{\|}{O}$ below NCN)

3.

$$R^1 - NCO + R^1 - \overset{H}{N}\overset{H}{C}N - R^1 \longrightarrow R^1 - \overset{H}{N}C - \overset{R^1}{N} - \overset{H}{C}N - R^1$$

urea — biuret

4.

$$R^1 - NCO + R^2 - OH \longrightarrow R^1 - \overset{H}{N}CO - R^2$$

poliol — uretano

5.

$$R^1 - NCO + R^1 - \overset{H}{N}CO - R^2 \longrightarrow R^1 - \overset{H}{N}C - \overset{R^1}{N} - CO - R^2$$

urethane — allophanate
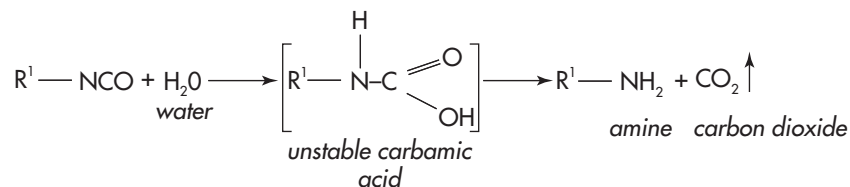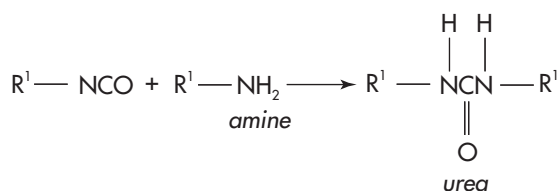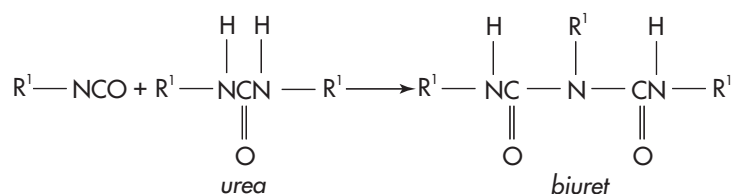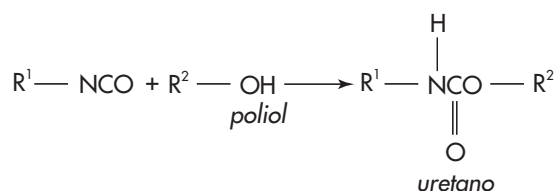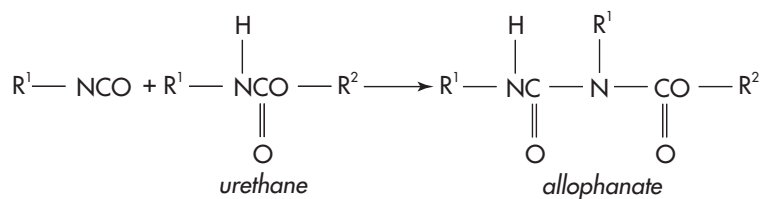
Reaction 1 causes the mixture to foam due to the formation of carbon dioxide. The amine formed in this reaction takes part in reaction 2 and contributes to the formation of the polymer.

Reactions 2-5 inclusive result in the formation of cross-links causing first an increase in the viscosity of the reaction mixture, and eventually the formation of a gelled polymer.

Reactions 3 and 5 increase the number of cross-links in the polymer and therefore influence the final physical properties of the foam.

THE FOAMING PROCESS

The following sequence of events is a simple picture of what happens when a flexible foam is made by mixing together the materials mentioned in the section: "THE RAW MATERIALS AND THEIR FUNCTIONS".

Mixing

In the first step the foam ingredients are mixed by means of a stirrer. Good mixing is essential to produce a homogeneous foam. The silicone surfactant assists in achieving good mixing since it lowers the surface tension of the polyol.

Nucleation

During the mixing air bubbles are created in the liquid. These act as nucleation points for the expansion gases. When making a box foam with simple equipment, it is not always possible to regulate the size or the number of these bubbles. On a continuous slabstock machine however there are a number of ways in which to ensure that there are sufficient of these initiating points for foam formation and that they are of the right size. This is discussed later in the section: "FOAM PROCESSING: *Effect of mixing parameters*".

After about 10 seconds the blowing gases (CO_2 and an ABA if used) diffuse into these small air bubbles and enlarge them, giving the mixture of ingredients a 'creamy' appearance. The time from initial mixing to the change in appearance is called the cream time.

Expansion

As more blowing gas is generated, the bubbles expand and the foam begins to rise. During the foam rise the number of bubbles remains constant. The silicone surfactant stabilises the bubbles preventing them from coalescing; without surfactant the mixture appears to boil and the foam collapses. At the same time as the bubbles are expanding, polymerisation reactions are taking place in the liquid phase and viscosity increases. At full rise time, about 2 minutes after mixing, the gas reaction stops. The foam now occupies 30-50 times the original liquid volume. The polymer part of the foam has begun to gel in the form of gas-filled cells with thin walls and somewhat thicker struts along the edges.

Cell opening

In the flexible foams the cell walls are unable to contain the full gas pressure: at about the full rise time, they break and the polymer contracts into the struts. At the same time the polymer is sufficiently gelled for the struts to be strong enough to stand while the gas escapes through the open cells.
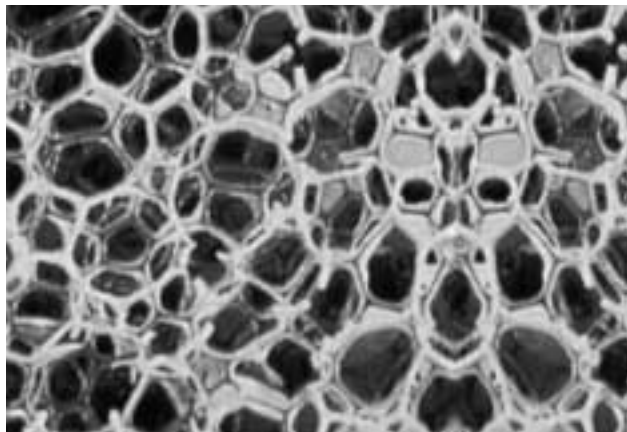
Gelation

Continuing polymerisation increases the strength of the polymer which reaches the gel time about 2-3 minutes after mixing.

Curing

The foam is then left for at least 24 hours to cure, during which time various slow cross-linking reactions take place to give the foam its final physical strength.

Note: *In the foam formation just described the two types of reaction, one causing gas evolution and the other polymerisation of the cell walls and struts, must be finely balanced. If the balance is wrong then various faults can occur in the foam. In the simplest terms, the two main types of fault are caused by the polymerisation reaction occurring too soon or too late.*

When polymerisation occurs too soon polymer strength develops too early. Some of the cell walls will not burst under the gas pressure. The result of this is that the foam will have poor resilience and feel 'dead', often called a 'tight' foam: if many of the cells remain closed, then as the foam cools and the internal gas pressure falls below atmospheric, the foam shrinks.

When the polymerisation occurs too late the struts will be weak at the time when the cell walls burst. If this happens the struts can break and, since the struts of one cell are shared by all the immediately surrounding cells, the result is a series of struts breaking, forming a split. The extent of this split can be increased by the expanding gases forcing the split further apart and breaking even more struts. (Thus it can be seen that the weaker the foam, i.e. the later the polymerisation, the larger the split.) Splits due to late polymerisation usually occur at the top edges (shoulders) of a block where the foam is weakest (coldest and therefore slowest to polymerize) and in the centre of the block where the exotherm is highest (highest gas pressure). (See section: "FAULTS: CAUSES AND REMEDIES".)

A TYPICAL FOAM FORMULATION

Setting up the formulation

Let us now consider the setting up of a typical slabstock foam formulation based on CARADOL SC56-02, a polyol with a hydroxyl (OH) value 56 mgKOH/g and water content 0.03% by weight, and CARADATE 80, on a slabstock machine having a nine stream metering pack, i.e. polyol, di-isocyanate, water, amine, silicone surfactant, stannous octoate solution, an auxiliary blowing agent and two colours.

Basic foam formulations are presented, by industry convention, in a standardised format based on 100 parts by weight (pbw) of polyol. Most other constituents are then shown as parts per 100 of polyol, often abbreviated to php, though the di-isocyanate required is also shown as an index figure (see the calculations later) as well as a weight.

The water shown is the total present, not just that added in the aqueous activator, and the tin catalyst is shown as 100% material. Though at first sight this may appear a little complex, with a little practice it enables the essential chemical proportions and their relationship to final foam properties to be seen clearly. The basic formulation has to be converted to a set of machine settings for a run; this is most conveniently recorded on the run sheet which is a record of all the relevant parameters.

Taking as an example a foam of 25-26 kg/m^3 block density (the cut foam density will be 5-10% lower depending on the type of process and machinery) and medium hardness, a typical basic formulation is:

CARADOL SC56-02		pbw	100
CARADATE 80		index	107
Water		php	3.3
Tertiary amine catalyst	Amine 1	php	0.1875
(3:1 by weight)	Amine 2	php	0.0625
Silicone surfactant		php	1.0
Stannous octoate		php	0.24
Auxiliary Blowing Agent (ABA)		php	6.0
Colour paste – Red		php	0.2
Colour paste – Blue		php	0.3

The method to convert this basic formulation to machine throughput settings in kg/minute for the 9 streams is shown in detail on the following pages.

Figure 1 is an example of a simple run sheet and the steps shown below are the normal ones taken prior to running a slabstock machine. Run sheets should be carefully and accurately compiled and then filed, as these are the basis of future machine runs.

Figure 1: Slabstock run sheet

Flexible slabstock foam runsheet								
Company	*EXAMPLE*				**Operator**	*EXAMPLE*		
Grade reference	*25 kg/m³ MH*				**Date**	*EXAMPLE*		
Stream	Material	Details	Formulation parts by weight		Throughput kg/min		Temperature °C	Flowmeter reading or Dial setting
			Basic	Actual	Theory	Actual		
Polyol	Name: Delivery date: OH value: Water content:							
Di-isocyanate	Type: Index:							
Activator 1								
Activator 2								
Activator 3								
Activator 4								
Blowing agent								
Colour 1								
Colour 2								

10 steps to successful foam making

STEP 1 – The raw materials

Complete the column headed 'Material' as shown in Figure 2, inserting the water content of the polyol as a minus quantity in the 'Activator 1' section.

Figure 2: Slabstock run sheet Foam grade 25 kg/m³ medium hardness

			Flexible slabstoc
Company	*EXAMPLE*		
Grade reference	*25 kg/m³ MH*		
Stream	Material	Details	Formulation parts
			Basic
Polyol	Name: Delivery date: OH value: Water content:	*CARADOL SC56-02* *EXAMPLE* *56.3* *0.03*	
Di-isocyanate	Type: Index:	*CARADATE 80* *107*	
Activator 1	*Water*	*(-0.03)*	
Activator 2	*Amine 1* *Amine 2*	*3* *1*	
Activator 3	*Silicone*		
Activator 4	*Stannous octoate* *Polyol*	*1* *9*	
Blowing agent	*Methylene chloride*		
Colour 1	*Red*		
Colour 2	*Blue*		

STEP 2 – The basic formulation

Under the heading 'Formulation Basic' write down the recommended Shell formulation - Figure 3 (for TDI calculation – see next step).

Figure 3: Slabstock run sheet Foam grade 25 kg/m³ medium hardness

			Flexible slabstoc
Company	*EXAMPLE*		
Grade reference	*25 kg/m³ MH*		
Stream	Material	Details	Formulation parts
			Basic
Polyol	Name: Delivery date: OH value: Water content:	*CARADOL SC56-02* *EXAMPLE* *56.3* *0.03*	*100*
Di-isocyanate	Type: Index:	*CARADATE 80* *107*	
Activator 1	*Water*	*(-0.03)*	*3.3*
Activator 2	*Amine 1* *Amine 2*	*3* *1*	*0.25*
Activator 3	*Silicone*		*1.0*
Activator 4	*Stannous octoate* *Polyol*	*1* *9*	*0.24*
Blowing agent	*Methylene chloride*		*6*
Colour 1	*Red*		*0.2*
Colour 2	*Blue*		*0.3*

STEP 3 – Calculating the amount of TDI

Figure 4: Slabstock run sheet Foam grade 25 kg/m³ medium hardness

			Flexible slabstoc	
Company	**EXAMPLE**			
Grade reference	**25 kg/m³ MH**			
Stream	Material	Details	Formulation parts	
			Basic	A
Polyol	Name: Delivery date: OH value: Water content:	CARADOL SC56-02 EXAMPLE 56.3 0.03	100	
Di-isocyanate	Type: Index:	CARADATE 80 107	43.48	
Activator 1	Water	(-0.03)	3.3	
Activator 2	Amine 1 Amine 2	3 1	0.25	
Activator 3	Silicone		1.0	
Activator 4	Stannous octoate Polyol	1 9	0.24	
Blowing agent	Methylene chloride		6	
Colour 1	Red		0.2	
Colour 2	Blue		0.3	

Calculate the amount of CARADATE 80 required in the following way.

The CARADATE 80 reacts with the polyol and the water; for this the amount required is given by:

■ For the polyol, the amount equals (polyol hydroxyl value x 0.155) parts by weight.

■ For the water, the amount equals (parts weight water in formulation(total) x 9.67) parts by weight.

In the example formulation:

For the polyol 56.3 x 0.155 = 8.73 parts by weight
For the water 3.3 x 9.67 = 31.91 parts by weight

Total = 40.64 parts by weight

Now this quantity of CARADATE 80 would satisfy the stoichiometric reactions 1, 2 and 4 given in section: "THE BASIC CHEMISTRY". This quantity is referred to as that required for an index of 100 (sometimes written as 100°). However, to make good flexible foam, the cross-linking obtained with the secondary reactions 3 and 5 is needed and an excess of di-isocyanate is therefore used. This excess is usually between 3 and 15% expressed as an index of 103° and 115° respectively. In the example the index is 107°. The total amount of CARADATE 80 required is therefore:

$$\frac{40.64 \times 107}{100} = 43.48 \text{ parts by weight.}$$

Enter this amount in the 'Formulation Basic' column as shown in Figure 4.

STEP 4 – Converting the basic formulation to actual amounts

Figure 5: Slabstock run sheet Foam grade 25 kg/m³ medium hardness

			Flexible slabstock foam ru	
Company	*EXAMPLE*			
Grade reference	**25 kg/m³ MH**			
Stream	Material	Details	Formulation parts by weight	
			Basic	Actual
Polyol	Name: Delivery date: OH value: Water content:	*CARADOL SC56-02* *EXAMPLE* *56.3* *0.03*	*100*	*97.87*
Di-isocyanate	Type: Index:	*CARADATE 80* *107*	*43.48*	*43.48*
Activator 1	*Water*	*(-0.03)*	*3.3*	*3.27*
Activator 2	*Amine 1* *Amine 2*	*3* *1*	*0.25*	*0.25*
Activator 3	*Silicone*		*1.0*	*1.0*
Activator 4	*Stannous octoate* *Polyol*	*1* *9*	*0.24*	*2.4*
Blowing agent	*Methylene chloride*		*6*	*6*
Colour 1	*Red*		*0.2*	*0.2*
Colour 2	*Blue*		*0.3*	*0.3*

This step converts the basic formulation into the actual amounts which will be used to calculate the machine stream outputs.

Subtract the water content of the polyol from the amount of water to be added, i.e. in this case:

water 3.3 – 0.03 = 3.27 parts by weight

and add it back to the polyol, i.e. polyol plus water is now 100.03 pbw.

Multiply the amount of stannous octoate required by:

$$\frac{100}{\text{solution strength \%}}$$

(solution strength in this case is 1 part of stannous octoate in 10 parts of solution, i.e. 9 parts of polyol and 1 part of stannous octoate)=1/(1+9)=10%)

which is = 0.24 x $\frac{100}{10}$ =   2.4 parts by weight.

Subtract the amount of polyol present in the stannous octoate solution from the 100.03 parts by weight of polyol, i.e.:

100.03 – (2.4 – 0.24) = 100.03 – 2.16 = 97.87 parts by weight.

Enter the amounts calculated in the 'Formulation Actual' column as shown in Figure 5.

STEP 5 – Calculating the polyol throughput

Calculate the polyol throughput required as follows.

If for example a block size of 2.1 metres wide by 1.1 metres high is required, the volume of foam produced per minute must be:

2.1 x 1.1 x V where V is the conveyor speed.

(V depends on the formulation and type of machine but is usually between 3 and 6 metres per minute. In this case we are running a medium density, medium hardness formulation on an 'average' machine so we will assume a conveyor speed of 4.5 metres per minute.)

2.1 x 1.1 x 4.5 = 10.4 m³/min
and at a density of 25 kg/m³ this will weigh 10.4 x 25 = 260 kg.

This figure is called the total foam output and is the total amount that will be dispensed from the machine in one minute.

The polyol throughput is now calculated by multiplying the total foam output by the ratio of the polyol to the total weight of foam ingredients. The total foam weight is obtained by adding together the parts by weight in the 'Formulation Basic' column on the run sheet and deducting the gas loss. The gas loss is made up of the amount of carbon dioxide released by the water/di-isocyanate reaction and all of the auxiliary blowing agent. The carbon dioxide loss can be calculated as the total water x 2.44 *(the weight of carbon dioxide generated is in proportion to the ratio of molecular weights of water and carbon dioxide. The molecular weight of water is 18 and the molecular weight of carbon dioxide is 44. The ratio is 44/18 = 2.44)* which in this case is:

gas loss = 3.3 php of water x 2.44 + 6 php of methylene chloride = 8.052 + 6 = 14.052

The total foam weight is therefore 154.77 – 14.052 = 140.72
and the total throughput should be:

$$\frac{\text{total foam output x total parts by weight}}{\text{total foam weight}} = \frac{260 \times 154.77}{140.72} = 286 \text{ kg/min.}$$

The polyol throughput is then:

$$\frac{\text{parts by weight actual x total throughput}}{\text{total parts by weight}} = \frac{97.87 \times 286}{154.77} = 181 \text{ kg/min.}$$

Enter the polyol throughput (theory) on the run sheet as shown in Figure 6.

Figure 6: Slabstock run sheet Foam grade 25 kg/m³ medium hardness

Flexible slabstock foam runsheet						
Company	**EXAMPLE**			**Operator**		**EXAMPLE**
Grade reference	**25 kg/m³ MH**			**Date**		**EXAMPLE**
Stream	Material	Details	Formulation parts by weight		Throughput kg/min	
			Basic	Actual	Theory	Actual
Polyol	Name: Delivery date: OH value: Water content:	CARADOL SC56-02 EXAMPLE 56.3 0.03	100	97.87	181	
Di-isocyanate	Type: Index:	CARADATE 80 107	43.48	43.48		
Activator 1	Water	(-0.03)	3.3	3.27		
Activator 2	Amine 1 Amine 2	3 1	0.25	0.25		
Activator 3	Silicone		1.0	1.0		
Activator 4	Stannous octoate Polyol	1 9	0.24	2.4		
Blowing agent	Methylene chloride		6	6		
Colour 1	Red		0.2	0.2		
Colour 2	Blue		0.3	0.3		
		Check Totals	154.77	154.77		

STEP 6 – Determining the actual polyol output

Calibrate the polyol to be as close as possible to the theoretical throughput. Enter this figure in the 'Throughput Actual' column as shown in Figure 7. As an example we have used 180 kg/min but remember that accuracy is essential if factors like block shape and height are to be optimised. If you have sufficient confidence in your metering equipment and have carried out regular calibration checks, you can enter 181 in the 'Throughput Actual' column and proceed.

Figure 7: Slabstock run sheet Foam grade 25 kg/m³ medium hardness

Flexible slabstock foam runsheet								
Company	*EXAMPLE*				**Operator**	*EXAMPLE*		
Grade reference	*25 kg/m³ MH*				**Date**	*EXAMPLE*		
Stream	Material	Details	Formulation parts by weight		Throughput kg/min		Temperature °C	Flowmeter reading or Dial setting
			Basic	Actual	Theory	Actual		
Polyol	Name: Delivery date: OH value: Water content:	*CARADOL SC56-02* *EXAMPLE* *56.3* *0.03*	*100*	*97.87*	*181*	*180*		
Di-isocyanate	Type: Index:	*CARADATE 80* *107*	*43.48*	*43.48*				
Activator 1	*Water*	*(-0.03)*	*3.3*	*3.27*				
Activator 2	*Amine 1* *Amine 2*	*3* *1*	*0.25*	*0.25*				
Activator 3	*Silicone*		*1.0*	*1.0*				
Activator 4	*Stannous octoate* *Polyol*	*1* *9*	*0.24*	*2.4*				
Blowing agent	*Methylene chloride*		*6*	*6*				
Colour 1	*Red*		*0.2*	*0.2*				
Colour 2	*Blue*		*0.3*	*0.3*				
		Check Totals	154.77	154.77				

STEP 7 – Calculating the 'Throughput Factor'

Calculate the 'Throughput Factor' as follows:

$$\text{Throughput Factor} = \frac{\text{Polyol 'Throughput Actual'}}{\text{Polyol 'Formulation Actual'}}$$

which in our case $= \dfrac{180}{97.87} = 1.839$.

Multiply the 'Formulation Actual' figures by the 'Throughput Factor' and put the resulting figures in the 'Throughput Theory' column as shown in Figure 8.

Figure 8: Slabstock run sheet Foam grade 25 kg/m³ medium hardness

<table>
<tr><td colspan="9" align="center">Flexible slabstock foam runsheet</td></tr>
<tr><td colspan="3">Company   <i>EXAMPLE</i></td><td colspan="4">Operator   <i>EXAMPLE</i></td><td colspan="2"></td></tr>
<tr><td colspan="3">Grade reference   <i>25 kg/m³ MH</i></td><td colspan="2">Date</td><td colspan="4"><i>EXAMPLE</i></td></tr>
<tr><td rowspan="2">Stream</td><td rowspan="2">Material</td><td rowspan="2">Details</td><td colspan="2">Formulation parts by weight</td><td colspan="2">Throughput kg/min</td><td rowspan="2">Temperature °C</td><td rowspan="2">Flowmeter reading or Dial setting</td></tr>
<tr><td>Basic</td><td>Actual</td><td>Theory</td><td>Actual</td></tr>
<tr><td>Polyol</td><td>Name:
Delivery date:
OH value:
Water content:</td><td><i>Caradol SC56-02
EXAMPLE
56.3
0.03</i></td><td><i>100</i></td><td><i>97.87</i></td><td><i>181</i></td><td><i>180</i></td><td></td><td></td></tr>
<tr><td>Di-isocyanate</td><td>Type:
Index:</td><td><i>CARADATE 80
107</i></td><td><i>43.48</i></td><td><i>43.48</i></td><td><i>79.96</i></td><td></td><td></td><td></td></tr>
<tr><td>Activator 1</td><td><i>Water</i></td><td><i>(-0.03)</i></td><td><i>3.3</i></td><td><i>3.27</i></td><td><i>6.01</i></td><td></td><td></td><td></td></tr>
<tr><td>Activator 2</td><td><i>Amine 1
Amine 2</i></td><td><i>3
1</i></td><td><i>0.25</i></td><td><i>0.25</i></td><td><i>0.46</i></td><td></td><td></td><td></td></tr>
<tr><td>Activator 3</td><td><i>Silicone</i></td><td></td><td><i>1.0</i></td><td><i>1.0</i></td><td><i>1.84</i></td><td></td><td></td><td></td></tr>
<tr><td>Activator 4</td><td><i>Stannous octoate
Polyol</i></td><td><i>1
9</i></td><td><i>0.24</i></td><td><i>2.4</i></td><td><i>4.41</i></td><td></td><td></td><td></td></tr>
<tr><td>Blowing agent</td><td><i>Methylene chloride</i></td><td></td><td><i>6</i></td><td><i>6</i></td><td><i>11.03</i></td><td></td><td></td><td></td></tr>
<tr><td>Colour 1</td><td><i>Red</i></td><td></td><td><i>0.2</i></td><td><i>0.2</i></td><td><i>0.37</i></td><td></td><td></td><td></td></tr>
<tr><td>Colour 2</td><td><i>Blue</i></td><td></td><td><i>0.3</i></td><td><i>0.3</i></td><td><i>0.55</i></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td><i>Check Totals</i></td><td>154.77</td><td>154.77</td><td></td><td></td><td></td><td></td></tr>
</table>

STEP 8 – Calibrating the streams

Calibrate all the streams (except the polyol which has already been done) to within an accuracy of at least ±1%, preferably ±0.5%, and enter the actual throughputs in the 'Throughput Actual' column as shown in Figure 9. To obtain consistent products with the properties required, it is most important that this is done accurately and that the flow levels are constant.

As a cross check the total 'Throughput Actual' should be very close to the total throughput figure as calculated in step 5 with a correction for the difference in actual polyol throughput:

Total throughput = $\dfrac{180 \times 286}{181}$ = 284.4.

We have given some possible values for guidance.

Figure 9: Slabstock run sheet Foam grade 25 kg/m³ medium hardness

Flexible slabstock foam runsheet								
Company	**EXAMPLE**				**Operator**	**EXAMPLE**		
Grade reference	**25 kg/m³ MH**				**Date**	**EXAMPLE**		
Stream	Material	Details	Formulation parts by weight		Throughput kg/min		Temperature °C	Flowmeter reading or Dial setting
			Basic	Actual	Theory	Actual		
Polyol	Name: Delivery date: OH value: Water content:	Caradol SC56-02 EXAMPLE 56.3 0.03	100	97.87	181	180		
Di-isocyanate	Type: Index:	CARADATE 80 107	43.48	43.48	79.96	80		
Activator 1	Water	(-0.03)	3.3	3.27	6.01	6		
Activator 2	Amine 1 Amine 2	3 1	0.25	0.25	0.46	0.45		
Activator 3	Silicone		1.0	1.0	1.84	1.85		
Activator 4	Stannous octoate Polyol	1 9	0.24	2.4	4.41	4.4		
Blowing agent	Methylene chloride		6	6	11.03	11		
Colour 1	Red		0.2	0.2	0.37	0.35		
Colour 2	Blue		0.3	0.3	0.55	0.55		
		Check Totals	154.77	154.77		284.6		

STEP 9 – The metering conditions

Fill in the metering conditions.

Dial setting - the position of the pump output or pump speed regulator.

Flowmeter reading - the output display reading, pump motor speed or the position of the float in the flowmeter tube.

Temperature - normally only taken for polyol and di-isocyanate.

The machine is now fully calibrated. The mechanical parameters will now have to be decided upon before the run can commence. Some of these parameters, such as mixer speed, air injection, mixing head pressure, injector pressure, are discussed later in this manual. Others which are associated with the particular type of machinery and flat-top process being used are dealt with in detail in the machinery modules. The final small adjustments made while running to optimise foam quality or correct faults are discussed in subsequent sections. An example of a fully completed run sheet, with some possible values for guidance, is given in Figure 10.

STEP 10 – Checking

Check the formulation, check the run sheet calculations, regularly check the pump outputs against the calibration curves, check the dial settings, check the machine conditions, check, check and check again – have a nice run.

Figure 10: Slabstock run sheet Foam grade 25 kg/m³ medium hardness

Flexible slabstock foam runsheet							
Company EXAMPLE				**Operator** EXAMPLE			
Grade reference 25 kg/m³ MH				**Date** EXAMPLE			
Stream	Material	Details	Formulation parts by weight		Throughput kg/min		Temperature °C	Flowmeter reading or Dial setting
			Basic	Actual	Theory	Actual		
Polyol	Name: Delivery date: OH value: Water content:	Caradol SC56-02 EXAMPLE 56.3 0.03	100	97.87	181	180	21	76%
Di-isocyanate	Type: Index:	CARADATE 80 107	43.48	43.48	79.96	80	22	52%
Activator 1	Water	(-0.03)	3.3	3.27	6.01	6	-	6 l/min
Activator 2	Amine 1 Amine 2	3 1	0.25	0.25	0.46	0.45	-	33
Activator 3	Silicone		1.0	1.0	1.84	1.85	-	42
Activator 4	Stannous octoate Polyol	1 9	0.24	2.4	4.41	4.4	-	48
Blowing agent	Methylene chloride		6	6	11.03	11	25	9.4 l/min
Colour 1	Red		0.2	0.2	0.37	0.35	-	24%
Colour 2	Blue		0.3	0.3	0.55	0.55	-	34%
		Check Totals	154.77	154.77		284.6		

FORMULATION COSTING

Calculating the cost of foam is a relatively simple process. The details and some additional steps, associated with the manufacturing techniques, are shown here.

For this exercise the same formulation as used for setting up the run sheet has been selected:

				cost/kg	weight x cost/kg
CARADOL SC56-02		pbw	100	1.2	120
CARADATE 80		php	43.48	2.0	86.96
Water		php	3.3	0	0
Tertiary amine catalyst	Amine 1	php	0.1875	2	0.3750
(3:1 by weight)	Amine 2	php	0.0625	5	0.3125
Silicone surfactant		php	1.0	5	5
Stannous octoate		php	0.24	6	1.44
Auxiliary Blowing Agent (ABA)		php	6.0	1	6
Colour paste – Red		php	0.2	4	0.8
Colour paste – Blue		php	0.3	4	1.2
	Total weight		**154.77**	**Total cost**	**222.09**

The formulation parts per hundred polyol (php) are multiplied by the material cost. In this case the cost per kilogram has been selected. The total weight and total cost are calculated.

Because the gas generated by the water/di-isocyanate reaction (carbon dioxide) and the auxiliary blowing agent which evaporates are lost after the foam rise is complete, the weight of these gases is deducted from the total weight.

				cost/kg	weight x cost/kg
CARADOL SC56-02		pbw	100	1.2	120
CARADATE 80		php	43.48	2.0	86.96
Water		php	3.3	0	0
Tertiary amine catalyst	Amine 1	php	0.1875	2	0.3750
(3:1 by weight)	Amine 2	php	0.0625	5	0.3125
Silicone surfactant		php	1.0	5	5
Stannous octoate		php	0.24	6	1.44
Auxiliary Blowing Agent (ABA)		php	6.0	1	6
Colour paste – Red		php	0.2	4	0.8
Colour paste – Blue		php	0.3	4	1.2
	Total weight		**154.77**	**Total cost**	**222.09**
	Carbon dioxide loss (see note)		**8.05**		
	Auxiliary blowing agent loss		**6**		
	Net foam weight		**140.72**		

Note: *The weight of carbon dioxide generated is in proportion to the ratio of molecular weights of water and carbon dioxide. The molecular weight of water is 18 and the molecular weight of carbon dioxide is 44. The ratio is 44/18 = 2.44. The loss in this case is therefore 2.44 x 3.3 = 8.05.*

The net ('ex-head') cost of the foam is therefore 222.09/140.72 = 1.58 monetary units/kg.

There are however many more factors which must be considered before arriving at a cost of a foam block and even more before arriving at the cost of a cut piece of foam.

Paper – continuous machines use paper or polyethylene to form a 'U' shaped channel protecting the conveyor and side walls. The cost of this should be added to the total. Also, if paper is used, there is an absorption factor as the liquid foaming material soaks into the porous paper. This can be determined by measuring the weight/m^2 of virgin paper and comparing it to weight/m^2 of used paper per running metre of foam block. The factor is usually about 1-2% of the net foam weight depending on the quality of paper used. In box foams, paper and polyethylene are sometimes used but, in a lot of cases, there is direct contact between the foam and the box bottom and sides. Foam adheres to these surfaces, sometimes as much as 3-4% of the foam weight. The amount should be measured and a factor applied to the net foam weight.

Production waste – blocks with faults such as splits, closed cells, etc., and blocks which are outside specification. For a continuous machine this includes start and end blocks, change-over blocks. Wet waste, such as the remnants of a foaming run in a Maxfoam trough or the foam deliberately run to waste at the start of production, should be included. If, as recommended, samples are cut for quality control purposes, the weight of these sample blocks should also be included. Some foam is recovered through sales as 'second quality' and re-bonding or other recycling techniques. These recoveries should be added back. The production waste costs should be looked at as a moving average and a good working practice should be to minimise these in the long term.

Solvents – these are used for general cleaning of equipment and, in the case of continuous machines, for flushing out the mixing head or cleaning the Maxfoam trough after a run. Quite often the auxiliary blowing agent is used for this purpose. The cost of this must not be forgotten, especially the cost of disposal of solvents and wet waste by an approved industrial waste disposal company.

Overheads – these include factory rental or depreciation, machinery depreciation, labour, power and other services and maintenance. Inclusion of an 'unforeseen' expense of 5-10% is advisable to cover the unscheduled and unexplainable events which are part of industrial life.

This should enable the cost of a foam block to be calculated with a reasonable degree of accuracy. Further operations such as block trimming can generate up to 10% and conversion up to 30% of remnant prime foam which is looking for a use. Other products can be made from this foam such as small articles, packaging or, if a further investment is made, re-bonded foam as described in the module *"Making use of your conversion trim"*.

And don't forget – sales promotion and advertising, transport costs, raw material stock costs, foam and finished goods stock costs, packaging, re-investment costs and, of course, a profit margin.

PREPARATION OF THE AUXILIARY STREAMS

Aqueous activator

When preparing to make a box foam or setting up for a foam run on some older machines, it can be necessary to blend the water, amine and silicone and use as one component – the 'aqueous activator'. When a hydrolysable silicone is used (the supplier should identify it as such) the effectiveness of a solution of this silicone in amine and water decreases rapidly after approximately 24 hours. Therefore, to save waste, only enough solution for one day's production should be made. The amount of solution required can be calculated from the run sheet (running time x amount per unit time). An extra quantity of solution must be made to flush out the lines to remove any material remaining from previous runs, also to fill the lines and provide sufficient depth of liquid in the tank to prevent air being pulled into the pump inlet.

The solution should be made by weighing the correct amount of water into a clean container, adding the amine and stirring until the amine has dissolved. The silicone surfactant should then be added and the mixture again stirred until it is dissolved. When a non-hydrolysable silicone is being used, the aqueous activator can be prepared in larger quantities since it is stable for up to 7 days (or more depending on local conditions and the advice of the supplier).

Stannous octoate

Stannous octoate concentration is the most important control parameter in an established formulation. It is quite normal to make changes on a day-to-day basis. These changes tend to be small and therefore it is strongly recommended, for the sake of accuracy, that a dilution of stannous octoate is used. Typically this would be a 10% solution in polyol.

Note: *On hydrolysis this solution becomes 'milky' and such a solution must be discarded. It has been noticed also that in hot, dry climates the solution can change colour from the normal pale yellow to dark brown within 3-4 hours. This colour change is not accompanied by any loss in activity within the 12 hour period.*

A typical solution is made by adding the correct amount of stannous octoate to a known weight of polyol. The mixture should be stirred well because of the high viscosity. But care must be taken not to stir in any air as this takes a long time to come out of the solution.

The stability of a stannous octoate solution can be increased by capping the storage container or the machine day tank with dry air or nitrogen.

Stannous octoate is readily hydrolysed. Contact with, moisture in the air, or a small amount of water in the polyol used to make the working solution, is sufficient to cause the stannous octoate to lose its effectiveness as a catalyst after about 12 hours. Therefore a fresh solution must be made each day, but since the same concentration of solution can be used for all grades of foam, the amount sufficient for the entire day's production can be made at the same time. For the production of box foams it is recommended that the stannous octoate be added separately and as the final component to the polyol blend before adding the TDI. The lifetime of stannous octoate in a polyol blend containing water and amines is very short. The use of such blends will be characterised by a gradual reduction in reactivity. If blends with polyol are essential to ensure consistent or economic production, it is suggested that the use of dibutyl tin dilaurate (known as DBTL) be considered. This is stable in a polyol blend for a day's production. It is more efficient as a gelation catalyst than stannous octoate so lower levels are required.

FLEXIBLE BLOCK FOAM PRODUCTION

Flexible block foam production consists of the following stages:

Raw material storage and temperature conditioning
Metering or weighing out of components
Mixing
Formation of the block
Followed by block curing, cutting, etc.

Raw material storage and conditioning

Let us consider each step in this process.

Notes on suitable conditions for storage before materials are required for production are included in the product data sheets and reference should be made to these. Particular attention should be paid to ensuring that none of the raw materials becomes contaminated with water.

Polyol and di-isocyanates are usually kept in drums or stored in tanks of 10-30 cubic metres capacity. As the foaming reactions are strongly influenced by temperature, the materials should ideally be kept at constant temperature. The drums and tanks should therefore be in a place, such as an air conditioned room, where the temperature is within the range 18°-25°C or in hot countries 20°-28°C.

Note: *Toluene di-isocyanate freezes at 17°C. This will produce 2,4 isomer rich crystals which are white and semi-transparent (as compared to urea formed by water contamination which is a white opaque material). If this happens a reduction in reactivity will be noticed during foaming and, in severe cases, foam splits, which cannot be corrected by normal means such as an increase in stannous octoate level, will occur. TDI crystals can be melted by the application of gentle heat (not more than 40°C) to a drum. Drums should be rolled after thawing to ensure a homogeneous material. In a tank, circulation of warm TDI (25°C) for a few hours should be sufficient. Note that there is a risk that filters can become blocked with crystalline material and may have to be cleaned during this recirculation period.*

To obtain consistent results in the foaming, the temperature of the polyol and di-isocyanate entering the mixing vessel or mixing head should be the same each time. The actual temperature is of less importance. A normal recommendation would be to use the polyol and TDI controlled to ±1°C within the range of 20°-25°C. However, in hot countries it is not uncommon to find polyol and TDI temperatures of up to 30°C. As temperature increases the amount of catalyst, especially the tin catalyst, has to be reduced. The temperature at which the materials are used should be selected on the basis of the one most easily maintained. On more sophisticated units, temperature control is achieved by conditioning in a small day tank between the main tank and the pump, or by in-line heat exchangers between the tank and the mixing head.

Catalysts, silicone surfactants and amines are stored in the drums or IBC's* in which they are delivered and solutions made up as required.

For other materials, and those discussed above, the storage and handling instructions of the supplier must be followed.

It is important that tanks and lines are designed to minimise the entrapment of air. Transfer of materials to mixing vessels should be made without undue splashing. Pipes to the inlet side of pumps should be large in diameter to prevent pump starvation. On the discharge side of the pump, smaller diameter piping is desirable to generate a back pressure of about 1-6 kg/cm^2 so that a low pressure pump gives a steadier output. (See section below for definition of low pressure.)

Tanks for high pressure machines have to be pressurised to about 2 kg/cm^2.

Metering and mixing of components

The materials must be delivered to the mixing head in the correct ratios and at the right overall throughput. As stated earlier, metering accuracy is most important and the flow levels must be stable. Once in the mixing head, the materials must be mixed together completely. The mixing conditions used will influence the size of the foam cells.

There are two distinctly different ways of achieving metering and mixing. These are referred to as low pressure and high pressure, the pressure referred to being the pressure of the materials at the inlet to the mixing head. The essential features of these two systems are described in the table below.

Intermediate Bulk Containers

Component pumps	Low pressure machines (LP)	High pressure machines (HP)
Polyol	Gear pump	Low pressure gear pump
Di-isocyanate (TDI)	Piston pump	High pressure piston pump
Activators (aqueous and stannous octoate)	Gear or annular piston pumps	High pressure piston pump
Auxiliary blowing agents	Annular piston pump or pressure feed through flowmeter	High pressure piston pump
Delivery line pressures	1-15 kg/cm^2	20-100 kg/cm^2
Entry to mixing head	Via interchangeable jets	Via injectors with adjustable opening pressure (except polyol)
Mixer	Variable speed peg-in-barrel stirrer	Variable speed peg-in-barrel stirrer
Mixing head pressure	0-1 kg/cm^2 depending on design (although many low pressure machines are now fitted with head pressure adjustment)	Fully adjustable 0.5-3 kg/cm^2
Control over cell size	Increasing stirrer speed gives smaller cells. Increasing head pressure gives larger cells. Increasing air injection rate gives smaller cells.	Increasing stirrer speed gives smaller cells. Increasing head pressure gives larger cells. Increasing injector pressure gives smaller cells.

Whichever method of production is used, it is recommended that the following sequences should be followed.

At the start of the run
1. Start the stirrer
2. Bring polyol stream on to delivery
3. Bring blowing agent and activators on to delivery
4. Bring di-isocyanate on to delivery.
This whole sequence should take less than 5 seconds.

At the end of the run
1. Stop di-isocyanate
2. Stop all other streams
3. Flush mixer with polyol or cleaning solvent
4. Stop stirrer.

Mixing heads

On a low pressure machine the components are mixed by the use of a peg-in-barrel stirrer. The speed of the stirrer also influences the cell size of the foam (see section: "FOAM PROCESSING: *Effect of mixing parameters")*. In the high pressure system, most of the mixing is by the injection of the di-isocyanate and activators into the lower pressure polyol stream. The large pressure drop of 60 to 100 atmospheres across the injector nozzle causes the material stream to break up into a fine spray and this spray is forced into the polyol stream. On most large high pressure machines a peg-in-barrel stirrer is also provided: cell size is controlled by varying the head pressure by means of a throttle valve (see section: "FOAM PROCESSING: *Effect of mixing parameters"*).

In both types of machine the auxiliary blowing agent is usually metered as a separate stream and, on most machines, is fed into the polyol line just before the mixing head rather than directly into the head. Similarly the nucleating air is best put into the polyol line and, on many machines, colours and fire retardants are also added to the polyol. This reduces the number of entry points on the head and also provides a small degree of premixing.

Outlet nozzles

The mixed material leaves the mixer at a high velocity and if allowed to fall directly onto the paper there is a lot of splashing leading to holes in the foam. To avoid this splashing and to give a smooth lay-down on the paper, an outlet nozzle of larger diameter than the mixer is used to reduce the velocity of the liquid. On low-output machines a simple nozzle brought close to the paper (1 cm) is sufficient. On high-output machines more complicated devices with paper honeycombs or gauze fitted in the outlet are used.

Conveyor and tunnel

The conveyor and the tunnel form a mould in which the block of foam is formed with a starting and a finishing block as the ends of the mould. To produce foam free from faults the conveyor must have a flat surface, and must run smoothly. The tunnel walls should be smooth, straight and form a square cross section with the conveyor. It is essential that they are parallel, or slightly diverging, otherwise the foam may jam in the tunnel. The conveyor, or plate onto which the foam is poured, is tilted downwards at an angle of between 3 and 5 degrees away from the mixing head end: this ensures that the newly laid material runs away from the mixing head and assists in building up the block height.

Paper feed and take-off systems

On most current stabstock machines it is customary to use 3 papers. The 3 papers must run at exactly the same speed to avoid tearing the foam. The side papers are usually fed from free-running rollers and pulled by a motor driven take-off roller at the end of the primary conveyor. Normally the bottom paper is pulled off at the end of the secondary conveyor, but it can be left on and cut off later during block trimming. Many machines now use a polyethylene film instead of paper or a polyethylene film between the paper

and the foam – the film in some cases is lightly tacked to the paper and stays on the foam after the paper take-off.

Foam preparation – general points

- To enable a full height block to be produced from the very start of a run, a piece of scrap foam or wood, the full expected height of the block and 2-3 cm narrower in width, is put in the paper mould on the conveyor. This acts as a wall for the liquid and supports the front of the rising foam block. It should be as close to the mixing head as possible at the start of the run.

- When starting, the conveyor speed should be slightly faster than the calculated figure to ensure that the first section of foam will clear the lay-down device (the first section is usually faster creaming). After 20 to 30 seconds of running, the speed can gradually be reduced in steps until the optimum is reached. This will depend on the process and machinery. This speed will in turn give the highest block that can be produced from a given formulation and throughput of components.

- The stannous octoate level can be optimised whilst the machine is running by adjusting the level in small steps (0.01 php is recommended). Reduce the initial setting by this amount. At the change, mark the foam and look for small splits in the shoulders of the block at the paper take-off. If no splits appear, reduce by further steps until they do, then increase the stannous octoate level just sufficiently to remove the splits. This process will give the most open foam with good springy feel.

BLOCK HANDLING

Block cutting

As the foam block leaves the conveyor it must be cut into pieces of convenient size for transport to a storage and curing area. This is achieved by the use of a travelling cut-off saw which can move along the conveyor with the block as the cut is made. For man handling, blocks can be cut into 2-3 m lengths, for stack-a-truck handling 3-4 m lengths, and for conveyor transport systems 10-100 m lengths depending on the length of the storage conveyors.

Block storage

The block storage should be divided into two separate areas:

- Hot block curing

- Longer term storage.

Hot block curing

The design of the hot block curing facilities and the handling of the blocks in this area must be done correctly to produce top quality foam and to minimise health and fire risks.

The foam blocks leave the cut-off knife about 5-8 minutes after the foaming reaction begins near the mixing head. The reaction is strongly exothermic and the open-celled foam is a good insulator: the blocks therefore become very hot.

Typically, for a water blown formulation containing 4.8 php water with a block cross-section between 70 and 200 cm wide and 70 cm to 100 cm high, the centre of the block will reach 160-170°C. The time to reach this temperature will be about 20-30 minutes after foaming and the block will not start to cool for another 3-4 hours. After that it will take about 20 hours to cool to room temperature. This means that the whole curing cycle takes about 24 hours from the formation of the block on the machine.

During this hot stage the block will give off gases which contain free toluene di-isocyanate, auxiliary blowing agent and amine catalyst. Furthermore, as discussed in section: "FAULTS: CAUSES AND REMEDIES: *Scorching in slabstock foams",* it can, if incorrectly made, scorch or even catch fire spontaneously. Therefore the design of the curing area should take the following points into consideration:

■ Ideally the area should be completely separate from the other buildings of the plant and have a fire gap of 3-4 metres all round. All doorways should be fire proof and should be kept shut at all times when foam is not being moved in or out. If the area is part of a building, it should be separated from the rest of the building by a fire wall with fire proof doors.

Adequate ventilation should be provided by either:

■ Setting the roof slightly above the walls to provide an opening all round the top

■ Fitting exhaust fans.

In case of a fire, the former method will also allow the smoke to escape, so assisting in fire fighting. If the latter method is used some form of automatic smoke vents which open in the event of a fire should be provided.

■ The building should have a high-output, automatic water sprinkler system.

■ Block storage layout should provide good escape routes for personnel in the case of fire.

■ The area should be large enough to store one day's production.

When handling blocks during the first 24 hours after making, the following precautions should be taken:

■ Blocks should be stood on, or moved onto, a smooth surface to prevent damage to the skin of the block which is still soft.

- Blocks must not be stacked one on top of the other, which would increase the effective mass of hot foam. This will prevent blocks surrounded by others from cooling normally and can lead to excessive heat build-up and fire. If space is limited, racks should be provided with at least 30 cm air gap all the way round each block.

- Blocks should be kept in the store until cold, which is usually about 24 hours after making, and then moved out to a longer term storage area.

Longer term storage area

The design of this area is not so critical and the health and fire risks are somewhat less; however, it should still be constructed taking the combustible nature of foam into account.

- The store should be isolated from the rest of the plant by fire walls and fire doors.

- An automatic sprinkler system and smoke ventilators should be fitted.

- Block storage layout should provide good escape routes for personnel in the case of fire.

PLANT LAYOUT

A flow scheme for a flexible slabstock foam plant is given in Figure 11 and a typical floor plan in Figure 12.

Figure 11: Flexible polyurethane foam plant – Scheme for continuous production and conversion
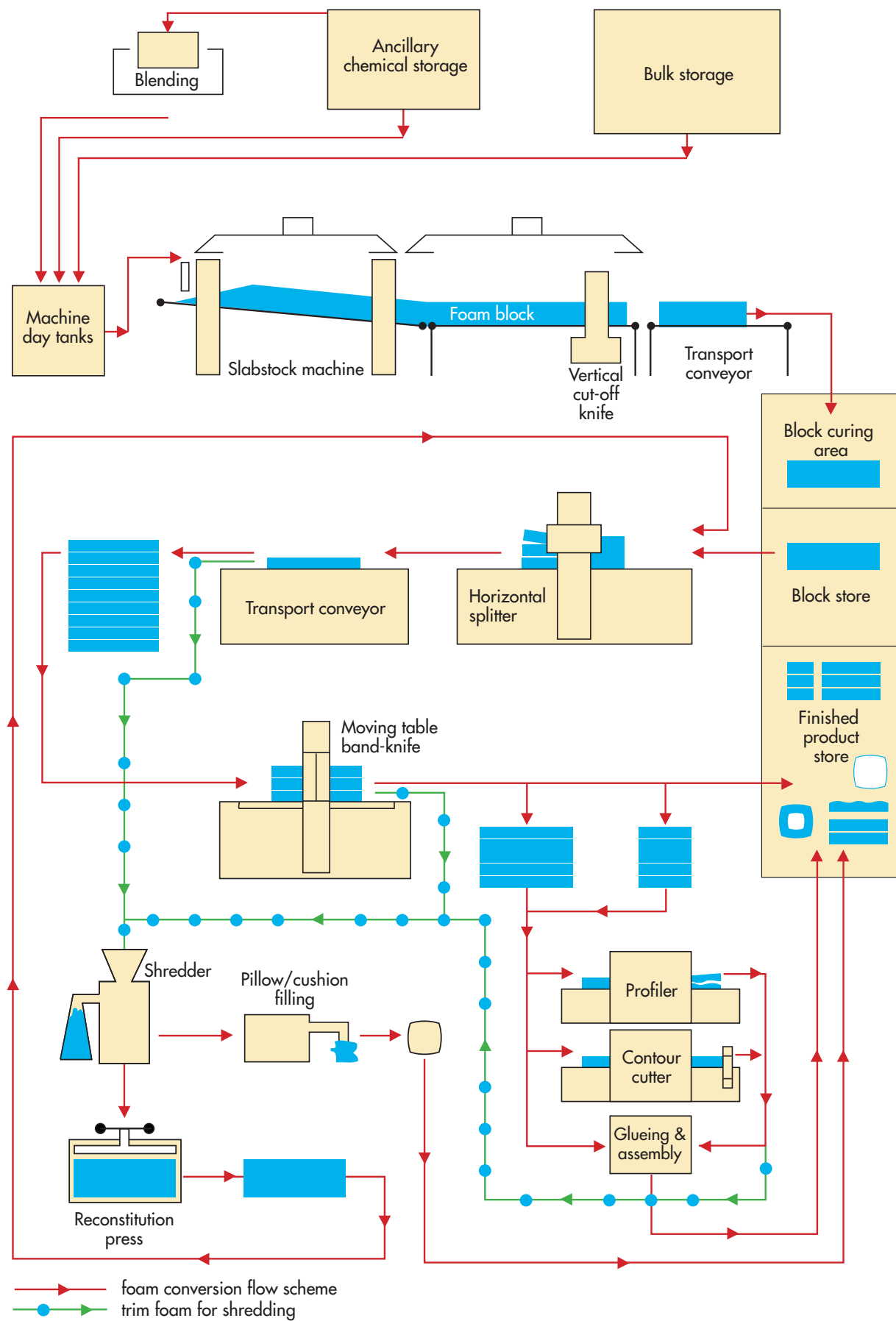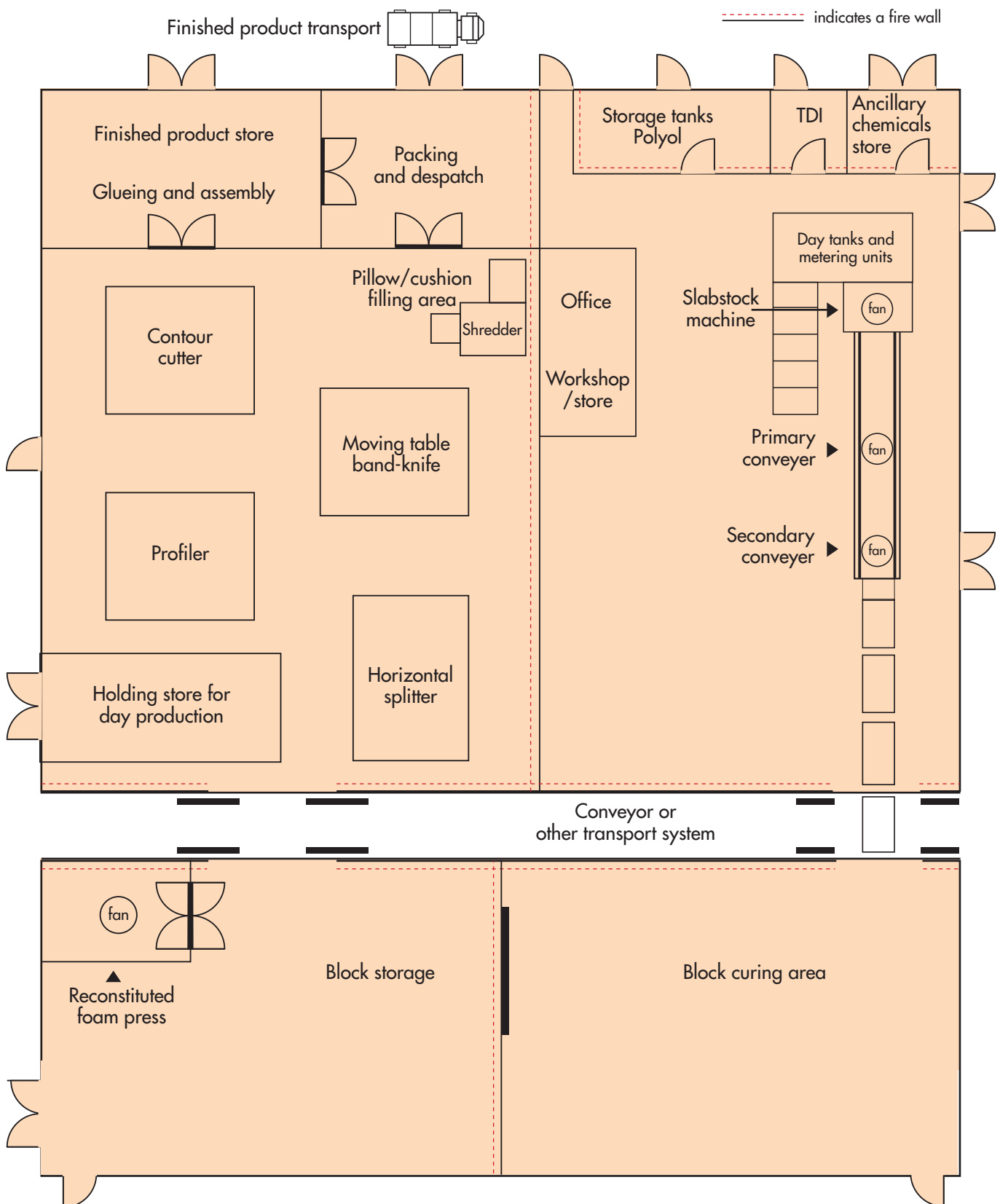
Blending

Ancillary chemical storage

Bulk storage

Machine day tanks

Slabstock machine

Foam block

Vertical cut-off knife

Transport conveyor

Block curing area

Block store

Finished product store

Transport conveyor

Horizontal splitter

Moving table band-knife

Shredder

Pillow/cushion filling

Profiler

Contour cutter

Glueing & assembly

Reconstitution press

foam conversion flow scheme

trim foam for shredding

Figure 12: Idealised slabstock plant layout

Finished product transport

- - - - - indicates a fire wall

Finished product store

Glueing and assembly

Packing and despatch

Storage tanks Polyol

TDI

Ancillary chemicals store

Pillow/cushion filling area

Shredder

Office

Workshop /store

Day tanks and metering units

Slabstock machine

fan

Contour cutter

Moving table band-knife

Primary conveyer

fan

Profiler

Secondary conveyer

fan

Holding store for day production

Horizontal splitter

Conveyor or other transport system

fan

Reconstituted foam press

Block storage

Block curing area

This topic is complex and in a manual of this kind only the basic concepts of processing can be examined and some guidance on the causes and correction of the more common types of faults given.

Fully satisfactory production, that is the consistent, fault-free manufacture of slabstock of the densities and hardnesses required, depends on a finely controlled balance of formulation and machine factors. Hence the importance of keeping accurate records in the run sheets. (See section: "A TYPICAL FOAM FORMULATION".)

Effect of catalysts and silicone

The effect of catalysts and silicone surfactant is described in Figure 13. The catalyst and silicone levels increase in magnitude in the direction of the arrows in Figure 13. The region between the lines BB and CC is the area where the levels of the two catalysts and silicone are correctly balanced and good foam is produced. The region between the lines AA and BB is the area in which some foam manufacturers prefer to operate. In this area the foam is still fairly open and the probability of the foam splitting is very small. In this region however, it can be seen that more catalyst (stannous octoate) is required. The thickness of the arrows gives an indication of the relative effectiveness of the individual components.

Note: *Figure 13 shows the effects of the individual catalysts and the silicone over a narrow range of levels (approximately ±25% from the optimum values). If a gross excess or deficit of any of these components is used or if the balance between them is incorrect then a different set of foam faults will arise.*
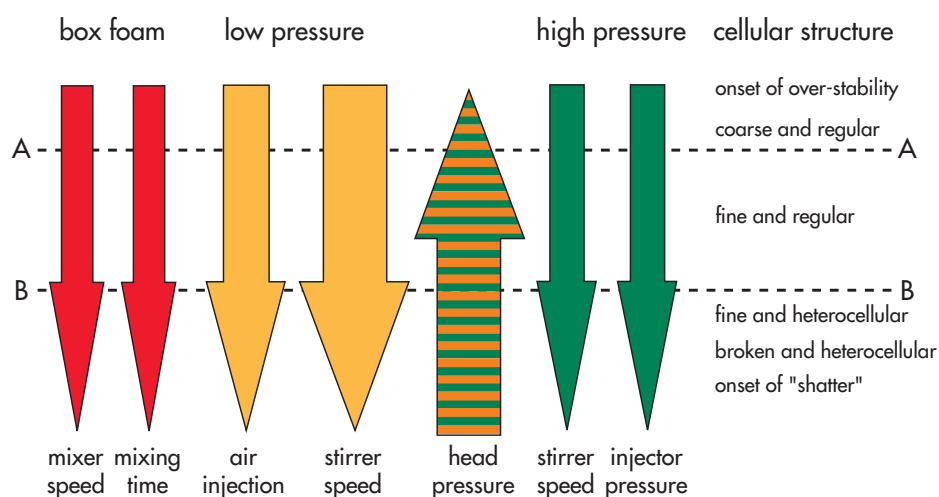
Figure 13: The effect of catalysts and silicones
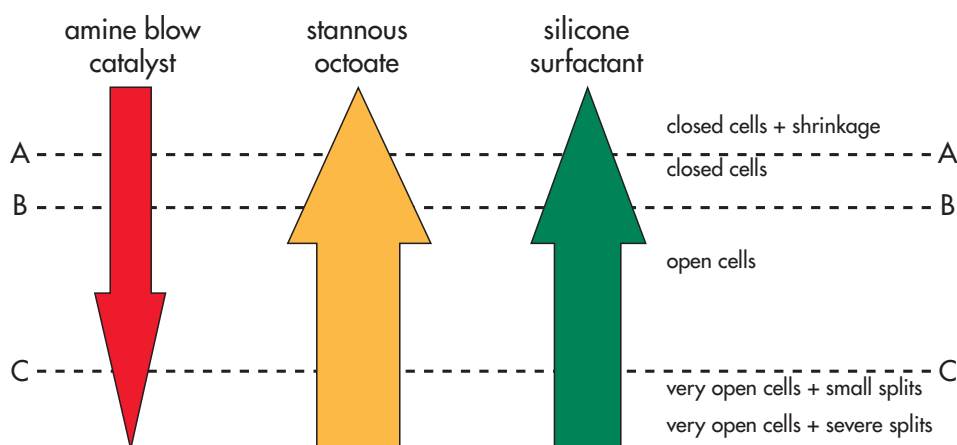
Effect of mixing parameters

The effect of mixing parameters is described in Figure 14. The mixing parameters increase in magnitude in the direction of the arrows in Figure 14. The region between the lines AA and BB is the region normally considered to be 'good cell structure'. The thickness of the arrows gives an indication of the relative effectiveness of the individual mixing parameters.

Figure 14: The effect of mixing parameters

box foam   low pressure   high pressure   cellular structure

onset of over-stability

A ---- coarse and regular ---- A

fine and regular

B ---- ---- B

fine and heterocellular
broken and heterocellular
onset of "shatter"

mixer speed | mixing time | air injection | stirrer speed | head pressure | stirrer speed | injector pressure

FAULTS: CAUSES AND REMEDIES

Keeping these general trends in mind, individual formulation errors and also some possible machine or mechanical faults can be described. Some of these can be rectified whilst the machine is running, but for others it is best to stop production and allow time for all the pertinent facts to be considered before deciding how to correct the fault.

Closed cells

Here the bubbles which form the foam cell have not burst and the foam still contains closed cells, resulting in poor resilience and a 'dead' feel, plus possibly shrinkage. The unbroken walls in the closed cells reflect the light and can be seen on the cut face of the foam. Blocks containing a low proportion of closed cells can often be rendered more open by crushing. If there is a high proportion of closed cells the foam may shrink on cooling to give distorted blocks.

The causes of closed cells are:

| Cause	Effect
Excess tin catalyst	The polymerisation is too fast compared to the blow reaction, and hence the cell walls are too strong at the full rise time and are not burst open.
Excess silicone	Over-stabilises the bubbles and prevents the walls from developing weak spots at which they normally burst.
Too little nucleating air or too low stirrer speed	These result in a coarse cell structure. When cells are large, their walls are thick and less easily blown open (see Figure 14).
Too high material temperatures	An increase in temperature increases the rate of polymerisation and gelation more than the rate of 'blow', so that a formulation which was 'balanced' at a lower temperature, now gives 'tight' foam.

Splits

There are many reasons for splits in the foam: some are formulation errors, some are chemical and some are mechanical. In diagnosing the cause for splits the first point to notice is the frequency of their occurrence. If the split is continuous through the block or occurs at regular intervals through the block then it is usually a formulation error or errors. If the splits are random in their occurrence then some mechanical fault is probably the cause.

Formulation errors

too little tin catalyst

The most common fault is known as the 'tin split'. It occurs at regular intervals along the shoulder of the block as shown below on the left. If the tin catalyst is much too low the splits may extend right through the block.
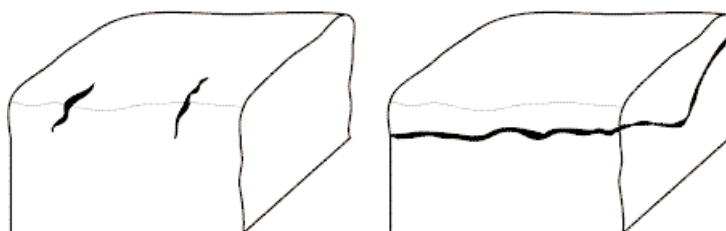
These splits occur at weak spots in the block. Usually these are at the block shoulders or sides. On older machines they are also at the turn round position of the traverse.
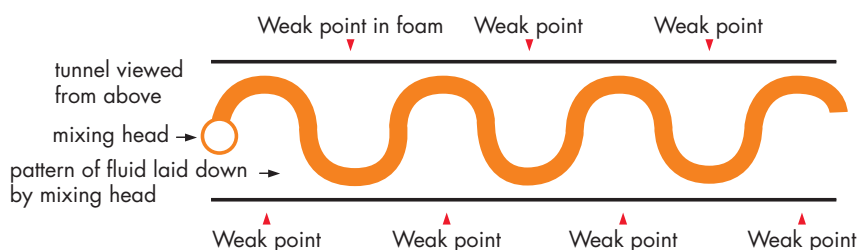
As shown, the traversing mixing head lays down a pattern of liquid and at the point where successive passes of the mixing head meet there is a weak point in the foam. In most cases, 5-10% more tin catalyst will remove these splits. Other types of machines have characteristic splits. These are dealt with in the individual machinery modules.

too little silicone

Insufficient silicone leads to bubble instability at full rise, the bubbles burst and run together to give splits (see Figure 13).

too much amine catalyst

Basically the same effects as too little tin catalyst. Check reaction times which may be too short (see Figure 13). Recommended safe working ranges are:
cream time 7-14 seconds
full rise time 80-120 seconds.

too low TDI index

This is particularly a problem when making soft foams of less than 20 kg/m^3 density, using high levels of auxiliary blowing agent and a low index, say 103°-104°. Better processing can be obtained by increasing the index to 107°-108° and lowering hardness by adjustment of water/ABA balance (see section: "THE EFFECT OF FORMULATION VARIABLES ON FOAM PROPERTIES").

wrong TDI isomer ratio

This can occur when the TDI has been exposed to low temperatures and has frozen or partially crystallised. The 2,4 isomer will crystallise more rapidly than the 2,6 isomer forming a eutectic mixture. The liquid remaining will therefore be 2,6 rich and will give rise to splits similar to those observed when the stannous octoate level is too low.

colours

Occasionally splits can be caused by adding colour to or changing the colour in a previously satisfactory formulation. The pigments may act as nucleating agents or a paste may contain dispersing agents which affect the foam stability. In either case a change may upset the balance of the running conditions and cause splits.

Mechanical causes

mixing conditions

When the reactants are subject to 'over-mixing' the cells become very fine (see Figure 14). The cell walls are now so thin that the cells coalesce and run together giving rise to splits. This fault is usually recognised by areas of very fine cell structure surrounding the split. It is cured by reducing the degree of mixing, either by reducing the stirrer speed on a low-pressure machine or by increasing the head pressure on a high-pressure machine.

mechanical disturbances

Creases in the paper, jerky paper movement, jerky or uneven conveyor, changes in conveyor channel width, all lead to random splitting. This splitting however, is usually confined to the shoulders and sides of the block.

Splits and closed foam

This combination is caused by an incorrect balance of the stannous octoate catalyst and silicone surfactant levels. Either the silicone is too high and the stannous octoate too low or vice-versa.

Sink-back

A silicone level which is too low will cause the foam to collapse partially immediately after full rise. This is referred to as 'sink-back' and the degree can vary between less than 1% and total collapse. Normally, sink-back of less than 2%, especially in low density foams, is not regarded as a serious

problem. In some cases sink-back can be caused by a low stannous octoate level.

Note: *Sink-back should not be confused with the apparent sink-back observed when large splits form, causing the foam to expand locally and then fall back.*

Under-running

Under-running is a characteristic of incorrect operation of inclined conveyor slabstock machines. Freshly laid down liquid layer runs under the rising foam causing top or shoulder splits.
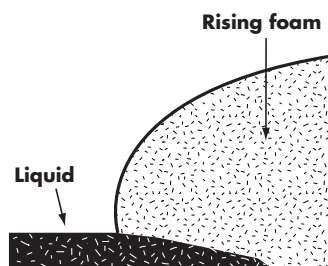
This is corrected by increasing the conveyor speed such that the cream line is further away from the lay-down point or re-formulating to a lower reactivity system thus delaying the beginning of the foaming reaction.

Scorching in slabstock foams

Scorching is the term used to describe the pale yellow to brown colour sometimes found at the centre of blocks of flexible polyurethane foam. It is caused by thermal decomposition occurring in the hottest part of the block. Large blocks, especially those made from high water/low auxiliary blowing agent formulations, are particularly prone to scorching.

The following factors can lead to scorching.

Excess water in the formulation

The use of formulations with higher water levels and no auxiliary blowing agent to produce hard, low density foams (see section: "THE EFFECT OF FORMULATION VARIABLES ON FOAM PROPERTIES") is the most common source of scorching problems. The higher the water level in the formulation the higher is the temperature in the foam block. The maximum recommended water level used with CARADOL polyols in the absence of an auxiliary blowing agent is 4.6 parts per 100 parts of polyol. At higher water levels there will be a risk of scorching which may, if combined with other formulation errors, machinery malfunctions or poor block handling or storage, lead to a fire.

As the maximum level of water is critical, any water present in addition to that deliberately added in the aqueous stream could increase the total water level to above the safe figure. Therefore, when producing high water level formulations, particular care must be taken to ensure that polyol or other streams are not contaminated.

Di-isocyanate index

Most of the heat generated in the foaming process comes from the water/di-isocyanate reaction. Consequently in entirely water-blown foams or foams made from formulations with high water/ABA ratios producing foams of density less than 25 kg/m³, the di-isocyanate index should not be higher than 107°.

Metal contamination

Minute traces of transition metals – iron, copper, nickel, etc. – can promote scorching since they greatly accelerate certain oxidation processes. This contamination can arise from new storage tanks or supply lines, or from raw materials being stored in rusty drums.

Fire retardants

The use of phosphorus- and halogen-containing fire retardants invariably increases the likelihood of scorching. The maximum water level may have to be reduced depending on the type and level of retardant being used. Further information on the use of specific fire retardants can be obtained from the manufacturers.
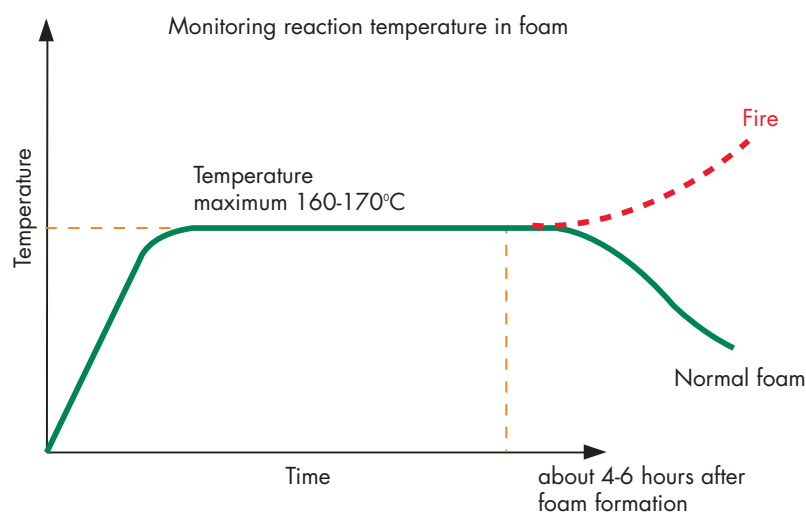
Antioxidant level

CARADOL polyols contain antioxidant which protects the polyol during storage and reduces the risk or severity of scorching. However, if polyol is left for long periods in contact with air especially at high ambient temperatures, then some antioxidant will be used up and the risk of scorch will be increased.

Machine faults

In view of what has been said about the use of high water levels and high di-isocyanate indices, it follows that any machine irregularity leading to an excess of either water or di-isocyanate or, conversely, a deficiency of polyol can cause serious scorching problems. Leaking component lines which can lead to excess air being drawn into the components can also increase the chance of scorch.

As described, scorch is usually seen in the block as a pale brown discoloration. This browning can be masked by coloring the foam brown or black but its significance should not be overlooked. That is, that scorching represents conditions within the foam block which are approaching the point when the whole cure reaction can 'run away' resulting in a fire. For this reason, many experienced foam manufacturers monitor the reaction temperature in the block with a thermocouple. Although the actual curve obtained will depend on the foam density and the block size, etc., four to six hours after manufacture is the critical point where the temperature can begin to rise again if a fire is imminent (see Figure 15).

Figure 15: Monitoring reaction temperature in foam

Monitoring reaction temperature in foam

[Graph with "Temperature" on vertical axis and "Time" on horizontal axis. A green curve rises steeply then plateaus at "Temperature maximum 160-170°C" before declining ("Normal foam"). A red dashed curve branches upward labelled "Fire". A vertical dashed line at "about 4-6 hours after foam formation".]

THE EFFECT OF FORMULATION VARIABLES ON FOAM PROPERTIES

The most important property is density. Flexible slabstock foam density is controlled by the amount and type of blowing agent in the formulation. The primary blowing agent is carbon dioxide derived from the reaction between water and di-isocyanate (see section: "THE BASIC CHEMISTRY"). The more water in the formulation the lower is the density of the foam.

However, the maximum level of water that can be used as the sole blowing agent is 4.6 parts per 100 parts weight polyol (see section: "FAULTS: CAUSES AND REMEDIES"). This gives a foam density of about 21 kg/m³. To produce lower density foam, an auxiliary blowing agent has to be added as well as water.

Figure 16 shows an example of the relationship between blow index* and block density. This graph is based on data obtained at sea level at a temperature of 23°C. At higher temperatures and at altitudes above sea level lower densities will be obtained; the addition of non-reactive ingredients, fire retardants, fillers, etc., will also alter the relationship.

It can be seen from the figure that for, say, a cut foam density of 25 kg/m³ a blow index of 4.05 is required. This can be either 4.05 parts of water per 100 parts polyol or the combinations of water and auxiliary blowing agents such as:

3.3 php water and 6 php Methylene Chloride ($3.3 + {}^{6}/_{8} = 4.05$)

3.2 php water and 2 php liquid carbon dioxide ($3.2 + {}^{2.65}/_{3.3} = 4.05$).

*Blow index is defined as: $\text{Total water} + \dfrac{\text{auxiliary blowing agent}}{\text{ABA factor}}$

where, for example, the ABA factor for Methylene Chloride is 8 and for liquid carbon dioxide is 3.3.

This variation of water/ABA ratio enables foams of various hardnesses to be made at the same density (see below). However, there is a limit to the amount of ABA which can be added without affecting the processing. This limit depends on the ABA used.

Figure 16: Density variation with blow index
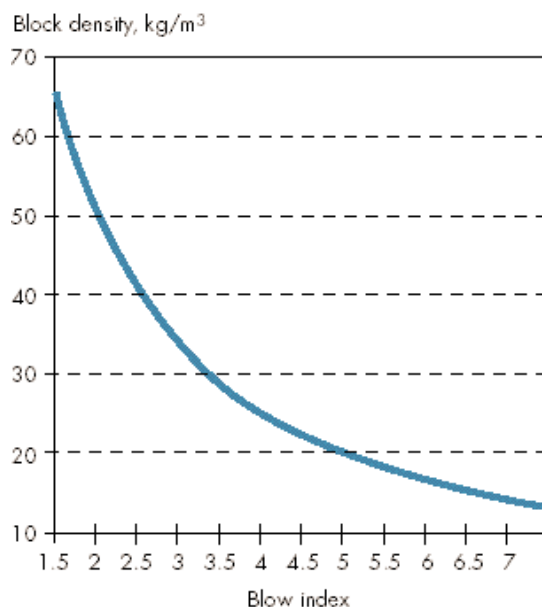
Flexible slabstock foams based on CARADOL SC56-02 and CARADATE 80

The following shows the formulation variables that have a major influence on the physical properties of the foam and their effects. More detailed numerical results are given in the appropriate Shell Urethane Chemicals Technical Bulletins on CARADOL/CARADATE systems for slabstock production.

Di-isocyanate index: an increase will increase:

> *hardness*

and reduce:

> *tear strength*
> *tensile strength*
> *elongation.*

ABA level: an increase will decrease:

> *density*

but if density is held constant by using the same blow index, then increasing the ABA level will be the same as lowering the water level, i.e. an increase will decrease:

> *hardness*
> *tear strength*
> *tensile strength*
> *elongation.*

Water level: an increase at fixed ABA level will decrease:

> *density*

but if density is held constant by decreasing ABA level to give constant blow index then an increase in water will produce an increase in:

> *hardness*
> *tear strength*
> *tensile strength*
> *elongation.*

THE EFFECT OF CLIMATIC CONDITIONS ON FOAM PROPERTIES

Atmospheric pressure during foam manufacture and absolute humidity during foam storage have a great influence on foam physical properties and if not allowed for can result in the foam being out of specification. As the drive for product consistency increases, the ability to predict the effect of climatic variations and to correct formulations to counteract these effects is of great benefit.

An increase in atmospheric pressure (compared to the 'normal' pressure which depends on the geographic location and especially the altitude of the factory – see Figure 17 below for atmospheric pressure and altitude guidelines) will result in an increase in foam density which in turn will produce an increase in foam hardness. An increased absolute humidity (the weight of water per unit volume of air) during curing will cause foam hardnesses to decrease but will not affect the foam density.

To demonstrate the effect, Figures 18 and Figure 19 below show the variations which could be expected at a 'standard' factory, with temperatures maintained at 20°C and located at sea level, using our formulation above in the course of a production year.

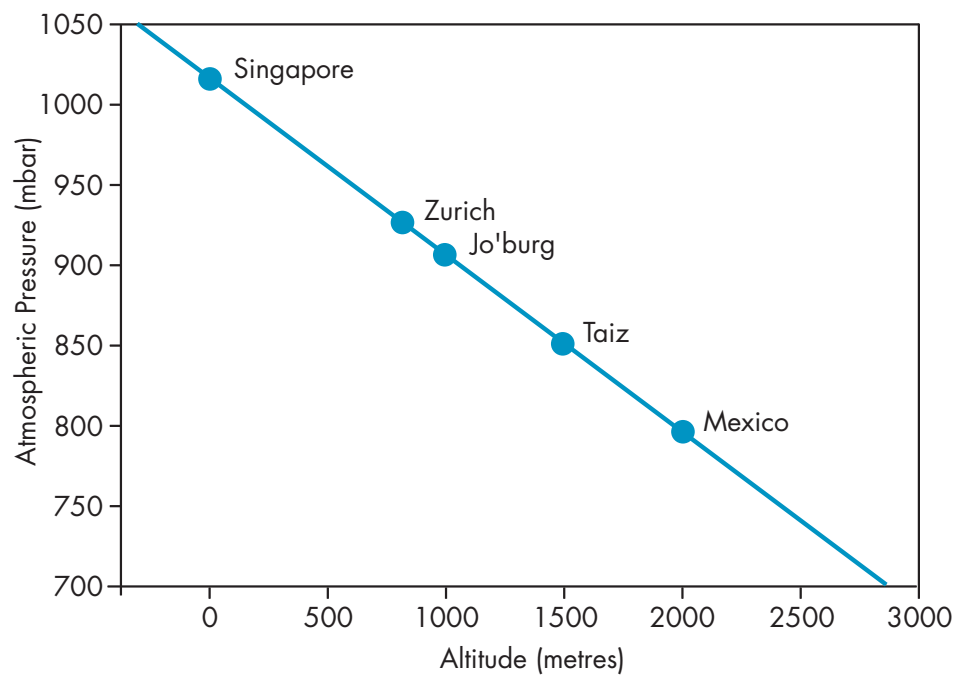## Figure 17: Atmospheric pressure variation with altitude

Figure 18: Effect of atmospheric pressure on density
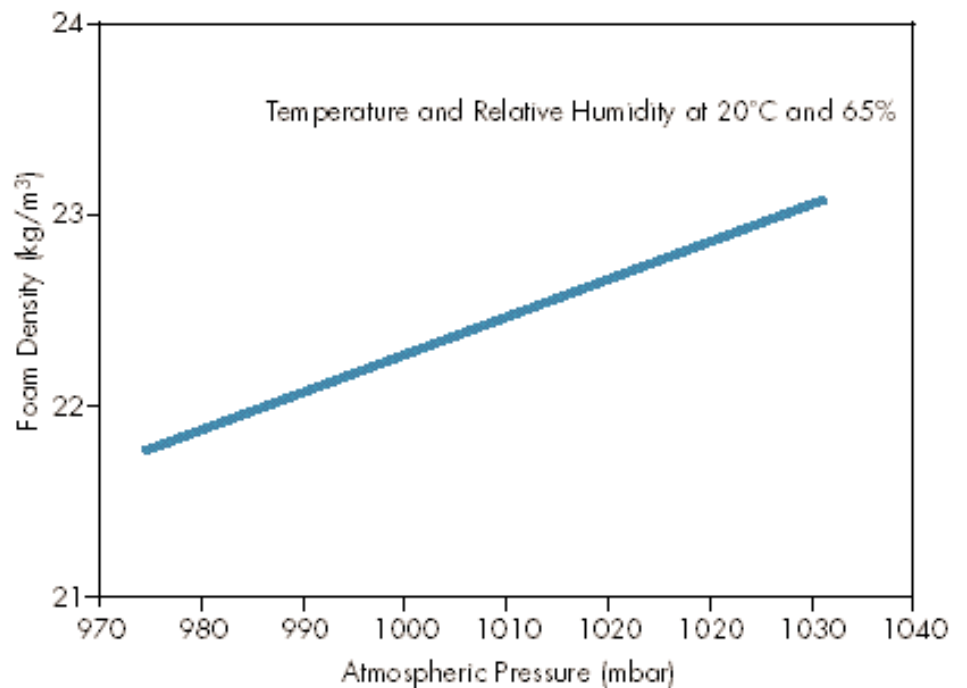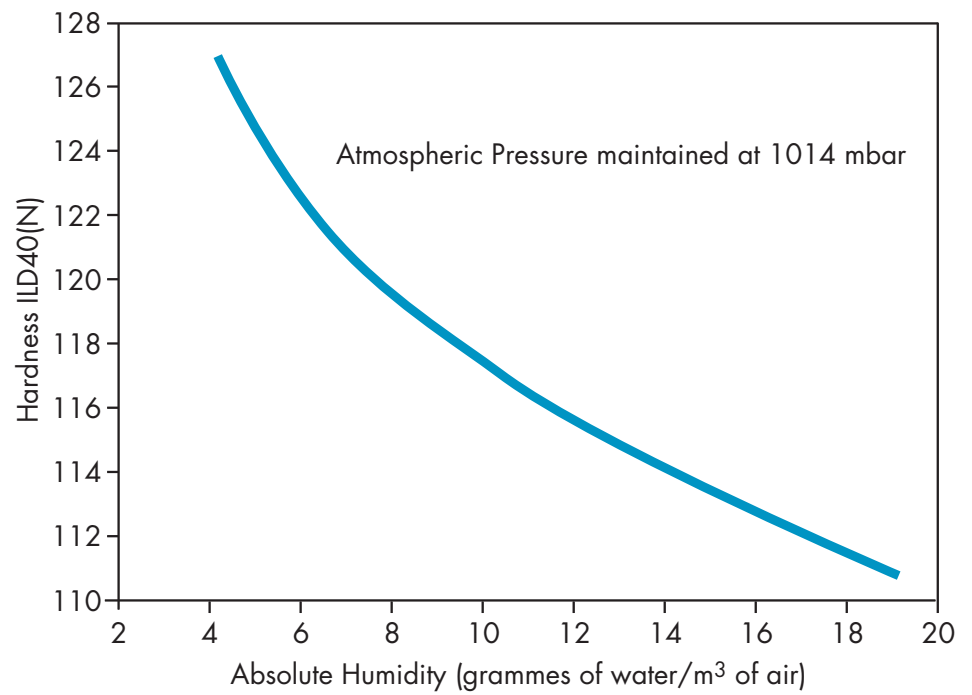
Figure 19: Effect of absolute humidity on foam hardness

A detailed study of a foam producer's data over a period of time enables the accuracy of the predictions to be tailored to suit a particular machine in a particular environment.

FOAM TESTING

The three most important tests for flexible foam are:

density, porosity and hardness.

Other tests such as tensile strength, elongation at break, tear strength, compression set and effect of heat and humid ageing may be required.

Reference should be made to the "*Foam Testing*" module of this manual for more information.

HEALTH RISKS AND INDUSTRIAL HYGIENE

The technical data sheets on Shell Urethane Chemicals contain a section on handling precautions which outlines the hazards, if any, associated with each product and the recommended handling procedures. The major points on the main hazards are discussed in the *"HSE"* module of this manual and must be read along with the data sheet and safety data sheet. It is also considered essential that producers of polyurethane foams view the videos available from the International Isocyanate Institute or ISOPA, available from any reputable di-isocyanate supplier, and read the accompanying notes.

FIRE HAZARDS

As emphasised in the section: "BLOCK HANDLING", the greatest hazards of fire are in the hot block curing and longer term storage areas; the precautions advisable in these areas are reviewed there.

Strict fire precautions should also be maintained in raw material storage areas and around the slabstock machine. Although most of the raw materials used have relatively high flash points (an exception is DMAE, flash point 40°C) they are organic materials and are flammable or decomposed by fire. Fires involving tanks and lines containing di-isocyanates are particularly dangerous since the heat increases the vapour hazard. Other materials, e.g. tin catalysts and blowing agents, produce hazardous thermal decomposition products.

A fire-fighting contingency plan should be drawn up in consultation with the local fire brigade and made known to all plant personnel. Fire-fighting equipment, including the full face breathing equipment with independent air supplies needed in case of a fire involving di-isocyanates, should be regularly inspected and maintained. Fire-fighting drills should be held at regular intervals.

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Readers' Notes and Comments