# METALLURGICAL PILOT PLANTS (*)

## Theory and Practice

M. J. Shahani &
T. Banerjee,
National Metallurgical
Laboratory, Jamshedpur.

In this presentation, a brief review is made of the theory and practice of piloting industrial prototypes and attention is particularly focussed on methods of scale-up and their usefulness in equipment and plant design.

There exist prolific references in the literature on general Pilot Plant engineering and Scale-up Fundamentals. What may be considered a 'Bible' on the subject is a recent volume by R.E. Johnstone and M.W. Thring on "Pilot Plants, Models, and Scale-up Methods in Chemical Engineering".

## The Pilot Plant:

Engineering in all its branches, and particularly the design of metallurgical process equipment, is profusely interlaced with empirical relationships and practical approximations. As a result, the pilot plant and scale-up stage in research and development has become quite essential and is perhaps the most exciting and fascinating phase in development work. This is, of course, followed by the more ardous assignment of processing the small scale data and its translation into design data for the industrial prototype.

The necessity of undertaking a pilot plant programme is likely to remain undiminished until our knowledge of reaction kinetics, heat transfer, fluid flow, and general engineering properties and their correlation accumulates to the extent that scale-up becomes possible on purely fundamental bases or perhaps even by means of reliable statistical analysis.

Summed up: the justification for piloting a plant is stated in the words of Baekeland: "Commit your blunders on a small scale and make your profits on a large scale" by minimizing the costs of error and

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(*) Paper for presentation at the Symposium on Pilot Plants in Metallurgical Research and Development - 15th to 18th February, 1960, Jamshedpur.

variation. The final decision to set up a pilot plant is governed by the merits of individual projects in view of three possible alternatives:

(i) The direct design and installation of production units.

(ii) Procurement of existent engineering and production know-how

(iii) The piloting or modelling of a suitably scaled down plant or portions of a plant.

The decision having been made, the first most desirable step is that of detailed programming in order to unravel and to remedy any possible pit-falls that may hamper or in any way set back the programme.

Weighty factors in such planning are considerations such as capital and operating costs, costs of calculating, correlating, and interpreting data; selection of imaginative personnel with a talent for practical improvization and an ability to visualize a process in all its detail and foresee any possible scale-up pitfalls; provision of adequate safety precautions and the recovery or disposal of waste effluents; and most of all, the close and active co-ordination of all groups in the programme as a pre-requisite for smooth liaison and communication among the groups.

Pilot plants may serve a specific purpose or may be utilized for several concurrent functions as shown in Table I.

## Design and Fabrication:

The data available to the pilot plant engineer from bench experiments or crude small scale operations are, usually, at best sketchy and scanty. Nevertheless, bench data serve as the bed-rock basis for pilot plant investigations and later for scale-up computations.

Actual techniques of scale-up may not play as big a role at this stage of development as they will later for the design of the full scale prototype.

What may be done at this stage is to rationalize the process under investigation into sections or unit processes upon which the design of individual items of equipment may be used. Factors that should be recognized for the design of small scale pilot units are versatility of operation and easy amenability to modification during the course of experimental campaigns. At the same time, these factors must invariably be compatible with the fundamental and engineering requirements of heat, mass, and energy transfer processes, etc. It would, for example, be inadvisable to utilize a crude open pan filter for a small scale run when a pressure filter is likely to be utilized for the job in the full scale plant. Similarly, data

| PILOT PLANTS | | | | | | COMMERCIAL |
|---|---|---|---|---|---|---|
| TYPE → | SEMI TECHNICAL | | | PILOT | | SEMI COMMERCIAL |
| SCALE → <br> FUNCTIONS ↓ | BENCH | SEMI | MULTI PURPOSE | DEVELOPMENT | CONTROL | |
| DETERMINATION OF BASIC DATA | * | * | * | | | |
| SCALE-UP EFFECTS | * | * | * | * | | |
| TRANSITION: BATCH TO CONTINUOUS | * | * | | (*) | | |
| ECONOMIC ASSESMENT | * | | | * | | * |
| MATERIALS OF CONSTR. | * | * | | (*) | | |
| TYPE OF PLANT & EQUIPMENT | * | * | * | * | | |
| VERIFICATION OF BASIC DATA | * | * | * | * | | |
| IMPROVEMENT STUDIES MINIMIZE OVERDESIGN | | | * | * | * | |
| OPERATIONAL KNOWHOW PERSONNEL TRAINING | | (*) | * | * | * | * |
| FEED STOCKS CATALYST QUALITY | * | * | * | | | |
| VARYING OPERATING CONDITIONS | | | | * | * | * |
| MARKET EVALUATION CONSUMER ACCEPTABILITY | | | | | * | * |
| TROUBLE SHOOTING | | | | | * | * |
| PRODUCT SPECS. | | | | * | * | * |
| UTILIZATION OF LOW GRADE MATERIALS | | | * | * | * | * |
| ENVIRONMENTAL RESEARCH | | | * | * | * | * |
| DEMONSTRATION | | * | | * | * | |

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TABLE - 1

based on diffusion and reaction rates in stationary non-agitated solids-gas reactors can scarcely be expected to be useful in the design of a continuous rotary kiln or a fluo-solids reactor envisaged in the full scale plant.

Throughputs should be controllable by instruments and related to yields. Yields should be large enough for testing and analysis and, if necessary, for market research.

Above all, the design of small scale pilot equipment must keep in sight the techniques that will be used for scaling-up data. Equipment may need to be modified so that data procured will fit scale equations. For example, it may be necessary to incorporate suitable mechanical devices in equipment to minimize scale effects due to non-ideal conditions such as eddy currents, vortexing, cavitation, channelling, etc.

Fabrication of pilot plant equipment should be keyed to the basic requirements of versatility and ease of modification. In all events, the intentions and purposes of the designer must be respected by the fabricator in spirit as much as letter.

## Operation and Costs:

The commissioning of a pilot or prototype plant creates rather unique and numerous start-up problems compounded further by problems of stabilizing operating conditions and general 'line-out' till comparative steady state operation yields reliable and reproducible data.

Process control, automation, homogeneity of raw materials and other factors of a similar nature also influence the yielding of reliable and useful data by a pilot small scale campaign.

The actual tangible returns for expenditure incurred in piloting a plant or process are however unamenable to computation and often border on the speculative. Costs accounted may be capitalized and suitably amortized. General costing and accounting methods are fairly standard and plentiful sources of cost data and cost methods are available in the literature.

## Scale-up and Allied Problems:

The problem of scale-up comes in at two stages, viz. the setting up of a semi pilot or pilot plant from bench scale data, and then again at the stage of design, fabrication, and operation of the industrial prototype from pilot plant or model data. The former stage usually tends to be a hit and miss affair due to the comparative novelty of similarity principles, and as often due to a lack of significant design data at that stage.

## Similarity Concepts:

The fundamental principle for the scaling up or scaling down of physical and chemical processes is that of similarity which may be either for prediction in the case of new processes or diagnostic when an existing process or piece of equipment is under investigation. The application of this principle implies that a set of dimensionless groups have equivalent values for both the small scale equipment and the full scale industrial prototype. In practice, the similarity principle comprises four different ideal states. These are Geometric Similarity concerning the shape and orientation of the boundaries of a process system; Chemical Similarity which deals with the variation of reactant concentrations; Thermodynamic Similarity involving heat transmission; and finally Mechanical Similarity of four types, viz., Static Similarity in the mechanical and structural fields, Kinematic Similarity in solid and fluid systems in motion, and Dynamic Similarity in gravitational, centrifugal and similar systems.

Virgin regimes, however, seldom exist. Mixed regimes are generally encountered and the trick is in reducing the effects of all similarity regimes except that of the predominating one. This may be done by operating a model or pilot plant in more than one way to emphasize individual types of similarity and correlating the results as a whole. Or, the other method of utilizing mechanical devices may be resorted to.

## Tools for Scale-up:

Based upon similarity principles are several avenues of tackling scale-up problems. Some of the commoner ones are Integration of Differential Equations, Dimensional Analysis, Analog Approaches and Models, and as is often the case, a combination of these tools may be used in the extrapolation of results.

Fundamental differential equations are integrable only for simple cases and their use is therefore limited. One advantage of this method however is that significant variables are not likely to be left out. The Stokes-Navier equation

$$\frac{\Delta p}{\rho V^2} = \phi\left[\frac{\rho V L}{\mu}, \frac{V^2}{Lg}, \frac{\rho V^2 L}{\sigma}\right]$$

for Isothermal Flow of Newtonian Viscous Fluids is a classic example cited in many texts.

In this correlation, the pressure coefficient $\frac{\Delta p}{\rho V^2}$ is expressed in terms of the Reynolds Number $\frac{\rho V L}{\mu}$ and the Froude Number $\frac{V^2}{Lg}$. The last group is the Weber Number which accounts for the surface tension effects.

Dimensional Analysis is a more reasonably manipulative technique for deriving correlations. This tool relates the variables in a process in the form of dimensionless groups or numbers which indicate the prevailing similarity criteria and give ratios of dimensions useful in compiling design data for scaling up the model or pilot plant components.

An example of the usefulness of this tool is its application to heat transfer. For the simple case of free convection from a stationary flat plate with a laminar boundary layer, it is found by dimensional analysis that

$$\frac{h\,d}{k} = \phi\left[\frac{d v \rho}{\mu}, \frac{c\mu}{k}\right]$$

which in terms of the dimensionless notations is

$$\text{Nusselt} = \phi \text{ (Reynolds, Prandtl)}$$

If buoyancy forces arising from the convective process are included, the relationship becomes

$$Nu = \phi\left[Re, Pr, Gr\right]$$

Furthermore, if property values depend on the temperature

$$Nu = \phi\left[Re, Pr, Gr, \frac{T_w}{T_0}\right]$$

At high velocities in the sonic and supersonic ranges.

$$Nu = \phi\left[Re, Pr, Ma, \frac{T_w}{T_0}\right]$$

Then again, at high temperatures and low pressures in gases, the molecular structure influences the transfer of heat, so the ratio there used becomes

$$Kn = \frac{\sqrt{K\pi/8}}{0.499} \cdot \frac{Ma}{Re} = \phi\left[\frac{\mu}{V a d \rho}\right]$$

which is known as the Knudsen number.

Numerical values of these correlations are in the literature. Another use of Similarity and Dimensionless Groups is an application to models. If a model is to be 1/10 full size and the same fluid is utilized, $Re = \frac{d v \rho}{\mu}$ calls for a velocity in the model ten times that in the full scale plant. This may be extremely difficult. However, water may for example be substituted for air of the full scale plant. Then the ratio of kinematic viscosities is 1:12 for water and air. Dynamic similarity can be achieved with water in the model at 1/12 the air velocity of the full scale requirement.

Analog Approaches:

Analog computers based upon the electrical simulation of processes yield data suitable for design of large scale prototypes. It scores over statistical analysis by permitting consideration of a larger number of variables in a reasonable time and over digital

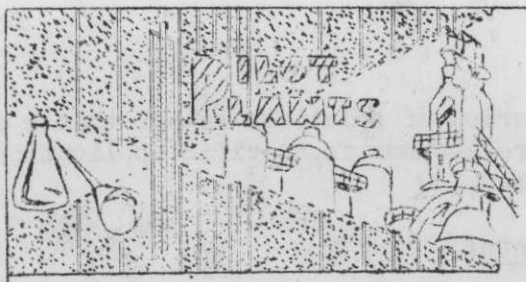

Table - 2

## DIMENSIONLESS GROUPS

1. ARRHENIUS ........ $\frac{E}{RT}$
2. BIOT ............ $\frac{hL}{k}$
3. CAPILLARY ....... $\frac{K(-\Delta p)}{Lg_c\sigma\cos\theta}$
4. CONDENSATION ..... $\frac{h}{k}\left(\frac{\nu}{a}\right)^{1/3}$
5. EULER ........... $\frac{g_c p}{\rho V^2}$
6. FLUIDIZATION ..... $\frac{V_g^3\rho_s}{g\nu\rho_z}$
7. FOURIER ......... $\frac{kt}{\rho c L^2}$
8. FROUDE .......... $\frac{V^2}{gL}$
9. GRAETZ .......... $\frac{wc}{kL}$
10. GRASHOF ......... $\frac{L^3\rho^2\beta g\Delta T}{\mu^2}$
11. KÁRMÁN .......... $\frac{d\rho}{\mu}\sqrt{\frac{2g_c(-l_{wf})}{L}}$
12. KNUDSEN ......... $\frac{\mu}{V_a d\rho}$
13. MACH ..... $\frac{V}{V_a}$
14. NUSSELT ... $\frac{hd}{k}$
15. PECLET .... $\frac{LV\rho c}{k}$
16. PRANDTL ... $\frac{c\mu}{k}$
17. POWER (MIX). $\frac{Pg_c}{\rho N^3 d^5}$
18. Pres.Coeff.. $\frac{\Delta p}{\rho V^2}$
19. REYNOLDS ... $\frac{dV\rho}{\mu}$
20. SCHMIDT .... $\frac{\mu}{\rho D}$
21. SHERWOOD ... $\frac{k_c L}{D}$
22. STANTON ... $\frac{h}{cV\rho}$
23. THRING .... $\frac{\rho c V}{s e T^3}$
24. Vap.Cond.... $\frac{L^3\rho^2 g\lambda}{k\mu\Delta T}$

24a:WEBER ..... $\frac{\rho V^2 L}{\sigma}$

a - acceleration
c - specific heat
D - diffusivity
d - diameter
E - activation energy
e - emmisivity
F - Force
g - acceleration gr.
$g_c$- Newton's factor
h - heat transfer coeff.
k - thermal conductivity
$k_c$- mass transfer coeff.
K - permeability
K - $c_p/c_v$
L - length
N - R.P.M.
P - power consumption
p - pressure
R - gas constant

s - Stefan Boltzmann Co.
T - temperature
t - time
V - linear velocity
$V_a$- velocity of sound
$V_g$- terminal velocity
w - mass flow rate
$\beta$ - cubical expansion
$\Delta$ - difference
$\sigma$ - interfacial tension
$\theta$ - contact angle
$\lambda$ - latent heat vap.
$\mu$ - viscosity
$\nu$ - kinematic viscosity
$\rho$ - density
$\rho_f$ - ref. fluid mass
$\rho_s$ - ref. particles mass
$\rho$ - apparent particles
$l_{wf}$ - friction losses

computers by giving a series of solutions rather than a specific solution. The literature abounds in specific application of analog approaches to actual cases.

## Metallurgical Pilot Plants:

Generally speaking, when a scaled model or pilot plant is employed in metallurgical investigations, a certain leeway is necessary for strict scale-down principles. For example, refractory thicknesses have to be kept greater than proportional scale-down. In other cases, it may be necessary to investigate the process 'piece-meal'. For example, burner design, tuyeres design, etc. can be individually investigated almost on scale under simulated operating conditions in specially designed models. Strict scale-down may actually result in absurd design as in the case of a baby blast furnace which would have to be 900 mm diameter by 24,000 mm tall. In such cases direct calculation of cross sectional areas, ports etc. from pre-set gas velocities and throughputs are made. Factors such as excessive heat losses in low shaft furnaces may be offset by higher blast temperatures, etc.

## The Baby Blast Furnace:

The major obstacle in designing a small blast furnace is that of abnormal heat losses. An increase in the lining thickness at the hearth and bosh is of little effect due to increased erosion and damage to the lining. The raw material size also cannot be scaled down in proportion to the furnace size. This is due to the limitations of pressure drop and possible fluidization of the bed. Uneven descent of the charge would also result. In practice, large sized materials are used for study of fuel rates at required gas velocities and retention times. Factors such as raceways at the tuyeres which are obscured in this manner are separately investigated in non-operating models.

Distribution of materials in a packed blast furnace shaft and its effect on heat and mass transfer has also been investigated.

Traustel has found that the bed depth in small blast furnaces is limited to 5000 mm/6000 mm due to excessive fluidization and blowing losses in shallower beds.

## Pilot Converters:

Similarity principles have been applied to slag and metal dynamics in a converter. It has been found that scale-up is possible on the basis of the Froude Number as the Reynolds group is negligible at the highly developed turbulence and the Froude Number allows for the effects of gravity. Similarly in metal slag emulsification studies, surface or interfacial tension is the controlling criterion and the Weber Group $\frac{L \rho V^2}{\sigma g_c}$ describes the scale-up picture. Other techniques used in converter investigations are oxygen enrichment or higher Si and Mn contents for getting higher temperature to offset the abnormal heat losses characteristic of scaled down furnaces. Small converters of upto 250 kg capacity have been operated to study factors such as refractory lining wear, design of linings and operating conditions versus metal and slag compositions.

References are also available in the literature for the small scale investigations of electric arc furnaces and small scale O.H furnaces.

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