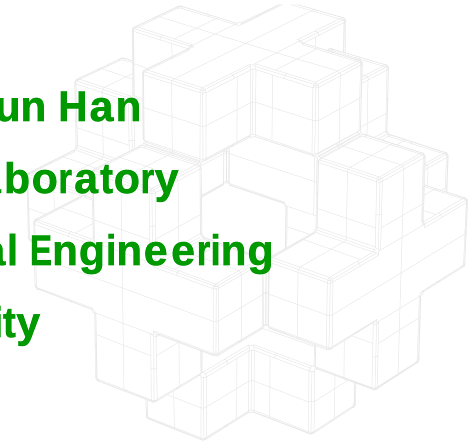
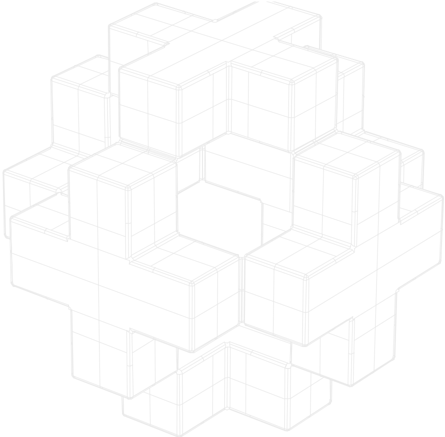
Chemical Product Design

Sungwoo Cho and Chonghun Han
Intelligent Process Systems Laboratory
School of Chemical and Biological Engineering
Seoul National University

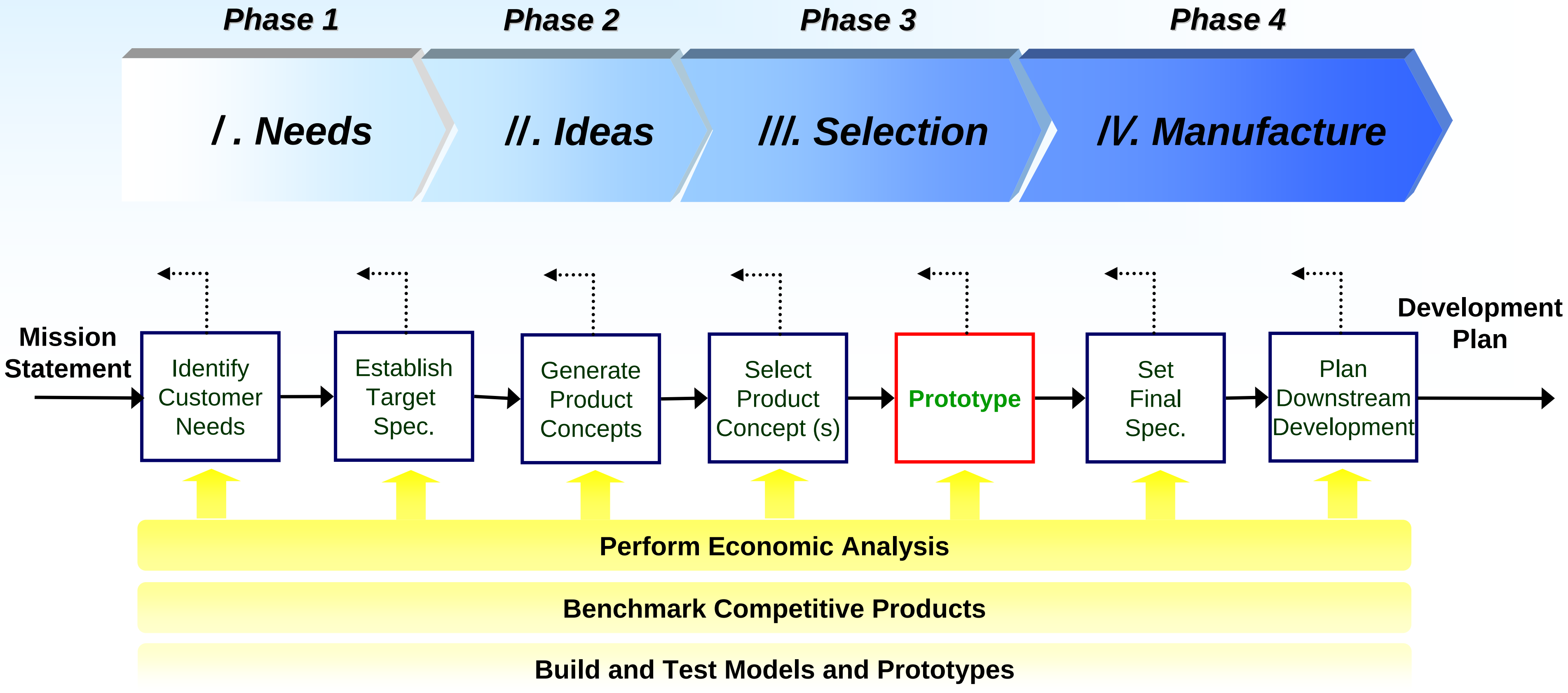


PART IX. Prototyping

- Prototyping



Procedure



Phase 1 *Phase 2* *Phase 3* *Phase 4*

I. Needs *II. Ideas* *III. Selection* *IV. Manufacture*

Mission Statement

Identify Customer Needs

Establish Target Spec.

Generate Product Concepts

Select Product Concept (s)

Prototype

Set Final Spec.

Plan Downstream Development

Development Plan

Perform Economic Analysis

Benchmark Competitive Products

Build and Test Models and Prototypes

Using Thermodynamics

A Thermodynamic Example: Solvent Selection

- **The solvent of choice must dissolve the substances of interest at specific levels – the traditional criterion**
- **The solvent should not be prohibitively expensive, another traditional criterion**
- **The solvent must also meet safety and toxicity constraints – the newer, yet equally important criteria !!!**

⬇

- So how do we choose? Trial and error using existing solvents?
- What about mixtures? This could get really expensive……
- What we would like is a way to screen solvent without actually testing solvents……

Using Thermodynamics

A Thermodynamic Example: Solvent Selection

- **Choosing an Alternative Solvent Blending Based on Solubility Parameter**

- Hildebrandt: Regular Solution Theory

$$\mu_2 = \mu_2^0 + RT \ln x_2 + \omega x_1^2$$

where μ_2 is the chemical potential of the product solute

μ_2^0 is its value in a reference state (pure 2 at the specified T and p), the “standard state”

ω is an activity parameter with the dimensions of energy per mole

x_1, x_2 are the mole fractions of the solvent and product

- ω is the key to selecting alternative solvents

$$\omega = \underline{V}_2 (\delta_1 - \delta_2)^2$$

where V_2 is the molar volume of the solute and the δ are the so-called solubility parameters

- **In traditional solubility parameter theory, it is assumed that if the excess enthalpy approaches zero, the two components are completely miscible**

Using Thermodynamics

A Thermodynamic Example: Solvent Selection

- **Given the previous development, it is assumed that if the solubility parameter**

  of the solvent is equal to that of the solute the pair will be miscible

- **There are several different ways to find the “right” solvent**

- **Using simple solubility parameter theory**

  - Knowing the value of δ for the solute, look up values of various solvents in tables
  - Choose solvent (intuitively), calculate δ using fundamentals
  - Group contribution theory: assemble a solvent using group contribution values

Using Transport Fundamentals

Example: A Perfect Coffee Cup

We have been asked by a chain of upmarket coffee shops to develop an improved coffee cup. The current cup has a volume of about 200 cm^3 and a total surface area, including the top and bottom, of 200 cm^2. The improved cup should keep the coffee area at an optimal “drinkable” temperature, estimated to be 51°C, for as long as possible. Data for coffee cooling in the current covered and uncovered cups are shown in Figure 4.2-1

Generating ideas has led to three major directions for an improved cup:

- **A better insulated cup**
- **A cup with its own, self-contained heater; and**
- **A cup with a thermal reservoir that melt around 50 °C**

Select among these ideas to see which merits further development !!!

Using Transport Fundamentals

Example: A Perfect Coffee Cup

First, a simple unsteady heat balance on the filled cup.

$$\frac{d}{dt}\left[\rho \hat{C}_v V T\right] = UA\left(T_0 - T\right)$$

where ρ is the coffee's density; $\hat{C}_v\left(=\hat{C}_p\right)$ is its specific heat capacity; V is its volume

t is the time; U is the overall heat transfer coefficient averaged over the coffee

T and T_0 are the temperatures of the coffee and the surrounding air, respectively

Assuming that the heat capacity is independent of temperature, this expression can be integrated

$$\frac{T - T_0}{T\left(t=0\right)0 - T_0} = e^{-t/\tau}$$

where, $\tau = \dfrac{\rho \hat{C}_v V}{UA}$

Using Transport Fundamentals

Example: A Perfect Coffee Cup

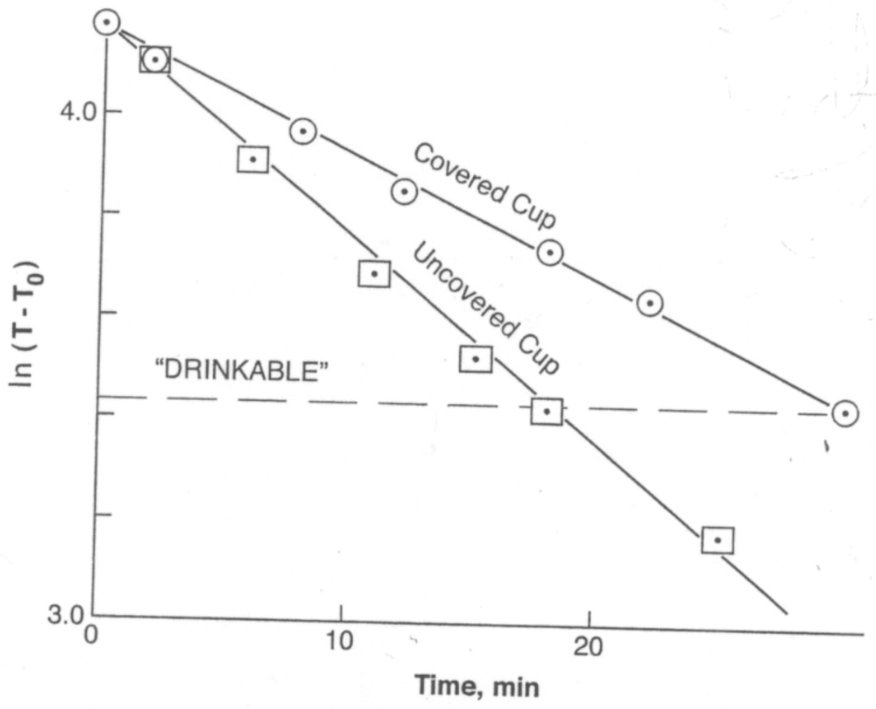


Figure 4.2–1. Cooling a Coffee Cup. The slope of the data on this semilogarithmic plot is a measure of the overall heat transfer coefficient of the cup. In these experiments, the ambient temperature was 20°C.

The slope of the line gives τ ; One then can look up values for P and $\hat{C}_v$ (use values for water), and estimate V and A assuming an 8-oz cup.

For the uncovered cup, the slope (τ) is 24 minutes, and hence one can solve for U (=57 W/m^2-°K).

For the covered cup, τ is 40 minutes and hence U is 17 W/m^2-°K

Using Transport Fundamentals

Alternative # 1 – Create Better Insulation

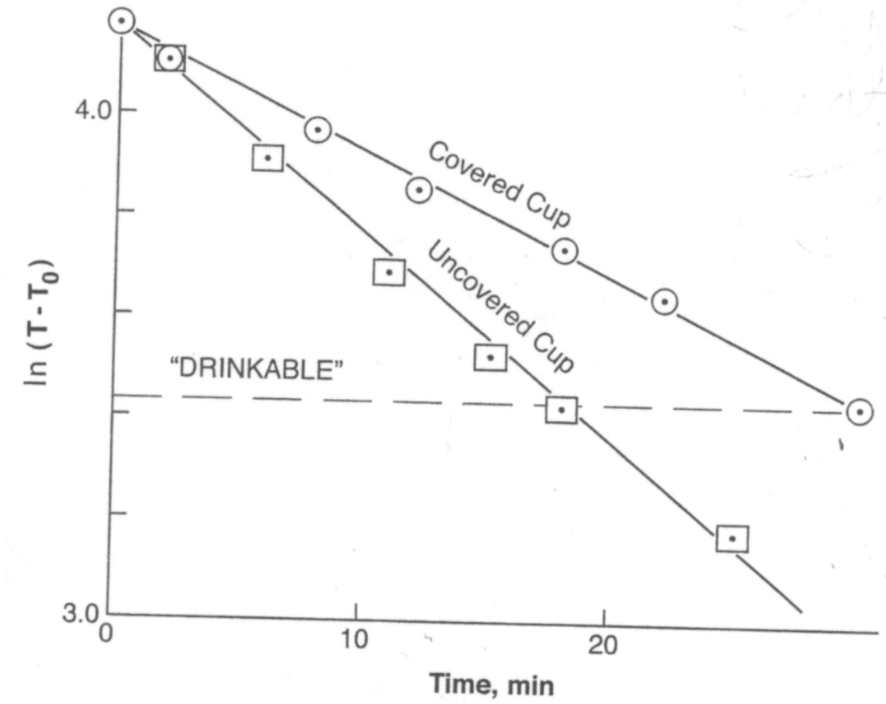


Figure 4.2–1. Cooling a Coffee Cup. The slope of the data on this semilogarithmic plot is a measure of the overall heat transfer coefficient of the cup. In these experiments, the ambient temperature was 20°C.

Here, the situation remains the same, although the slope of the line in Figure 4.2-1 is shallower (U becomes smaller). Hence, the coffee temperature drops more slowly, but still starts out above the "drinkable" temperature and finishes below the drinkable temperature. Basically, same product, one simply has to wait longer to drink ones coffee – could lead to road rage

↓

Powerful idea merits further development !!!

Using Transport Fundamentals

Alternative # 2 – A Cup with Its Own Heater

Here, we start with the same cup, when the temperature drops to the "drinkable" value, the heater kicks in and maintains the temperature at the drinkable point.

Again, $Q = U A\left(T - T_0\right)$, plugging in some representative numbers:

$$Q = \frac{57\ W}{m^2 K}\left(0.04\ m^2\right)\left(51 - 20\,°C\right) = 70\ W$$

An average c-cell battery provides about 1W, so we will need a lot of batteries for this concept… Perhaps a combination coffee cup / free weight.

⬇

It just does not make sense !!!

Using Transport Fundamentals

Alternative # 3 – Using a Chase Change to Generate the Needed Heat…

Again, we start with the heat flux $Q = U A \left(T - T_0 \right)$

Now, we choose a compound that melts near 50 °C with a heat of fusion of $\Delta \hat{H}_f$, such that when the coffee cools to 50 °C, the compound solidifies, releasing its heat of fusion, keeping the coffee temperature near 50 °C. How long can we keep the coffee warm after it reaches 50 °C ???

$$Q = energy \; / \; time$$

$$m \; \Delta \hat{H}_{fusion} = Q t = U A \left(T - T_0 \right) t$$

Hence, time is then:

$$time = \left(1 / Q \right) * \left(\Delta \hat{H}_{fusion} \right) * m$$

Compounds that we might choose to perform this task include hydrocarbon waxes such as pentacosane ($C_{25}H_{52}$) which melts at 53 °C or beeswax which melts at about the same temperature whose heats of fusion are 220 and 180 kJ/kg, respectively. As such, if we want to keep our coffee at 50 °C for 20 minutes in a covered cup, we need approximately 0.07 kg of beeswax, or 2,5 ounces

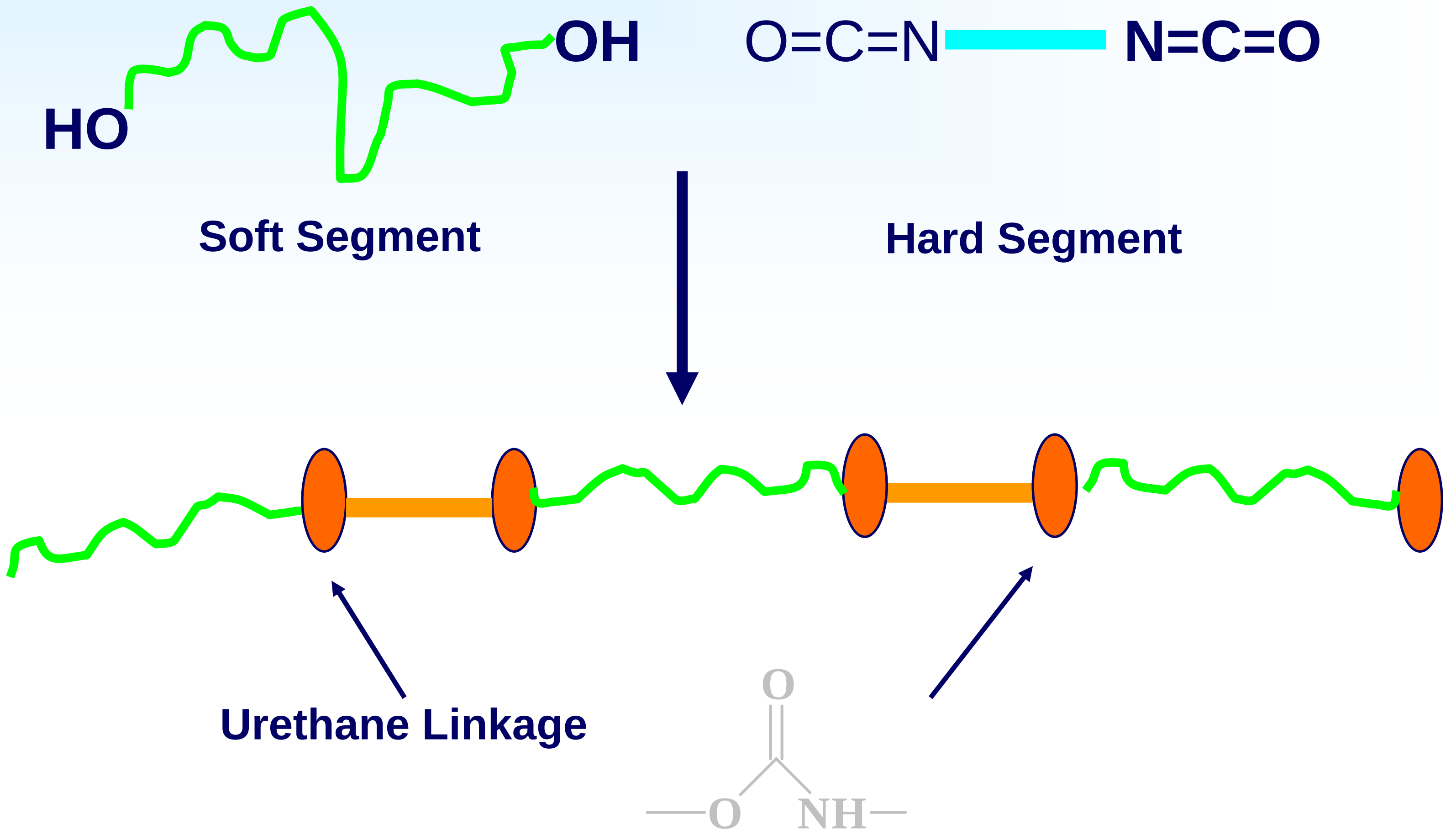
Polyurethanes

A new example: Creating a new polyurethane tissue engineering scaffold for bone repair

- Key Questions: How fast should it cure ?
- Hint: This involves both kinetics and heat transfer !!!

Polyurethanes

Polyurethane Structure



HO OH

O=C=N N=C=O

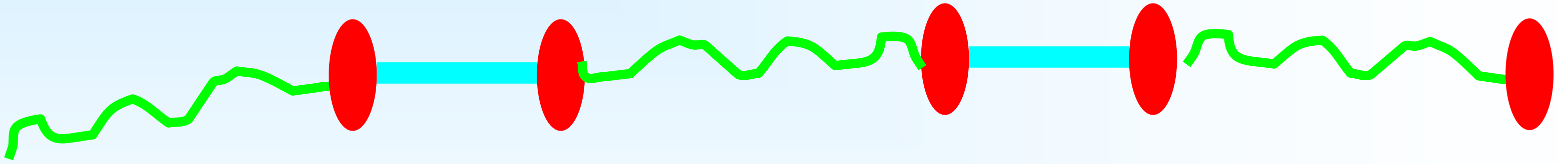
Soft Segment

Hard Segment

Urethane Linkage

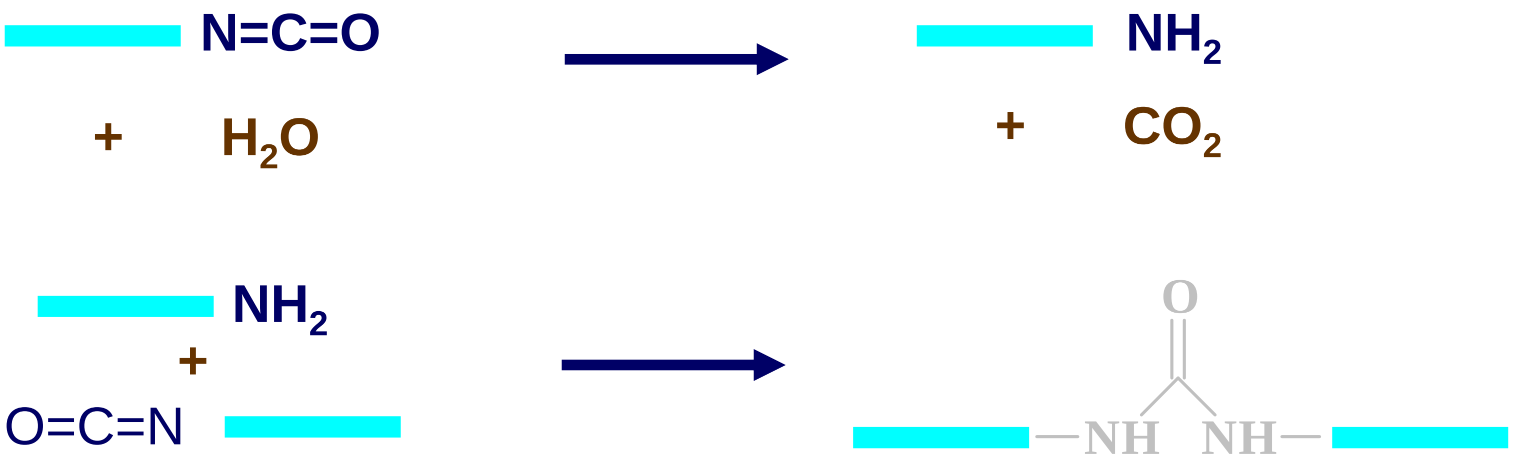
Polyurethanes

Polyurethane Diversity



Immense variety of "soft" and "hard" segments available; polyurethanes can be foamed continuously or in molds, can be spun as fibers from solvent or cast as films, can be used in injection molding.

Reaction Between Isocyanates and Water

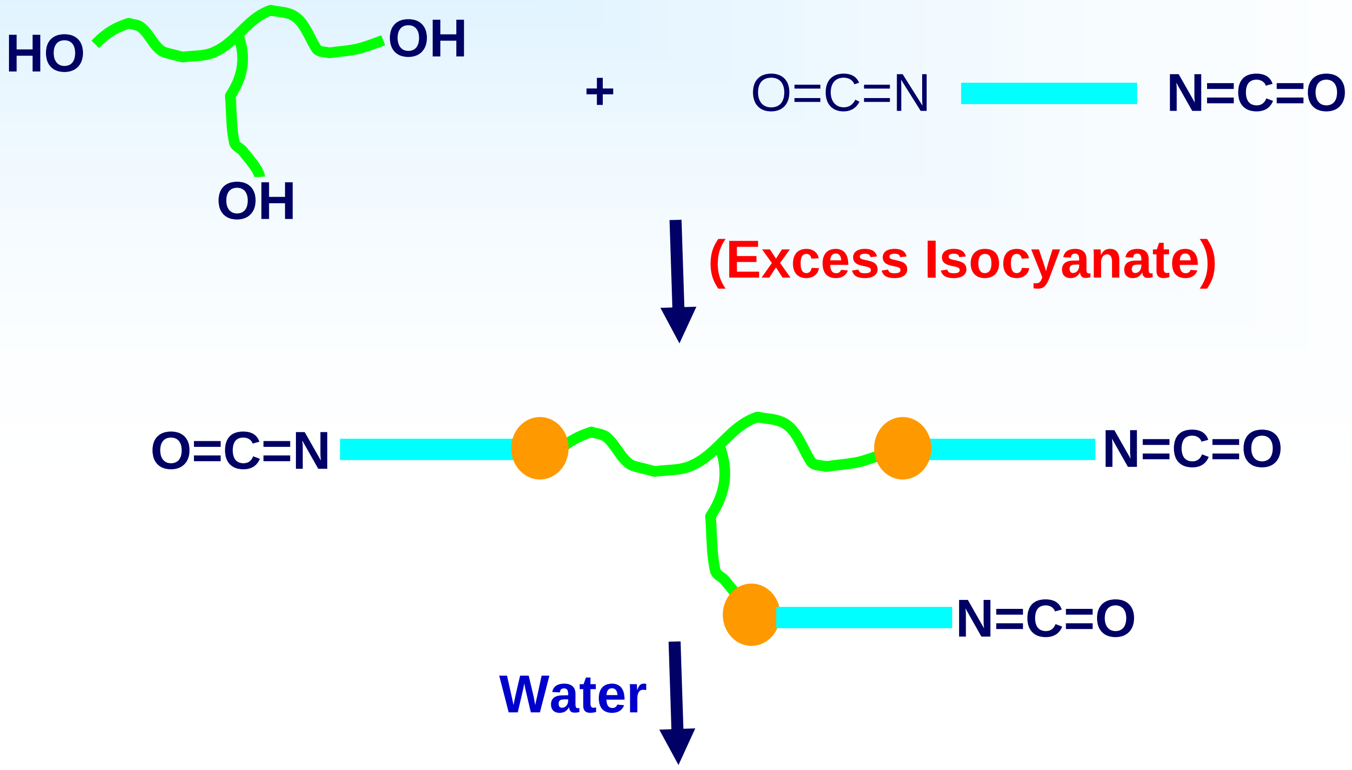


N=C=O + H_2O → NH_2 + CO_2

NH_2 + O=C=N →

Polyurethanes

Cross-linked Polyurethanes: Prepolymer Approach



(Excess Isocyanate)

Water

Cross-linked Foam Plus CO_2

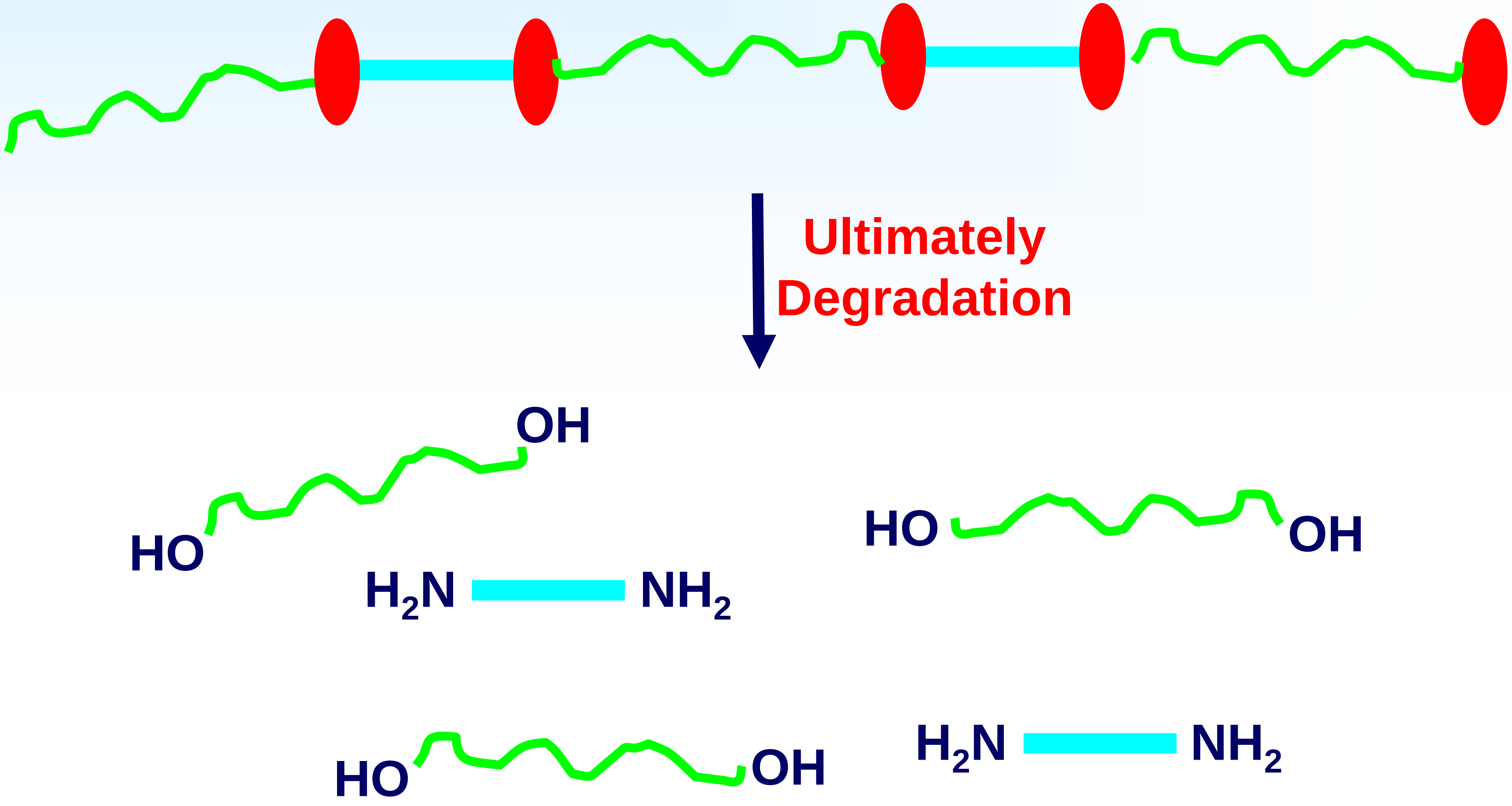
Polyurethanes

Extraordinary Versatility

- Thermoplastics (Automotive)
- Coatings, Organic and Water-Borne
- Foams, Flexible (seat cushions) and Rigid (insulation)
- Fibers, Thermoplastic Elastomers (Lycra, etc.)
- Thermosets

Polyurethanes

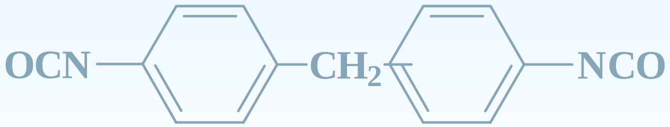
Why are they net typically used as scaffolds for tissue engineering ?



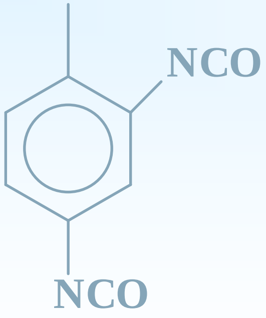
Ultimately Degradation

Polyurethanes

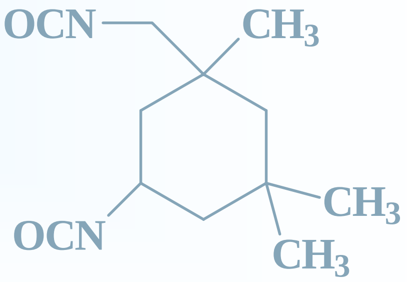
Commercially available di-isocynates are not meant to be used *in-vivo* !!!



MDI

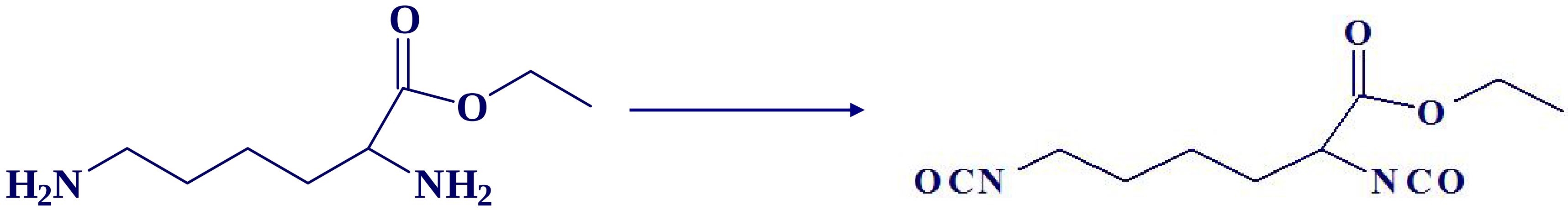


TDI



IPDI

Potential Solution

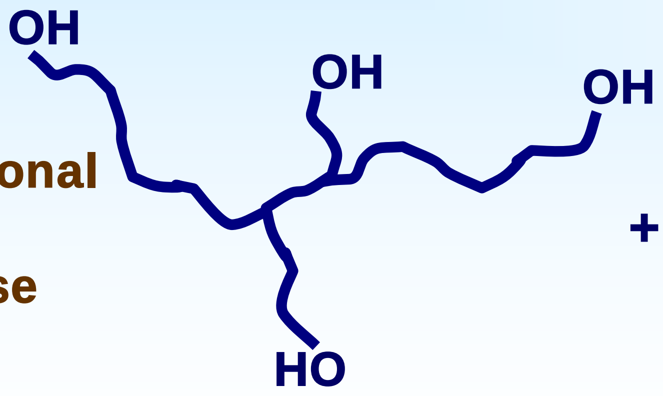


Lysine (ethyl ester) Di-isocyanate

Polyurethanes

Cross-linked Polyurethanes: Network Formation via Branched Polyol

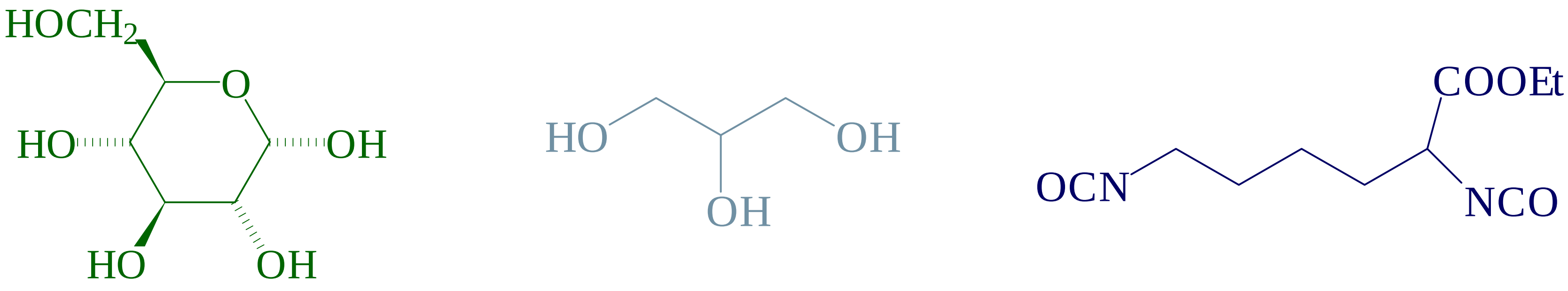
Multi-functional polyol,
or in our case glycerol
or glucose



+

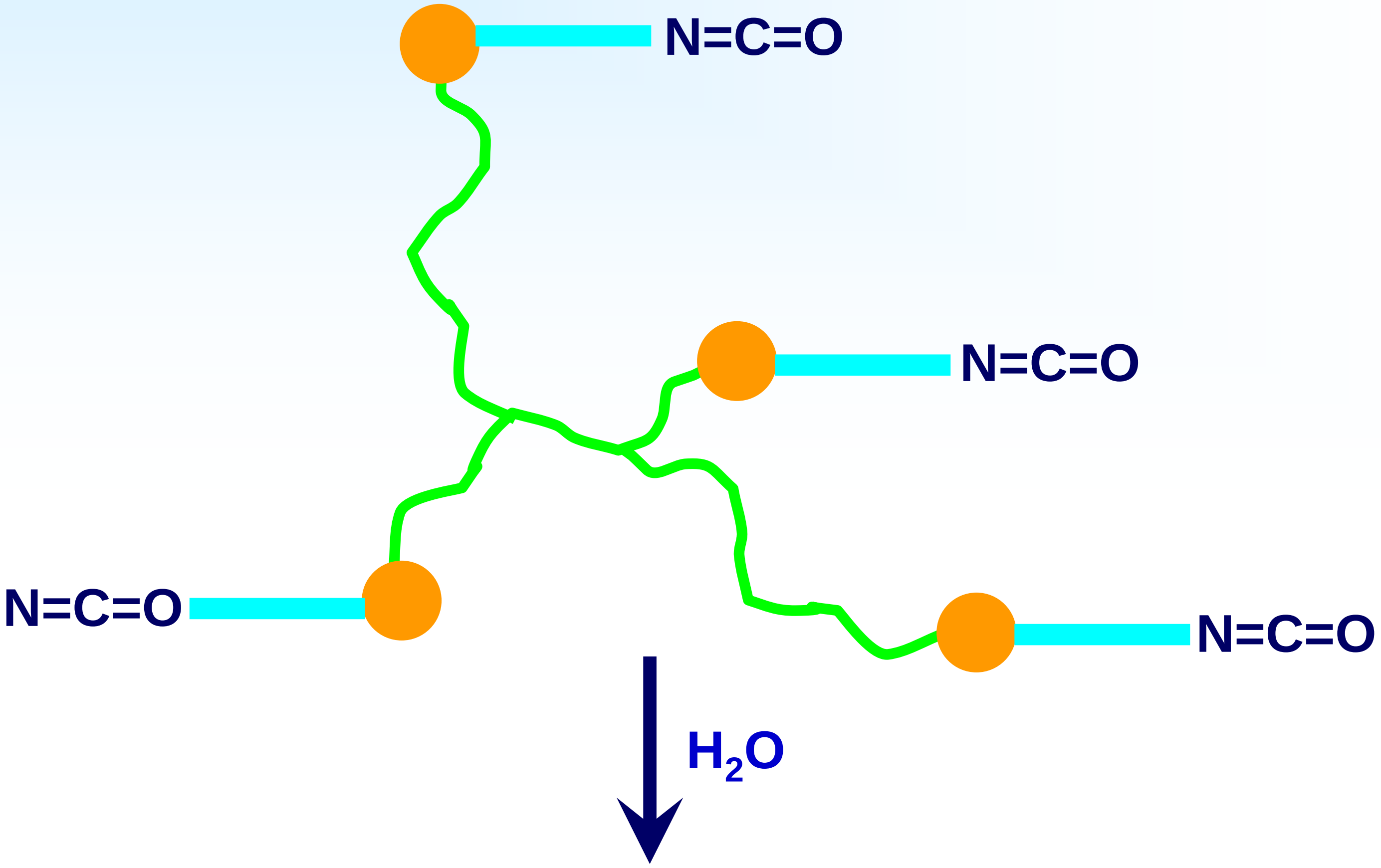
Lysine di-isocyanate, in excess

LDI-based Polyurethane-urea Foams



Polyurethanes

Generation of Foams from Prepolymers



Crosslinked Urea/Urethane Foam

Polyurethanes

Problem: **Hoe to design the tissue adhesive / scaffold such that it cures without**
creating so much heats as to damage surrounding tissue ?

Basically, we would like to determine what the temperature profile is within the curing
material – ideally the maximum temperature does not greatly exceed 40 °C
during the cure process.

$$\rho V C_p \left\{ dT \ / \ dt \right\}$$

= {heat generated by reaction}

– {heat transferred to surroundings by conduction/convection}

Polyurethanes

First, **the rate term**: If we assume a large excess of water at any given time,
we can approximate the rate as being first order in isocyanate:

$$Rate = r = -d[NCO] / dt = k[NCO]$$

Life is usually simpler if we put things in terms of extent of reaction, x, rather than concentration. Extent of reaction is defined by:

$$X = ([NCO] - [NCO]_0) / [NCO]_0 = 1 - ([NCO] / [NCO]_0)$$

$$\frac{dx}{dt} = \frac{-1}{[NCO]_0} \frac{d[NCO]}{dt}$$

Polyurethanes

As such, after substitution, the rate term becomes:

$$Rate = r = -d\left[NCO\right]/dt = k\left[NCO\right]$$

or $$dx/dt = k\left(1-x\right)$$

Integrating, we find: $$x = 1-\exp\left(-kt\right)$$

Such that the rate is $$r = \left[NCO\right]_0 dx/dt = \left[NCO\right]_0 k\exp\left(-kt\right)$$

⬇

This seems reasonable, but what has been forgotten ?

Polyurethanes

The temperature varies in this problem with time, such that the rate constant k also varies with time !!!

As such, we shall leave the rate, for the time being, as:

$$r = -d[NCO]/dt = [NCO]_0 \, dx/dt$$

where $dx/dt = k(1-x)$ and k varies with T

Hence, the generation term becomes the following:

$$Generation = \Delta H_r V\left([NCO]_0 \, dx/dt\right)$$

Where the volume has been added to create the proper units of energy/time. Further, the rate constant will vary with temperature in the usual way:

$$k = A \exp\left(-E / RT\right)$$

Polyurethanes

Finally, the heat transfer term, is as per usual:

$$Heat\ \ Transfer\ = UA\left(T - T_0\right)$$

where T_0 is the temperature of the surrounding tissue, or 37 °C

Hence, the design expression becomes:

$$dT/dt\ = \left(\left[NCO\right]_0 \Delta H_r/\rho C_p\right)\left(dx/dt\right) - \left(UA/\rho V C_p\right)\left(T - T_0\right)$$

- How does one then proceed to make decisions on the design of the product?
- Which parameters are critical? Which may require measurement?
- Can we make reasonable predictions as to behavior of the product?

Polyurethanes

Where do we find the necessary information ?

- Physical Properties: C_p *and* ρ
- Chemical Properties: $k\ (including\ A\ \&\ E),\ \Delta H_r$
- How do we deal with $U,\ V,\ A$? What is $[NCO]_0$?

Finding $[NCO]_0$:

If mass of material = m, weight fraction of –NCO groups in the material w_r

is M_r, and

the molecular weight of the reactive groups is M_r, then:

$$[NCO]_0 = \left(m * w_r / M_r\right) / \left(m / \rho\right) = w_r\, \rho / M_r$$

Polyurethanes

So, some qualitative observations:

$$dT/dt = \left(w_r \Delta H_r / M_r C_p\right)\left(dx/dt\right) - \left(UA/\rho V C_p\right)\left(T - T_0\right)$$

- The heat of reaction term increases as w_r, ΔH_r, or k increases, as expected. k is highly dependent upon T

- The heat transfer term is highly dependent upon the surface to volume ratio, U, and T as expected

- Euler’s method would probably give a reasonable first approximation at a solution

Polyurethanes

Euler's Method

$$Y_{new} = y_{old} + \left(dy \,/\, dx \right)_{x=x_{old}} * \Delta x$$

Flow sheet:

1. Set all physical parameters, calculate k at $T = T_0 , x = 0$
2. Choose Δt , set $t = 0$
3. Calculate new x given $dx / dt = k \left(1 - x \right)$, calculate new dx / dt
4. Calculate new T using dx / dt and dT / dt = function below.
5. Increment t , calculate new k using T, go back to step 3, iterate.

$$dT / dt = \left(w_r \Delta H_r / M_r C_p \right) \left(dx / dt \right) - \left(UA / \rho V C_p \right) \left(T - T_0 \right)$$

Polyurethanes

What about cure time ???

One could decrease the effect of the heat of reaction by reducing w_r but the cure time might then increase to the point where the product is untenable.

Once the numerical solution is developed, one can easily see how the maximum temperature and cure time depend upon the various para-meters, i.e.., how sensitive the system is to these parameters. This will allow one to make reasonable molecular choices.