American Institute of Chemical Engineers

STUDENT CONTEST PROBLEM

1973

345 East 47 Street • New York, New York 10017

Problem

The Commercial Development Section of Nabamo Chemical Company has completed a preliminary market survey of future demand for allyl alcohol and glycerine in the Caribbean zone. The Process Design Section proposes to synthesize these compounds from 3-chloro-1-propene (allyl chloride). The foreseeable market would require an allyl chloride plant with an approximate capacity of 22 million pounds a year. Gas-phase, thermal chlorination of propene has been proposed as the route to allyl chloride. See references 1 through 5.

The allyl chloride plant design given in simplified form in Figure 1 of reference *5* was checked by the Nabamo Process Design Section. Alternate processing schemes, such as hydrochloric acid recovery by a direct quench, and simplifications were studied with the aim of minimizing capital costs. The most recent suggestion is to use a fluidized bed reactor as an alternative to other chlorinator designs.

Although information on fluidization engineering and design is available (*7*), Nabamo Chemical Company prefers help from outside sources and is soliciting bids for the design, construction, and startup of the chlorination reaction section of the plant.

You as a chemical engineer for one of the prospective bidders are requested to prepare a report to serve as a basis for a bid for the package. The capital and the yearly operating costs of your bid must compete with Nabamo's costs shown in Tables I, II, and III. Information and suggestions to assist you in preparing the report follow.

INFORMATION AND SUGGESTIONS

1. For chlorination reactor design use the following operating conditions:

Reaction temperature:	Minimum 750°F.
	Maximum 1,040°F.
	Best range 950° to 990°F.
Reactor pressure:	Maximum 45 lb./sq. in. gauge
	Normal 30 lb./sq. in. gauge (inlet)
Space velocity:	2.61 sec.$^{-1}$ (at 32°F., 14.7 lb./sq. in. abs.)

2. Raw materials are supplied by pipeline at 80°F., 60 lb./sq. in. gauge. The propene is 99.8 wt. % pure, containing 0.2 wt. % propane. The chlorine is 99.5 wt. % pure, containing 0.5 wt. % inert gases of molecular weight 28.
3. The crude allyl chloride produced must be available at 120°F., 9 lb./sq. in. gauge minimum.
4. Nabamo's Process Design Section considers the following material balance representative of the actual process flows from a chlorination reactor designed to produce a net of 22.3 million pounds a year of allyl chloride.

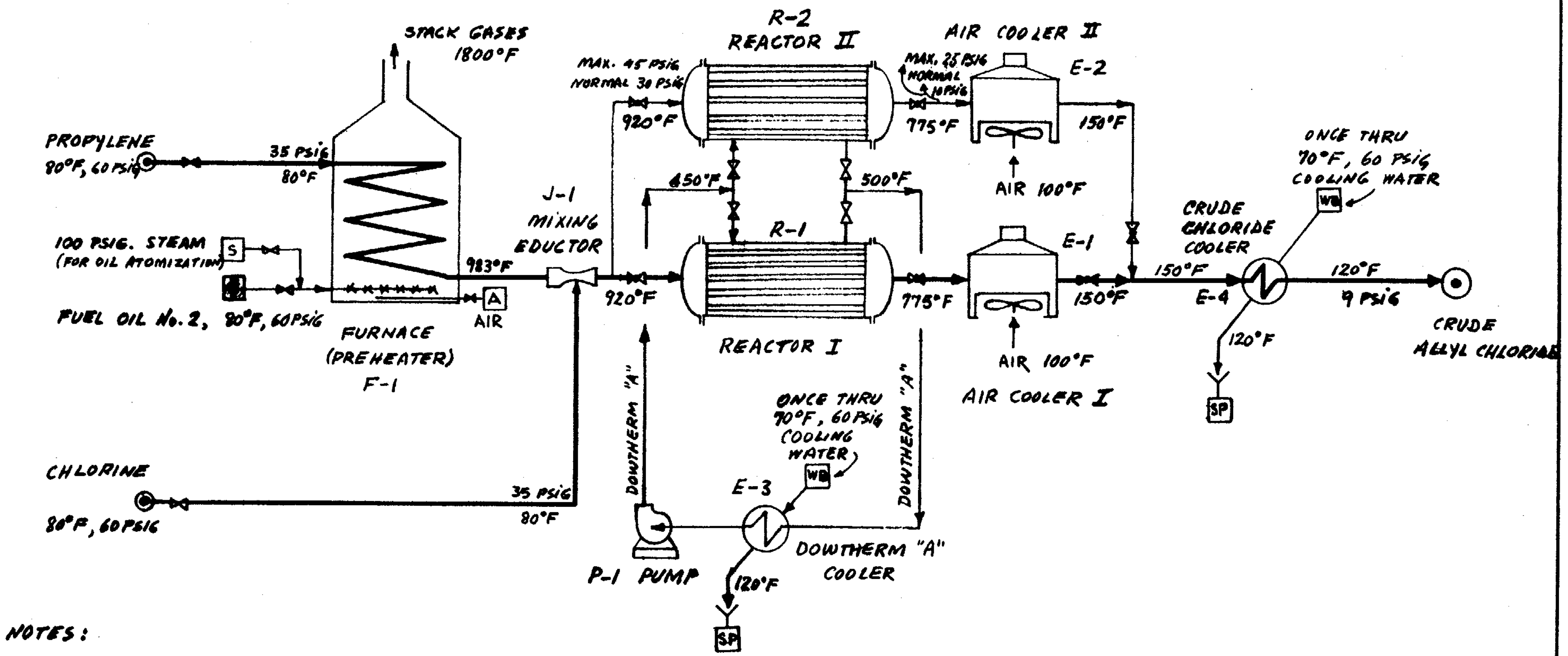
(lb.-moles/hr.)

Components	Molecular weights	Feed streams Propylene	Feed streams Chlorine	Product crude chloride
C_3H_8	44.09	0.357		0.269
C_3H_6	42.08	178.234		139.334
Cl_2	70.906		46.973	0.101
HCl	36.46			46.331
Isopropyl chloride	78.54			0.088
2-Chloro propene	76.53			1.010
Allyl chloride	76.53			37.359
1,2-Dichloropropane	112.99			1.141
1,3-Dichloropropene	110.98			2.854
2,3-Dichloropropene	110.98			0.351
Trichlorides	145.43			0.088
Carbon (lb.-atom)				1.497

Carbon, which sticks to the walls of the reactors and coolers operated above 400°F., must be scraped off every two weeks.

5. Prepare a process flow diagram similar to Figure 1 showing the fluidized bed chlorination reactor and other equipment in the chlorination section of the proposed allyl chloride plant.
6. Briefly describe the operation of the process shown by your flow sheet, pointing out the advantages and giving solutions to any possible problems that you foresee are inherent in the setup that you select. Justify, in terms of bench scale and pilot plant findings and the type of equipment used, the way ethylene and chlorine are fed to the reactor: mixed before or after preheating and then fed to the reactor, mixed inside the reactor, preheated, etc.
7. Summarize in one table, as shown in Table I, the equipment required by your flow sheet. Determine its f.o.b. cost by the technique of K. M. Guthrie (*8*) and, if needed, use cost data similar to those collected by Popper (*9*). Indicate in each case the source of your cost. For the purpose of your work, assume all costs, including equipment, labor, supervision, taxes, capital, etc., to be the same as in the continental United States.
8. In a table like Table II show the total capital costs, calculated by K. M. Guthrie's technique (*8*), scaled to July 1, 1973.
9. In a table similar to Table III, which defines specific costs, show your yearly total crude allyl chloride cost, determined with the technique reported by Peters and Timmerhaus (*11*).
10. Substantiate your design with engineering calculations based on accepted engineering design methods and equations properly referenced by bibliographic citations. Summarize the calculations in an appendix.

Additional information needed follows.



NOTES:

- R-2 AND E-2 OPERATE ONLY WHEN R-1 AND E-1 ARE BEING CLEANED
- THERE IS AN EMERGENCY PUMP P-2 INSTALLED
- MAXIMUM TEMPERATURE IN R-1 OR R-2 IS 1023°F

FIGURE 1

PROCESS FLOW DIAGRAM
CHLORINATION SECTION
ALLYL CHLORIDE PLANT

BY	FILE	DATE
N.B.		8-16-72

TABLE I. Allyl Chloride Reaction Section

EQUIP. NO.	NO. of PCS.	EQUIPMENT SERVICE	DESCRIPTION TYPE & SIZE	MAT'LS. OF CONSTR.	BY ESTIMATOR TOTAL QUANTITY	UNIT	UNIT COST $	TOTAL COST $
F-1	1	Propylene Furnace	q = 5.5 Million Btu/Hr	Steel	1		22,000	22,000
		(Process Heater)	Design Pressure 60 psig					
			Design Temperature 2000°F					
R-1	2	Chlorination Reactors	q = 3.0 Million Btu/hr	Steel	2		3,600	7,200
R-2		(1:1 Fixed Tube Sheet Heat	Design Pressure 50 psig	Tubes				
		Exchanger)	Design Temperature 1040°F	and				
			Heat Transfer Area 330 Ft²	Steel				
				Shell				
P-1	2	Dowtherm Circulating Pump	Normal Output 290 gpm.	Cast	2		1,980	3,960
P-2			Head: 65 Ft of Fluid	Steel				
		(Type: Centrifugal)	Motor: 7½ HP	Case				
			ΔP = 25 psi; gpm x ΔP = 7250	and				
			Operating Temperature 550°F	Impeller				
E-1	1	Allyl Chloride Air Coolers	q = 3.39 Million Btu/Hr	Finned Steel	2		2,300	4,600
E-2	1		Air Cooling Area 145 Ft²	Tubes				
		(Finned Tubes)	Design Pressure 50 psig.	and				
			Design Temperature 1040°F	Steel				
			Tube Length: 6 Ft.	Shell				
E-3	1	Dowtherm Cooler	q = 3.0 Million Btu/Hr	Steel	1		1,200	1,200
		(1:1 Fixed Tube Sheet	Design Pressure 50 psig	Tubes &				
		Heat Exchanger)	Heat Transfer Area 63 Ft²	Shell				
E-4	1	Crude Chloride Cooler	q = 0.709 Million Btu/Hr	Steel	1		3,840	3,840
		and Partial Condenser	Design Pressure 50 psig	Tubes				
		(1:1 Fixed Tube Sheet	Design Temperature 200°F					
		Heat Exchanger)	Heat Transfer Area 364 Ft²	Steel				
				Shell				
J-1	1	Propylene-Chlorine		Steel	1		200	200
		Mixing Eductor						
Total 1968 f.o.b. Equipment Cost					TOTAL			43,000

NOTE: SPACE AT LEAST ONE LINE BETWEEN ITEMS.

TABLE II. Summary of Capital Investment Estimate

Equipment	Furnace F-1	Pumps P-1, 2	Exchangers R-1, 2 E-1, 2, 3, 4	Eductor J-1	Total
1968 f.o.b. equipment cost	$22,000	3,960	16,840	200	43,000
Field materials	7,260	2,832	12,024	2	22,118
Direct field labor	6,578	2,760	10,609	18	19,965
Freight, insurance, and taxes	1,760	317	1,347	16	3,440
Indirect costs	13,266	3,532	14,600	64	31,462
Total installed cost, in 1968	50,864	13,401	55,420	300	119,985
Escalation to July 1, 1973	14,191	3,739	15,462	84	33,476
(escalation factor 1.279)	65,055	17,140	70,882	384	153,461
Add 20% for contingency	13,011	3,428	14,177	76	30,692
Fixed capital costs:	78,066	20,568	85,059	460	184,153
Fixed price contractor fees, 10%	7,807	2,057	8,506	46	18,416
Total capital costs	$85,873	22,625	93,565	506	202,569

TABLE III. Summary of Yearly Operating Costs[‡]

Basis: 8,000-hr. operation/year

Manufacturing Costs		
• Raw materials		
Propylene 1,851,2 (lb./hr.) × 8,000 hr./yr. × $0.035/lb.	$ 518,336	
Chlorine 3,330.7 (lb./hr.) × 8,000 hr./yr. × $0.038/lb.	$1,012,533	
		$1,530,869
• Utilities		
Electricity (P-1) (*) 10 kw. × 8,000 hr. × $0.01/kw-hr.	$ 800	
Fuel oil (F.1) 5.12mm. B.t.u./hr. × 8,000 hr. × $0.45/ mm. B.t.u.	$ 18,432	
Cooling water (E-3, E-4) 150 gal./min. × 60 × 8,000 × $0.022/1,000 gal.	$ 1,584	
Steam (F-1) 90 lb./hr. × 8,000 × $1.00/1,000 lb.	$ 720	
		$ 21,536
• Direct production costs		
• Operating labor: 2 men/shift × 4.2 (†) × $10,000/man	$ 84,000	
• Supervision and clerical labor: 25% (operating labor)	$ 21,000	
• Operating supplies: 10% operating labor	$ 8,400	
• Maintenance and repair labor: 5% (fixed capital costs)	$ 9,208	
• Maintenance and repair materials: 2.5% (fixed capital costs)	$ 4,604	
• Laboratory labor: 1 man × 1 shift × $12,500/man	$ 12,500	
		$ 139,712
• Fixed charges		
Depreciation: 10% (total capital costs)	$ 20,257	
Local taxes: 0.6% (fixed capital costs)	$ 1,105	
Insurance: 0.4% (fixed capital costs)	$ 737	
		$ 22,099
• Plant overhead: 100% operating labor	$ 84,000	
plus: 100% maintenance & repair labor	$ 9,208	
		$ 93,208
Total Book Manufacturing Yearly Costs		$1,807,424

*Includes 3 kw. for fan for E-1.
†Factor for continuous operation with men working 8-hour shifts.
‡mm. = 1,000,000.

SUMMARY OF PHYSICAL PROPERTIES

μ = Viscosity, centipoises
C_p = Heat capacity, B.t.u./(lb.) (°F.)
k = Thermal conductivity, B.t.u./(hr.) (°F.) (ft.)

Components	Chlorine			Propene			Reaction product		
T, °F.	μ	C_p	k	μ	C_p	k	μ	C_p	k
80	0.0134	0.115	0.0053	0.00865	0.357	0.0103	0.02	0.5	0.03
260	0.0178	0.119	0.0073	0.0115	0.451	0.0171	0.02	0.5	0.03
440	0.0220	0.122	0.0092	0.0141	0.539	0.0250	0.02	0.5	0.03
970	0.0329	0.125	0.0142	0.0209	0.741	0.0507	0.02	0.5	0.03
1,340	0.0391	0.126	0.0170	0.0248	0.836	0.0676	0.02	0.5	0.03

$\gamma = C_p/C_v$ of propene is 1.2

SAND FOR FLUIDIZATION PURPOSES

Screen analysis, diameter range, μ	Weight fraction in interval
100–125	0.167
125–150	0.250
150–175	0.330
175–200	0.167
200–225	0.083
	1.000

Physical properties

Shape factor	$\phi_s = 0.86$
Absolute density	$\rho_s = 165$ lb./cu. ft.
Thermal conductivity	$k = 0.23$ B.t.u./(hr.) (°F.) (ft.)
Voidage at minimum fluidization	$\epsilon_{mf} = 0.48$
Heat capacity	$C_{ps} = 0.17$ B.t.u./(lb.) (°F.)
Bulk density	$\rho_B = 86$ lb./cu. ft.

SUMMARY OF REACTION DATA

Heat of reactions are available (*5*).

Kinetic coefficients for some reactions of Table 2, reference *5*, are

Product	Kinetic coefficient, lb.-mol./[(hr.) (cu. ft.) (lb./sq. in.)^2]
Allyl chloride	$k_1 = 0.788$
Dichlorides {1-3 dichloropropene, 2-3 dichloropropene}	$k_2 = 0.455$
Trichlorides (not in Table 2)	$k_3 = 0.211$
1-2 Dichloropropane	$k_4 = 0.0222$
2 Chloropropene	$k_5 = 0.0192$

SUMMARY OF RECOMMENDED DESIGN PROCEDURES

	Literature cited
Fluidization technology references	*7, 10*
Cyclone design	*6, 12*
Finned-tube air-cooled heat exchangers	*13*
Furnace design	*14*

SUGGESTION FOR COST ESTIMATE

For cost estimation purposes, a fluidization unit may be priced as a pressure vessel, the cost being proportional to the weight of metal needed to fabricate the unit.

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