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Publication Date
1975-09-01

Submitted to Chemical Engineering
Education

LBL-4135
Preprint c.1

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September 1975

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

LBL-4135

Critical Path Planning of Graduate Research

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September, 1975

Abstract

Procedures and criteria are developed for applying the critical-path method to the planning of graduate research. Examples of graduate-level chemical engineering research programs utilizing the critical path method are presented.

Introduction

The critical path method (CPM) has proven to be exceptionally beneficial over the last fifteen years for the control of project operations, and for task planning and control in many industries. In addition to its proven success in industry, the critical path method has been applied successfully in the education educational sphere for the planning of chemical engineering curricula.[1] The vast majority of the literature on CPM concerns applications requiring computer solution of the critical path by parametric, linear programming,[2] whereas non-computer methods are needed for the routine application of this method in small laboratory research projects. In this paper, a simplified procedure is presented for applying the critical path method to graduate research programs, using noncomputerized techniques readily available to the student. Recent experience with the method is drawn from several graduate-level chemical engineering research programs.

Basic Concepts

The basic concepts of critical path planning were initially developed in two fundamentally different forms. The "probabilistic" approach was known as Program Evaluation of Research Tasks (PERT) or PERT with costs (PERTCO).[3] In this form, individual research and development tasks, whose duration and cost could not be accurately estimated, were assigned a range of probable duration and cost. These data were then incorporated into a computerized critical-path control program. A second form of CPM, called Project Planning and Scheduling System (PPSS), was predicated on a more deterministic approach, where the controlling variables of individual tasks are assumed to be estimated with reasonable accuracy.[4] The latter approach has been utilized effectively in the chemical and construction industries.[4,5] The deterministic approach is more suitable for graduate research planning provided that the controlling variables can be quantitatively assessed.

The application of the critical path method (CPM) in graduate research programs involves a number of unique differences from traditional applications, however. In industrial projects, the personnel can be periodically changed, whereas the graduate research "crew" cannot. Many operations in industrial programs can often be run in parallel, whereas the graduate student must complete separate tasks in sequence, with only a limited amount of subcontracted work. Also, the industrial product is usually a tangible piece of hardware or construction, whereas the product of graduate research is educational experience and publishable reports, or intangibles such as the acquisition of high-level experties, or a contribution to human knowledge. Finally, the computerized programs developed for large industries such as the chemical industry[6] impose an unnecessary complexity for the graduate student seeking a reasonable plan for his initial or intermediate research, or for the faculty director seeking to optimize his own research program. These differences are taken into account in the method presented below.

Noncomputer CPM

There are three important phases of the CPM method developed here for graduate research. These are summarized in Table I. In the first phase, the overall project is divided into distinct tasks. It

Table I

Steps in the Critical Path Method

Phase I. Project decomposition into a realistic network of task sequences.

A. Assignment of individual tasks.
B. Estimate of times and cost benefits.
C. Construction of a precedence - contribution matrix.
D. Assignments of topical sequences.

Phase II. Critical path determination for a normal project rate.

A. Construction of an arrow diagram.
B. Determination of the critical path.

Phase III. Time-cost-benefit optimization

A. Estimation of times and cost-benefits for a crash rate.
B. Calculation of incremental cost slopes.
C. Determination of the critical path.

Table II

Time, Cost and Cost-Slope Estimates for a Typical Project

Task	Task Name	Normal Rate Time(d)	Normal Rate Cost-Benefit($)	Accelerated Rate Time(d)	Accelerated Rate Cost-Benefit($)	Incremental Cost Slope($/d)
1	Define Problem	5	100	5	100	∞
2	Order Supplies	30*	520	30	520	∞
3	Lit. Survey	5	100	5	100	∞
4	Construct App.	20	1000	10	2000	100
5	Experimental	20	400	20	400	∞
6	Analyt. Calc.	20	700	10	1000	150
7	Data Reduction	10	200	5	200	0
8	Compare Theo & Exp.	10	200	10	200	∞
9	Write Reports	10	200	10	200	∞

*29 day dead time.

is useful to divide long project operations into a sequence of separate tasks. The tasks are then ordered into topical sequences with the aid of a precedence-contribution matrix: each task follows its precedents, but should come before tasks to which it contributes. An arrow diagram is then constructed from which the criticalpath is determined, again using information in the precedence-contribution matrix. The program is finally optimized by calculating the incremental cost-benefits per unit of time saved, for alternative forms of the project tasks.

The noncomputer critical path method proposed for graduate research planning is perhaps best illustrated with an example. Consider a typical set of research tasks arising in a project having both analytical and experimental components. Following the steps listed in Table I, one first lists the individual tasks of the project and assigns values of the time required and the cost-benefit to each, as shown in the left-hand part of Table II. Dead times requiring no work input are separately listed. Next, a precedence-contribution matrix is constructed, as shown in Table III, where the precedent steps are identified, as are subsequent steps which benefit from each step. The information on precedents is then used to construct the topical sequences shown in Table III. Here, for example, task 2 is listed following task 1 in sequence because task 1 is a precedent, whereas task 3 is placed at the start of a new sequence because no precedent step is required. All duplicate tasks numbers in this table could be deleted to simplify the table.

The second phase of the method is the determination of the critical path for a normal project rate. For this, an arrow diagram is first constructed from the information in Tables III and IV, with arrows connecting each step

Table III
Precedence-Contribution Matrix

Tasks Affected \ Tasks	1. Define Problem	2. Order Supplies	3. Lit. Survey	4. Const. App.	5. Exp.	6. Analyt. Calc.	7. Data Reduct.	8. Compare Theory & Exp.	9. Write Rept.
1		P	C	P		P			P
2					P				
3									P
4		C			P				
5	C	C		C			P		
6	C		C					P	
7			C			C		P	
8						C			P
9			C		C	C	C	C	

P = Precedence C = Contribution

Table IV
Assignment of Topical Sequences

	Step Number					
Sequence	1	2	3	4	5	6
A	1	2	5	7	8	9
B	3					
C		4	5	7	8	9
D		6				

to its required precedent steps, as shown by the solid lines in Fig. 1a. Then, Table II is examined to determine the first subsequent step to which a given step contributes. These contributions are denoted by the dotted lines in Fig. 1a.

It is evident from Fig. 1a that task 3 could preceed task 1, but there is no clear precedence requirement. It is appropriate, therefore, to further subdivide task 1 into two parts, where one part requires task 3 as a precedent. Note also, that several tasks are in parallel (i.e., 2, 4 and 6) and could be performed by a large work force. The graduate student constitutes a one-man crew, however, and therefore an addition criterion must be supplied to determine the task sequence. Two criteria are proposed here: (i) Table II is examined for each task in a parallel group (i.e., 2, 4 and 6). The number of contribution entries in the column for each is counted, and the task with the highest number of "C" entries is performed first. Alternately, (ii) the parallel tasks should be further subdivided and ordered so that the graduate student alternates his time between them, thereby gaining experience with all the tasks early in the program. Following criterion (i), one can readily arrive at the critical path program shown in Fig. 1b for the normal program rate. The critical path is denoted by double arrows, while idle time durations are denoted by wavey arrows (e.g., for task 2).

The third phase of the critical path method involves time-cost-benefit optimization by assessing the incremental cost of task modifications. This optimization is perhaps the most important part of the critical path method. The main question is which tasks can be modified, and at what expense in terms of money, required research product or lost educational benefit. Three factors determine the choices: 1) the task must lie along the critical path; 2) the modified task duration must not be less than any parallel task, and 3) the task must have a low cost slope associated with it. The method to follow is first to list the time and cost-benefits for each research task on, for example, an accelerated project rate, as shown in Table I. The incremental cost slope is computed by dividing the incremental cost by the incremental time saving. The acceptance of an accelerated rate for any task requires a low value of the cost slope.

The acceleration of any project step pre-supposes a subcontracting of project labor, often at the expense of graduate research experience. For example, the time required for construction of experimental apparatus can be shorted by purchasing ready-made apparatus, and data-reduction tasks could possibly be shortened by hiring an undergraduate assistant.

With accelerated project rates now accepted for tasks 4, 6 and 7, the resulting critical path becomes that shown in Fig. 1c. Here, the total project time is constrained by the duration of task 2 (i.e., waiting for ordered supplies to arrive) rather than by steps 6 and 4. Consequently, one of the two tasks need not be shortened. Table I shows that task 6 has the higher cost slope, and, therefore, this task should be carried out at the normal rate.

Recent Results with the CPM Method

The critical path method outlined above has been tested in a number of graduate research programs in solid-state electrochemistry, process kinetics and transport phenomena during the past few years. Experience has shown that the initial critical path plan must be revised periodically during the program to take advantages of new discoveries or to avoid limiting difficulties. Experience has also shown a high correlation between task identification and effective task completion by the student. It has also been found that long-term segments of the total program should be subdivided so that the student gains familiarity with all type of program tasks in operation terms early in the program.

The bases recommended for the assignment of individual tasks are summarized in Table V. In addition, task reassignment was found to be useful at an intermediate point in the project, on the basis of forward planning, e.g., use available equipment, or follow up interesting auxiliary results, or on the basis of reverse planning, e.g., application of alternative methods to the same problem, or re-examination of anomalous results. In an example of the method in a graduate research program, CPM was applied to a research project on a cylindrical vapor-phase reactor for the growth of silicon from chlorosilanes. The task list for this project and time estimates in days is shown in Table VI. The total time estimated for this project was 70 days, so that on a half-time research assistantship, a graduate student would be expected to complete this plan in seven months. The task list and priority assignment for this project are presented in the appendix. The arrow diagram constructed from topical sequences showed that tasks concerning the estimation and location of data on transport properties reaction kinetics contributed to many subsequent steps, even though they were not needed until the end of the project in growth process simulations. Consequently, it was important that these

Table V

Bases for Task Assignments in Graduate Research Programs

I. Task Assignment Based on Type of Research Operation

- A. Literature survey.
- B. Critical evaluation of published data.
- C. Analytical developments and computation.
- D. Experimental apparatus construction and operation.
- E. Evaluation of results.
- F. Thesis and report writing.

II. Task Assignment Based on Separation of Sequential Operations

- A. Literary and library activities.
- B. Series of related experiments.
- C. Related analytical developments.

III. Task Assignment Based on Subcontracted Services

- A. Shop construction (e.g., glass, metal, electronics).
- B. Analytical services (e.g., chemical analysis).
- C. Drafting and Photography.
- D. Typing (e.g., thesis, reports).

Table VI

Task List for a Graudate Research Program on Cylindrical Reactors for Chemical Vapor Deposition

Performance Evaluation of Cylindrical Epitaxial Reactors

CR1. Survey literature on performance and operating data (2d).
CR2. Evaluate experimental data for silicon epitaxy (2d).
CR3. Develop reactor models for optimizing the deposition rate and uniformity (10d).

Phase Equilibria

PE1. Literature search of Si-Cl-H system (2d).
PE2. Partial pressure calculation using available computer program (4d).

Transport Properties

TP1. Evaluate estimating methods for transport properties (2d).
TP2. Literature survey for experimental data in Si-Cl-H system (2d).
TP3. Selection of empirical equations for coefficient estimation (4d).

Reaction Kinetics

RK1. Literature survey for silicon growth rates from SiH_4, $SiCl_4$, etc. (2d).
RK2. Determine apparent rate laws and activation energies (5d).

Heat, Mass and Momentum Transfer

A1. Formulate boundary-value problems for cylindrical reactor (2d).
A2. Estimate silicon deposition rates using integral analysis (10d).
A3. Calculate T, c_i and v profiles using series solutions (10d).
A4. Calculate T, c_i and v profiles using available finite-difference program (15d).

tasks be introduced early in the project. The final critical path plan is shown in Fig. 2. Optimization was achieved by subcontracting library research and analytical calculations (tasks A2, CR2 and PE1) to an undergraduate student in a Special Studies program. The critical path plan proved invaluable to the success of this project.

Conclusion

The form of the critical path method presented here differs from earlier forms is having these important characteristics: (1) the educational experience derived from interacting research tasks is counted as a cost benefit, (2) the critical path is constructed with a minimum of subcontracted or simultaneous tasks, and (3) the method presented does not require a computer to apply it. These characteristics make the method readily usable by the student. Actual use in graduate, chemical engineering research programs has shown the method to be profitabily and effectively applied.

Work supported by US Energy Research and Development Administration.

References

1. Cunningham, R.C. and Sommerfields, J.T., Chem. Eng. Educ. 7 (1), 18 (1973).
2. Kelley, J.E. Jr., Operations Res. 9 (3), May-June (1971).
3. Chipman, J.S., "PERT with Costs," Technical Report 112 SRP, WSPACS Working Paper No. 4, Aerojet General Corporation, Feb. 15, 1961.
4. Walker, M.R. and Sayer, J.S., "Project Planning and Scheduling," Report 6959, E.J. duPont de Nemours and Co., Inc., Wilmington, Delaware, March 1959.

5. Fondahl, J.W., "A Non-Computer Approach to the Critical Path Method for the Construction Industry," Technical Report No. 9, Dept. of Civil Engineering, Stanford University, Stanford, Calif., November, 1961.
6. Kurzeja, J.T., Hydrocarbon Processing, April, 1965, p. 171.

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Fig. 1 Task sequencing of a typical graduate research program: a) arrow diagram, b) critical path for a normal program rate, c) critical path for an accelerated rate.

Fig. 2 Critical path plan of a chemical engineering research program on cylindrical reactors for vapor phase growth of silicon.

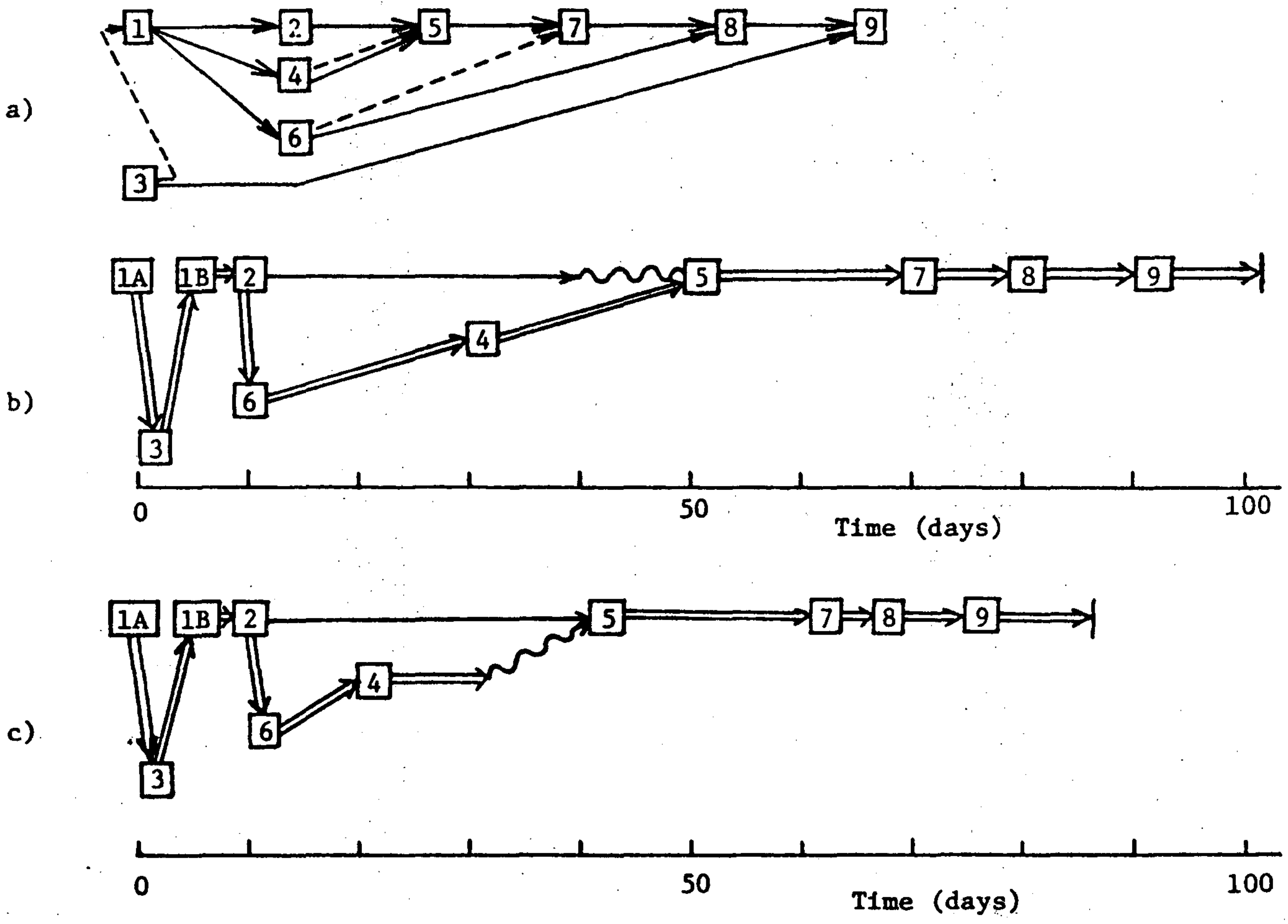

Fig. 1 Task sequencing of a typical graduate research program: a) arrow diagram, b) critical path for a normal program rate, c) critical path for an accelerated rate.

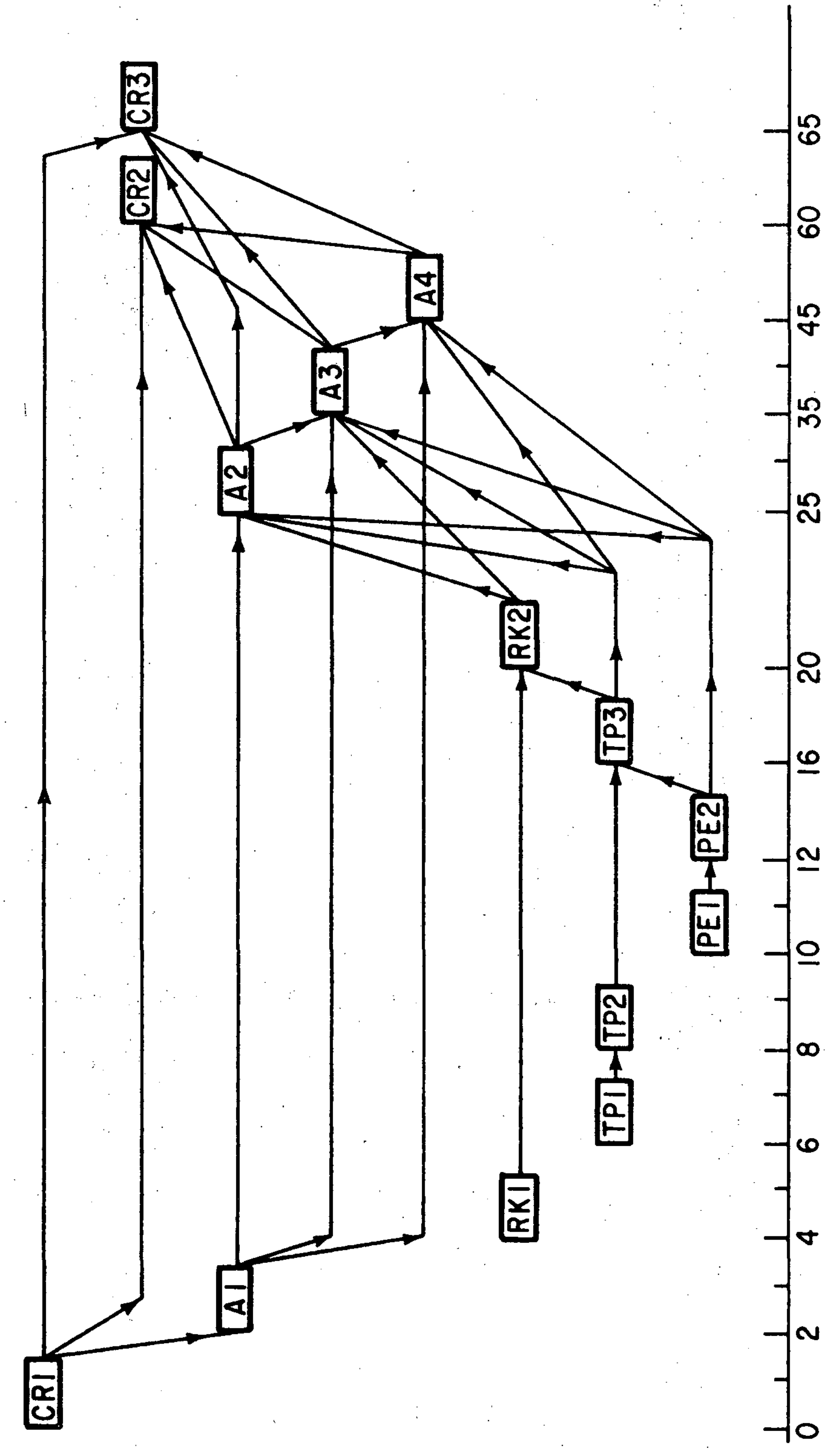

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Fig. 2

Fig. 2 Critical path plan of a chemical engineering research program on cylindrical reactors for vapor phase growth of silicon.

Appendix

Task List for a Chemical Engineering Research Program on Cylindrical Reactors for Vapor Phase Growth of Silicon

Phase Equilibria

Task PE1 (2 days):

Search the chemical literature for data on the vapor-solid phase equilibria in the Si - Cl - H system.

Task PE2 (4 days):

Use the computer program Equica to calculate the partial pressures of vapor phase species in equilibrium with silicon in the Si - Cl - H system ($SiCl_4, H_2$ = input), for component molar ratios Si/H and Cl/H in the range $0 \leq Si/H \leq 0.01$, $0 \leq Cl/H \leq 0.04$, and for an equilibrium temperature of 1200°C.

Transport Properties Determination

Task TP1 (2 days):

Read Reed and Sherwood, Properties of Liquids and Gases (Chemistry Library Reference Desk) to determine the optimum extrapolation and parametric equations for calculating μ, $\mathcal{D}_1$, H_2 and k of H_2 and dilute mixtures of chlorosilanes in H_2 versus temperature and vapor phase composition in the temperature range from 25 to 1200°C.

Task TP2 (2 days):

Search the chemical literature for experimental data on the viscosity, thermal conductivity and diffusion coefficients for H_2 and chlorosilanes in H_2 at 1 atmosphere total pressure and in the temperature range from 25 to 1200°C.

Task TP3 (4 days):

Calculate μ , $\mathcal{D}_i$, H_2 and k versus temperature between 25 and 1200°C for fixed values of the molar ratios Si/H and Cl/H in the equilibrium vapor. Determine parametric equations for μ , $\mathcal{D}_i$, H_2 and k versus Si/H , Cl/H and T .

Reaction Kinetics

Task RK1 (2 days):

Search the chemical vapor deposition literature to locate data on the deposition rate of silicon from SiH_4 , $SiCl_4$ or chlorosilanes in H_2 .

Task RK2 (5 days):

Determine the activation energy and rate law for the surface reaction for silicon deposition from SiH_4 , $SiCL_4$ and $SiHCl_3$ assuming consecutive, equal rates for reactant diffusion, surface reaction and product diffusion.

Analysis of Heat, Momentum and Mass Transfer

Task A1 (2 days):

Formulate the differential equations and boundary conditions for heat, mass and momentum transport in a cylindrical reactor with tapered susceptor. Assume an inner (susceptor) surface temperature of 1200°C, that the outer will heats to 500°C, that the velocity profile at the entrance of the reactor is uniform, and that no deposition takes place on the outer surface.

Task A2 (10 days):

Use the integral analytical method to determine the silicon deposition rate as a function of distance along the tapered-cylindrical reactor inner surface (susceptor). Assume constant transport properties, and a fully developed, laminar entrance velocity profile.

Task A3 (10 days):

Solve for the average temperature, velocity reactant concentration and silicon deposition rate distribution in the space between a right cylinder and a tapered inner cylinder, using the method of superposition of series solutions with predetermined eigenvalues.

Task A4 (15 days):

Use the finite-difference computational method to calculate the velocity profile, temperature profile, reactant and product concentrations and silicon deposition rate distributions in the cylindrical reactor with a tapered susceptor when the input reactant is H_2 containing 1% of a silicon reactant, SiH_4 , $SiCl_4$ or $SiHCl_3$.

Commercial Cylindrical Reactor Performance

Task CR1 (2 days):

Search the commercial and applied chemical engineering literature for performance and requirements data concerning cylindrical reactors for chemical vapor deposition of silicon.

Task CR2 (5 days):

Evaluate experimental data for the chemical vapor deposition of silicon in a cylindrical reactor.

Task CR3 (5 days):

Develop a simple model for interpreting the silicon deposition rate non-uniformity in commercial cylindrical reactors for silicon deposition, and predict the optimum reactor geometry and operating conditions to maximize the deposition rate uniformity within the reactor.

Table 1

Precedent Steps Required for Each Task

Task	Precedent Steps
PE1	-
PE2	-
TP1	-
TP2	-
TP3	TP2, PE2
RK1	-
RK2	SK1, TP3
A1	CR1
A2	A1, TP3, SK2, PE2
A3	A1, TP3, SK2, PE2
A4	A1, TP3, SK2, PE2
CR1	-
CR2	CR1, (A2 or A3 or A4)
CR3	CR2, (A2 or A3 or A4)

Table 2

Priority Assignments to Topical Sequences

Topic	Main Priority				Subsequence Priority
Cylindrical Reactors	I			CR1	3
			CR1 →	CR2	2
			A_i,i=2,3,4 ↗		
			CR2 →	CR3	1
			A_i,i=2,3,4 ↗		
Analyses	II		CR1 →	A1	1
				A2	2
			A1 →	A3	3
			RK2 ↗	A4	4
Reaction Kinetics	III			RK1	1
			RK1 →	RK2	2
			TP3 ↗		
Transport Properties	IV			TP1	1
			TP2 →	TP3	2
		PE1	PE2 ↗		
Phase Equilibria	V			PE1	1
				PE2	2

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