Design and Maintenance of Economically Failure-Tolerant Processes

CARL F. KING and DALE F. RUDD
Chemical Engineering Department
University of Wisconsin, Madison, Wisconsin 53706

SCOPE

This is a review of experiences in the development of design and maintenance policies to mitigate the economic effects of process equipment failure. Of primary concern is the analysis of fragmentary data on equipment failure in order to develop failure models useful in decision-making. Existing theories of reliability and maintenance must be altered to fit the problems of failure encountered in the processing industries, such as the heavy water production facility analyzed here. With this review we hope to establish a generally useful pattern of analysis which unites the theory to the realities of industrial practice.

CONCLUSIONS AND SIGNIFICANCE

The unexpected failure of process equipment can lead to the severe economic losses associated with process shut down, and even to disaster. Especially in modern, highly integrated processes it is essential that proper design and maintenance policies be established to provide protection against hazards of failure.

In this review we summarize the development of techniques to mitigate the economic losses caused by equipment failure (King, 1970). In economic loss prevention, the primary concern is the development of stochastic models of equipment failure and models of the effects of failure on the interacting process and maintenance system. Using these models, decisions are made on the development of proper maintenance policies and on the expenditure of additional capital for process redesign.

The analysis procedure is outlined in Figure 1, which also outlines the organization of this review. Analysis begins with the detailed examination of the processing scheme: Section I discusses processes for the production of heavy water, namely those now being operated by duPont for the Atomic Energy Commission on the Savannah River.

Next, an understanding of the systemic effects of equipment failure and of the modes of failure protection must be developed. During Failure Modes and Effects Analysis one finds the ways the components can fail and the effects of the failures on the operating system. During Protection Modes Analysis one seeks ways to reduce the number of failures or lessen their effects on the system. Safety protection substitutes equipment losses for human losses or prevents small events from cascading into large losses by proposing extra investment justified not by economics but by the reduction of the probability of major disaster. However, the protection modes for production loss analysis only add investment to increase the venture worth of the project by salvaging lost operating time. Section II deals with the empirical analyses needed for protection modes for production losses.

Central to any failure analysis is the frequency and nature of equipment failure and repair. Fragmentary operating records must be interpreted statistically to develop predictive models of failure which provide the numbers to accompany the non-numeric studies of section II. Adequate operating records have not been kept in most industries, although now some computer stored data bases are being developed. The records on the heavy water production facility analyzed in section III to set a pattern of model building useful in other processing industries are an exception.

Finally in section IV existing theories of failure and maintenance are examined to identify those we have found useful in the process industry. They combine mathematics and empiricism.

In the next section two processes for recovering heavy water are discussed. System 1 is in operation, while System 2 is only a proposed design. We show how the present plant (System 1) is analyzed to supply information for process improvement and to suggest changes in maintenance policies, and how the data from System 1 are to be used in the design of System 2.

Finally, it is convenient to show schematically the nature of the decisions to be made. In Figure 2 we visualize a single process element $\hat{a}$ which is subject to failure. To improve system performance, the element might be replicated or its design changed. Once a failure occurs or the element is pulled out of operation for maintenance, the system performance is determined by the repair and maintenance policies employed. Figure 2 shows the structure of the problem to be solved.

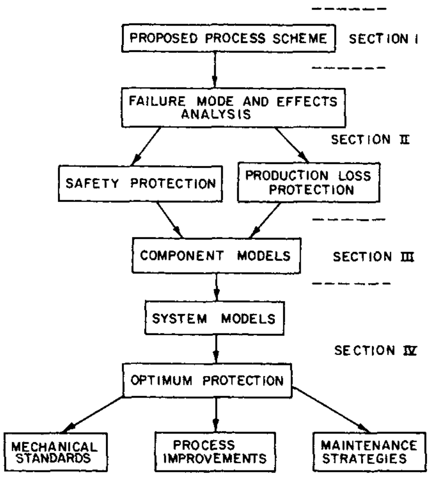

Fig. 1. Reliability analysis procedure.

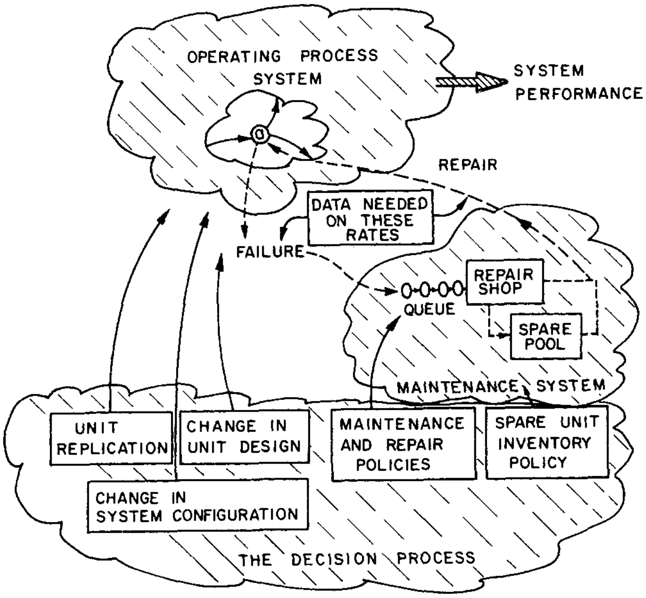

Fig. 2. Structure of the decision process (including only one of many failure prone units).

I. HEAVY WATER RECOVERY PROCESSES

The Girdler Sulfide process, used for the separation of 15% D_2O from naturally occurring water containing 0.015% D_2O, is the process scheme used as an illustration in this paper. The process now in use at Savannah River plant is System 1, and System 2 is the design as modified by Proctor and Thayer in 1962. The latter was used only for economic analysis and has not gone beyond the preliminary design stages [Bebbington and Thayer (1959), Proctor and Thayer (1962)].

The process is based on the reaction

$$H_2O + HDS = HDO + H_2S$$

which takes place in the liquid phase between the water and dissolved hydrogen sulfide. At high temperatures the equilibrium shifts to the left, that is, toward high concentrations of deuterium in the hydrogen sulfide. At low temperatures the equilibrium shifts toward the water. When both a liquid and a gas phase are present, the higher concentration of hydrogen sulfide in the gas and water in the liquid means that this shift is the concentration of deuterium in the cold liquid and in the hot gas.

Fresh water is fed to the top of cold countercurrent gas-liquid contacting towers. The deuterium rich liquid is sent from the bottom of the cold towers to the top of hot towers and then to waste. The gas is cycled countercurrently. The deuterium concentrates in the liquid in the bottom of the cold tower. The liquid and gas in the cold bottoms and hot tops can provide a feed for further similar stages.

The first stage produces a concentrate of 1.5% D_2O, subsequent stages of the process concentrate to 15% and this product is processed by distillation to 99.8% D_2O. Approximately 20% of the deuterium in the feed water can be recovered economically.

The flow sheets for the two systems are shown in Figures 3a and 3b. They differ in two respects. The heat recovery in System 2 is improved. The operating process System 1 has a single first stage feeding a second stage; this is reproduced identically eight times. The Proctor and Thayer design System 2 has a group of four first stages which share common equipment feeding the single second and third stages.

Data on the operation of System 1 to be used in analyzing equipment failures were drawn from four separate and independent sets of record kept by different groups within the plant. The separate information sources allowed the accuracy of the data to be verified and the most complete information possible on the failures to be retrieved. The failure events, separately recorded for each piece of equipment in the eight identical units, were the date of the occurrence and the nature of the event (catastrophic failure, preventive replacement, overhaul, or action taken during a long shutdown required for other work). From this list were tabulated the times between failures for the components.

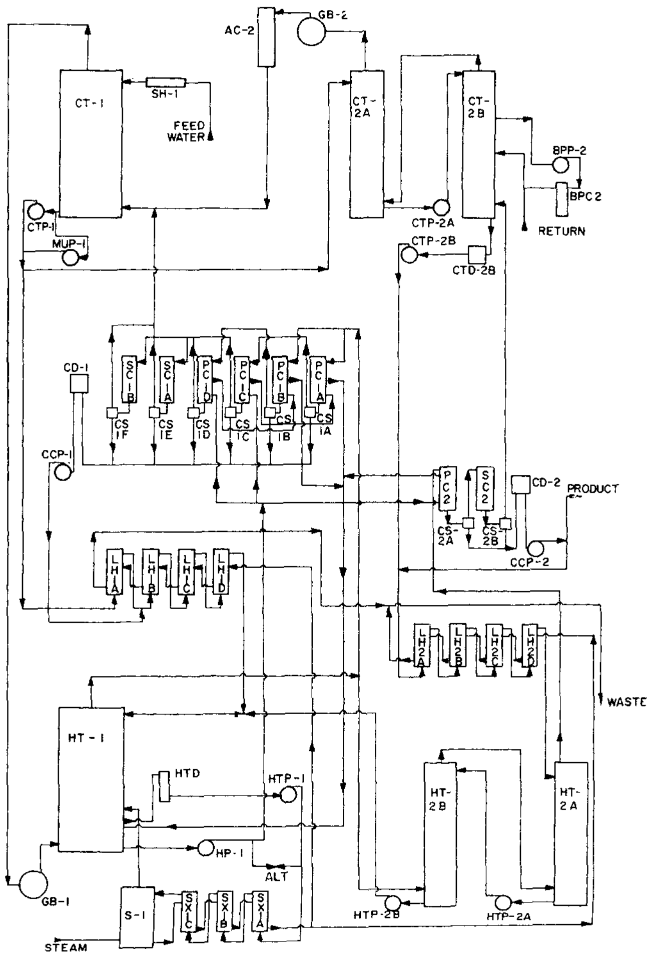

Fig. 3a. System I. In operation at the Savannah River plant.

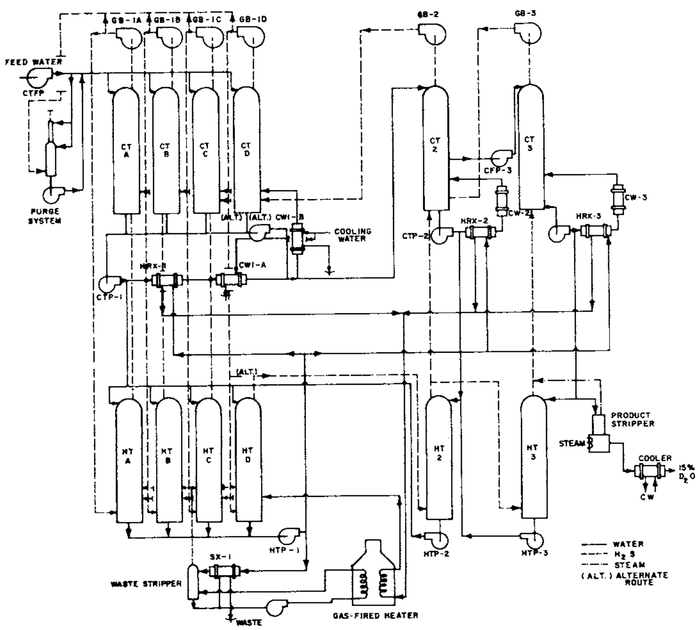

Fig. 3*b*. System 2. A proposed 200 ton/year heavy water unit. Notation for 3*a* and 3*b*. AC = After cooler for GB-2; BPP = By-pass pump for cooling loop; BPC = By-pass cooler for removing heat of solution; CCP = Cold condensate pump recycles condensate from gas; CD = Condensate drum stores condensate; CFP = Cold feed pump lifts liquid to tower tops; CS = Condensate separator for cooled gas; CT = Cold tower; CTP = Cold tower pump; CTD = Cold tower drum for surge volume; CS = Condensate separator for cooled gas; CW = Cooling heat exchangers for gas cooling; GB = Gas blower; GFH = Gas fired heater; GHP = Gas heater pump; HP = Humidifier pump; HRX = Heat recovery exchanger for gas flow; HT = Hot tower; HTP = Hot tower pump; HTD = Hot tower drum for surge volume; LH = Liquid heater; MUP = Pump in parallel with CTP-1; PC = Primary cooler for gas loop; S-1 = Stripper to remove H_2S from waste; SC = Secondary cooler for gas loop; SH = Feed water heater; and SX = Heat recovery exchangers on S-1 loop.

TABLE 1. PUMP STRESSORS

Pump	Temperature, °C.	Pressure, lb./sq.in.	Efficiency, %	Motor Utilization, %	Pump Utilization, %	Motor power, Hp
CTP-1	34	284	76	77.0	88.0	30.0
HTP-1	79	308	75	40.0	55.0	50.0
HP-1	79	308	74	96.0	87.0	50.0
MUP-1	34	284	44	67.0	28.0	15.0
CCP-1	79	300	65	78.0	52.0	15.0
CTP-2A	34	251	65	53.0	40.0	15.0
CTP-2B	34	261	66	60.0	36.0	10.0
HTP-2A	138	277	62	33.0	42.0	30.0
HTP-2B	142	290	60	60.0	42.0	15.0
BPP-2	34	255	34	64.0	25.0	5.0
CCP-2	72	260	35	70.0	31.0	10.0
Average	69	280	60	63.5	47.8	22.2
GB-1	34	—	—	—	—	1000.0
GB-2	34	—	—	—	—	600.0

Repair events and the time required for repair were also recorded. The failure times for equipment which did not cause unit shutdowns were also important.

The data represents a fairly complete record of the failures for System 1 during the period 1963 to 1969. During this time, there were no major changes in operating or maintenance policy. Because the eight units were identical in design and construction, the observations are

TABLE 2. SAMPLE FAILURE MODES: SYSTEM 2

Number	Failure mode description	Effect
0.	Rupture, any equip.	Local fire and becomes failed-open or internal.
General GS system failures:		
1.	Purge tower, fail-internal	Repair time less than critical: no effect. Longer times: gradual dilution of gas with CO_2.
2.	Product system loss	Repair times less than remaining storage capacity: no effect. Longer times: system stand-by.
3.	Electricity loss	Loss of pumps, gradual shutdown.
4.	Fuel gas loss	Loss of turbines and heaters: rapid shutdown and inventory mix.
5.	Steam loss	Loss of pipe tracing: possible freezing of lines.
6.	Feed-water preparation fail-internal	Added material deposited in towers, added CO_2 dilution: reduce overhaul period.
7.	Feed water flow, failed-internal	Stand-by down stages 1, 2, 3.
8.	Cooling water loss	Reduce flows, balance heat, and gradual shutdown.
Stage 1 failures:		
9.	CFP, CTP, HTP failure	Gradual collection of liquid in tower bottoms, immediate reduction in gas flow rate.
10.	GB, CT, HT, Piping	Immediate shutdown, loss of inventory in tower pair, other three tower pairs operate.
11.	Heat exchanger	Reduce flow rates, isolate module.
12.	GFH-1	Strip waste water with auxiliary steam. GFH-2 carry heat load.
13.	GHP-1	Emergency shutdown GFH-1 to prevent tube burn-out.
14.	GFH-2	Reduce flow rates, shift heat burden to GFH-1.
15.	S-1	Can not strip waste: shutdown.
16.	GFH-1 AND GFH-2	Loose all heat sources: shutdown all GS plant.
Stage 2 and 3 failures:		
17.	Pumps	Build-up of liquid in tower bottoms: gradual shutdown.
18.	Heat exchangers	Reduce flows in subsequent stages to the remaining fraction of flows allowable.
Additional failure modes:		
20.	Cold feed	Sub-cools top of CT-1 below the freezing point of 30°C.
21.	Boiling in GFH-1	Solids deposited: tube burn-out.

equivalent to 48 years of operation of a statistically representative unit. The 11 pumps are of similar design so that they provide a set of 11 distributions. The gas blowers provided similar data. The 21 heat exchangers did not suffer sufficient failures to develop models as detailed as those for the pumps, but simplified versions of the more complex models can be considered.

Notes on the construction of the equipment used in System 1 are provided so that the calculated failure rates can be extrapolated to future systems. All of this equipment is outdoors and subject to environmental conditions typical for Augusta, Georgia. The auxiliary equipment discussed are miscellaneous pumps with failure rates not sufficiently well known to justify using the information in other circumstances.

The process pumps are one-stage centrifugal pumps, of an overhung, back-pull-out design directly coupled to an electrical prime mover. Each pump is provided with a packed seal and fiber head-gasket. The conditions of service for the pumps are shown in Table 1.

The blowers are mechanically sealed centrifugal single-stage over-hung units, directly coupled to a three-phase induction motor. All pumps and blowers operate at 3,600 rev./min. with negligible vibration.

The heat exchangers are single pass, pull-through, floating-head, shell and tube units, mounted vertically with the fixed head at the top. All heads have fiber gaskets and the slip tube is fiber packed.

II. FAILURE AND PROTECTION ANALYSES

Before a failure problem can be analyzed by statistical methods, an understanding of the systemic effects of equipment failure and the modes of protection must be developed. The statistical techniques are later used to determine the economic value of the modes of failure protection. To provide a balanced review of the complete problem of failure tolerant design and maintenance, we present a severely edited paper on the failure and protection analyses discussed in more detail in the basic reference (King, 1970).

The procedure for performing the analysis is shown in Figure 1. During Failure Modes and Effects Analysis one finds the ways the components can fail and the effects of the component failures on the system operation. During Protection Modes Analysis one searches for ways to reduce the number of failures of the components or lessen their effect on the system operation.

Table 2 shows part of the failure modes and effects analysis for System 2. (A similar analysis made for System 1 is not shown.) Here a variety of equipment and operation failures have been postulated and the immediate effects of these failures analyzed. Table 3 shows part of the protection modes analysis in which the methods of protection are detailed. A brief discussion of these non-numeric methods of analysis is presented to emphasize the background engineering analysis which must precede statistical of failure data.

Failures are represented by placing the components in one of the failed modes and simulating a loss in the unit. The effect on the adjacent equipment by this failure must then be analyzed with more than just a tabulation of the obvious failures. For example, two failure modes do not result from equipment failure. The feed liquid must be warmed to 30°C. before it enters CT-1 to prevent formation of a solid phase in the first tower. Solid H_2S-H_2O formation blocks the tower, restricts flow, and may damage the tower with its weight. The second failure mode is the boiling of liquid in GFH-1. Boiling would deposit solids in the tubing and cause the tubes to burn out.

The protection modes analysis is very closely tied to the failure analysis. For every failure mode, methods are found for mitigating the effect of the failure. At this time, the cost of making these improvements should not limit our imagination in an attempt to deal with the problem. The list of failure modes and effects, such as those in Table 2, is then modified by adding a list of the protection modes for each of the failure modes. King (1970) details the strategy of protection detection.

TABLE 3. PROTECTION MODES: SYSTEM 2

Number	Protection modes, description	Number	Failure modes, method of mitigation
0	Improved gaskets	0	Reduce leaks
1	Improved repairability of components	All	Increased repair rate
2	Improved quality of components	All	Reduced failure rate
3	Emergency power	3	Emergency power for critical components
4	LPG alternate system	4	Short term alternative to allow orderly shutdown
5	Pair of half size steam boilers	5	Allow standby of DW during outage and prevent freeze
6	Redundant partial sized water units	6	Prevent total loss of feed
7	Redundant feed water pumps	7	Prevents loss of total flow
8	Allow feed water to feed cooling water	8	Allows functional redundancy in emergency
9	Redundant or spare full or partial pumps	9, 17	CTP and HTP could be standardized and all allow partial operation
10	Redundant and partial sized GB	10, 19	Partial thruput while repair prevent loss of inventory
11	Common GB header	10	Allow the four GB to be in parallel instead of separate
12	Added corrosion limits, nonclogable trays	10, 19	Raise time between required overhauls for deterministic reasons
13	Standardize design into common sizes	11, 18	Allow spares to be interchangeable
14	Modularize	11, 18	Group into smaller subsystems in parallel with added pipe and valves
15	GFH-1 partial size and redundant	12	Partial operations
16	Lower temperature and pressure; increase flow rate	12, 21	Reduce stress and failure rates
17	Redundant pump	13, 21	Assure sufficient flow to prevent GFH-1 burnout
18	Redundant partial sized heaters	14	Partial operations
19	Inject emergency steam in S-1	12	Strip waste and allow operate
20	Redundancy of S-1	15	Partial operations possible
21	Added corrosion and clogging limits	15	Define failure to be further degradations of operations
22	Standardize stage 2 and 3 pumps at 50 Hp.	17	Group all six pumps into common spare category
23	Control valve in HT-2 CT-2 gas line, GB-2 and 3 oversized and bypass lines added	19	Allow all flow in stages 2 and 3 to be handled by a single blower
24	Use feed water as cooling water	20	Warm feed water to above 30°C. and prevent freezing

III. STATISTICAL ANALYSIS OF EQUIPMENT FAILURE AND REPAIR

To predict the frequency and nature of the failures analyzed in Section II, operating records must be interpreted to develop statistical models of equipment failure. Failure and repair data are quite fragmentary in the process industry because the systems are too large and specialized to allow the massive life-testing programs effective in the electronic industry. However, the data analyzed here represent the most extensive data base known to the authors. We must be prepared to expand on data of this quality, using modern statistical methods of model building. Figures 4 through 7 give an idea of the amount of failure data from which predictions and extrapolations must be made; the three parameter model developed later in this section is shown on these figures.

Component models summarize the relevant information, describing the failure tendency of the component. The data reduction procedure is the model building process of Box and Hunter (1962) shown in Figure 8. Analysis begins with a postulated model and ends when a model evolves which is considered adequate. In each cycle, a new form for the model is proposed, fitted to the data, and tested for adequacy. Obviously, the definition of adequacy will change as our understanding of the mechanism of the failure phenomena increases; but for each level of understanding, some point will be reached at which all of the useful information is represented in the model. In the case of the data obtained from the Savannah River plant, this point was reached in three generations of model building. It is expected that other data sets of comparable equipment will also be summarized adequately by the final model which is proposed.

The initial assumption that the times between failures are identically and independently distributed must be clarified. This assumption means that there is no gross wearout of the equipment that cannot be rectified by the periodic maintenance. Further, it assumes that there is no learning process at work in the system and that the lifetime of one piece of equipment is not correlated to the lifetime of another piece of equipment. But this last condition may be false if the failure is caused by a universal external stress, such as adverse weather conditions, a type of phenomena beyond the range of the models used here. When there are no truncations (that is, all of the equipment is operated to failure with no preventive maintenance) statistical techniques are available to test these assumptions and build the necessary models. Unfortunately, when preventive maintenance is performed, all existing statistical methods for testing these assumptions are inadequate.

The techniques chosen for fitting the models and testing the adequacy will depend on the one's interpretation of the word *probability*. The attitude here is Bayesian, leading to the position that reliability is a property of our state of knowledge about a device or system and is not a property of the object itself. We are allowed to use the classical objectivist techniques of mathematical statistics if the results are properly thought of as representing our ignorance. The techniques proposed are based on the likelihood approach to statistics summarized by Schmitt (1969).

During the model building for the components, the inadequacies of the model must be diagnosed. Probably the simplest method of diagnosis is to plot both the failure rate defined by the model and the histogram of the failure data (see Figures 4 through 7). Using these plots, systematic lack of fit can be found. A second diagnostic technique is to plot the likelihood function as a surface. Very close to the values of the parameter models giving

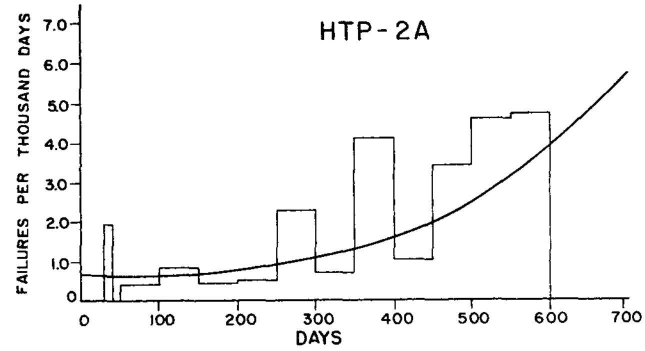

Fig. 4. Histogram and three parameter model. (hot tower pump 2A).

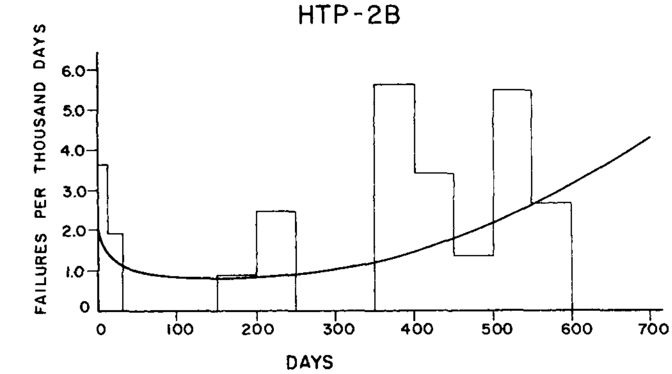

Fig. 5. Histogram and three parameter model (hot tower pump 2B).

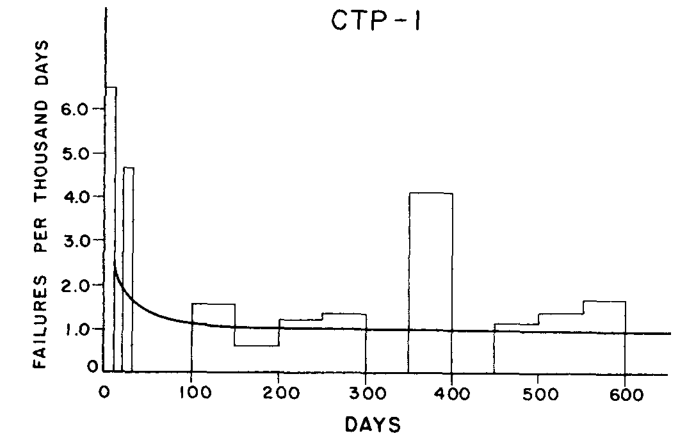

Fig. 6. Histogram and three power model (cold tower pump 1).

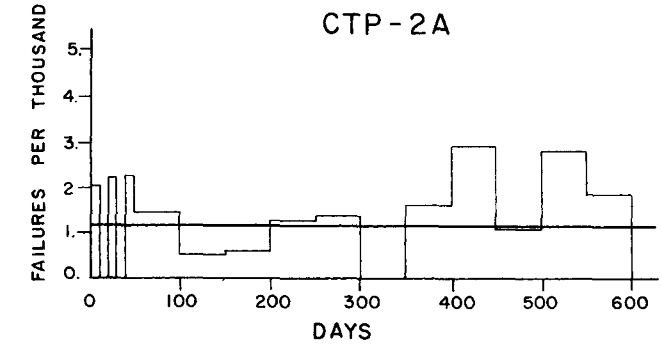

Fig. 7. Histogram and three parameter model (cold tower pump 2A).

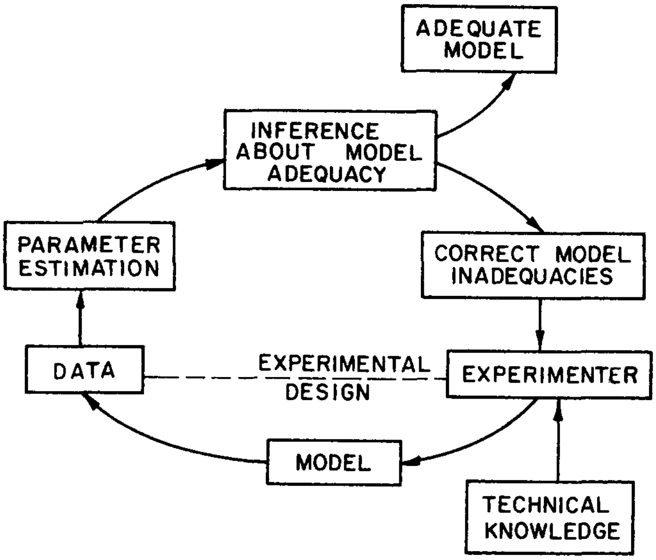

Fig. 8. Model building cycle—Box and Hunter (1962).

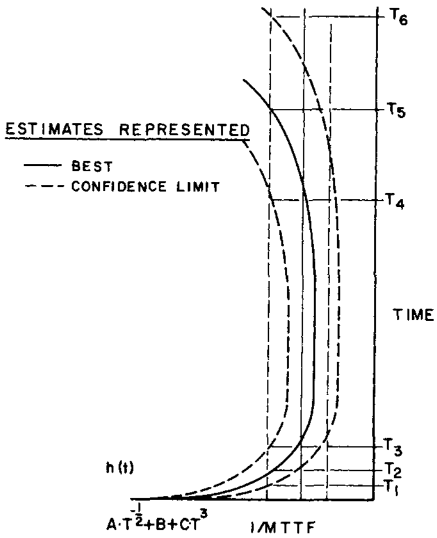

Fig. 9. Confidence bands for random period.

maximum likelihood, the contours of the likelihood surface are nearly normal and the surface will appear ellipsoidal. In the outer regions, the center of the elliptical contours shifts away from the maximum point or the contours lose their elliptical shape. The way this happens is a useful indicator of the inadequacies of the model. A third technique is needed when the information required to describe the surfaces is too extensive. The surface must then be described by a few parameters in addition to the maximum likelihood value. The natural candidates are quantities which were used by the objectivists to describe the inadequacy of the estimate of the *true* parameter.

The first model built in the cycle shown in Figure 8 was the Weibull model suggested by extreme value theory. This model did not adequately fit the data. A Double Weibull model was used as the second generation model in an attempt to remedy the obvious inadequacy of the first model. This model suggested a simple more easily usable model. This third generation model which proved adequate is

$$h(t) = At^{-1/2} + B + Ct^3$$

The first term was suggested by the wear-in region of the Double Weibull model. The second term describes a period of constant failure rate. The last term represents wear-out. The time dependence evolved from the adequate portions of the earlier models. The final estimates for the pumps in System 1 are shown in Table 4. Several of the estimates of the parameters were zero.

Lack of fit may be investigated in the histograms of the failure rate and the corresponding models. Because these are stochastic models, it is expected that there will be lack of fit due to the size of the sample. As the sample size grows larger, the histograms should converge to the model under the Glivenko theorem.

If there is lack of fit in addition to that due to the small sample size, the model should be altered or the limitations of the model noted. For example, there may be some lack of fit in the models around the 180 and 365 day points. The overhauls are performed during the summer and there may be failures due to freezing during the winter (around 180 days later). Further, during the next summer when the maintenance crews are doing overhauls there may be changes in the definition of failure. If the crews are overly busy, the operating units may be allowed to limp along in a semifailed condition which would normally be defined as a failed condition. On the other hand, extra maintenance may be performed during the overhauls in the summer. The presence of either of these conditions should be checked.

It is valuable to find the region over which the constant failure rate model is applicable. The three parameter model and the constant hazard rate models for a hypothetical piece of equipment are plotted in Figure 9. The best estimate of the model is given and then bounded by a dotted curve placed at a distance of one standard deviation in the parameters. Six points of interest should be noted. These are the best estimates of the wear-in and

Table 4. Three Parameter Model: Parameters

Pump	A	B	C
CTP-1	0.137	0.735	0.0
HTP-1	0.0	1.75	0.0
HP-1	0.0	0.725	0.0
MUP-1	0.0	0.717	0.0
CCP-1	0.090	0.0	2.70
CTP-2A	0.0	1.18	0.0
CTP-2B	0.224	0.606	0.0
HTP-2A	0.0	0.686	14.8
HTP-2B	0.0829	0.600	10.5
BPP-2	0.127	0.332	1.85
CCP-2	0.131	0.296	1.18
GB-1	0.0910	1.26	0.0
GB-2	0.263	0.666	1.22

Table 5. Random Period Limits

	Wear-in period			Wear-out period		
Pump	T_1 Low	T_2 Best	T_3 High	T_4 Low	T_5 Best	T_6 High
CTP-1	4	44	73		∞	
HTP-1		0			∞	
HP-1		0			∞	
MUP-1		0			∞	
CCP-1	3	20	49	535	691	1050
CTP-2A		0			∞	
CTP-2B	23	57	83		∞	
HTP-2A		0		357	382	440
HTP-2B	0	5	11	393	426	500
BPP-2	0	40	78		(734)	
CCP-2	0	41	88		(830)	
GB-1	0	26	52		∞	
GB-2	21	53	77		∞	

wear-out period and the corresponding limits on the estimate. These limits were determined for the pumps in System 1 and are shown in Table 5. Whenever the best estimate of A was zero, the corresponding estimate of the wear-in period is that none exists. Whenever the best estimate of the parameter C is zero, then the best estimate of the time till wear-out is infinite. These data are particularly useful when modeling components during the design of new plants. The initial wear-in period is a time when the equipment must be closely watched for signs of failure. The wear-out period is useful in determining optimum preventive maintenance times. The period between these two extremes (described by the simplified, constant-failure rate model) is substantially more easily analyzed.

In summary, this model is adequate for the description of the components in several respects:

It efficiently extracts the information contained in the data.

It efficiently stores the information in a reasonable picture of the component.

It reduces in scope to fit the expected simple cases in which wear-out or wear-in are not present.

It allows information to be retrieved from storage and used in a reasonable fashion.

Heat Exchanger and Auxiliary Pump Distributions

In addition to the data obtained for pumps and blowers, some information was gathered on the failure of heat exchangers and auxiliary pumps. The quality of the data is lower than that for the pumps so the models may not be as fully determined. The importance of the data is to show how even incomplete data can still contain useful information.

There are three failure modes for the exchangers. Gasket failure between the shell or the tube-sheet and the heads allow streams to mix or escape to the atmosphere. Failure of the packing between the slip-tube from the floating-head on the tube-sheet and the shell also allows process fluid to escape to the atmosphere. Tubes may fail by corrosion and mix the streams. All three failure modes were observed, but they were rarely recorded.

The nature of these failure modes causes great uncertainty in the definition of failure. Failures that tend to mix the process streams can go unnoticed until the rate is sufficiently large to cause a large loss of production capacity. These failure modes are detected by material balance or by hydrostatic testing during the overhauls. In our data, it cannot be determined which of the replacements at overhaul are due to a planned replacement and those which were replaced because the hydrostatic test revealed a leak. One replacement of each type of heat-exchanger per year is due to preventive maintenance and the others are a result of the testing. The presence of these semipreventive replacements and the ability of a failure to escape detection for long periods of time are the major reasons for the deficiency in the data.

The parameters fitted for the heat exchangers in System 1 are shown in Table 6. These parameters are determined using the constant hazard rate model. Work with more sophisticated models is not possible since the failures are so infrequent and the data are not sufficiently reliable. Failure rates for the auxiliary pumps are shown in Table 7. The data from different sets of records were quite different. The difference results because the failure rates are sufficiently high that the maintenance is routine and the effect of the failure of this equipment is not immediately evident. Also, abnormally high maintenance costs and lost opportunities for improvement may be hidden as routine work. The analysis of these data revealed the conflict in the records (Table 7).

TABLE 6. HEAT EXCHANGER PARAMETERS

Exchanger	MTTF (mean time to fail)	Number failed	σ_{MTTF}
PC-1A	1002.0	21	219.0
PC-1B	1709.0	13	474.0
PC-1C	1852.0	11	558.0
PC-1D	1377.0	14	368.0
SC-1A	677.0	29	126.0
SC-1B	1085.0	18	256.0
PC-2	1030.0	18	230.0
SC-2	2258.0	9	753.0
LH-1A	3337.0	6	1362.0
LH-1B	3559.0	6	1453.0
LH-1C	5558.0	4	2779.0
LH-1D	4224.0	5	1889.0
LH-2A	5240.0	4	2620.0
LH-2B	6750.0	3	3897.0
LH-2C	7865.0	3	4541.0
LH-2D	5542.0	4	2771.0
SX-1A	3448.0	6	1408.0
SX-1B	3048.0	7	1152.0
SX-1C	1705.0	14	456.0
BPC-2	—	—	—
AC-2	2293.0	9	764.0

TABLE 7. AUXILIARY PUMP MEAN TIMES TO FAIL (DAYS)

Pump	Production data	Maintenance data
A	12.5	51.0
B	32.6	59.0
C	237.0	385.0
D	439.0	398.0

Regression on Stressors

The approach so far has been to build models for the failure rate as a function of time from the failure data for components in operating systems. These models are then used in the design of new plants. It would be worthwhile if these parameters could be predicted by using some observable variables which would be known by the process designer. The pumps of System 1 are of similar construction and could provide data to test the ability to build a predictive model of the parameters in the models. There are 11 different types of pumps and six stressors as given in Table 1 so in lieu of a mechanistic model a first-order empirical model is all that could be expected. The linear model was fitted as

$$\theta_i = \mu_i + \sum_{j=1}^{6} \xi_{i,j} \cdot \alpha_{i,j}$$

where θ_i is the parameter in the model. μ_i is the mean value of that parameter for the set of pumps. $\xi_{i,j}$ is the deviation from the mean level of the j^{th} stressor. $\alpha_{i,j}$ is the coefficient for that deviation. The parameter estimates are shown in Table 8 for both the constant failure rate and the three parameter model.

These models have value in determining the general effect of the different sources of stress. Increases in temperature for example can be expected to have no effect on the wear-in problem, decrease the mean time to failure during the constant hazard rate period, and increase the tendency to wear-out or decrease the period between overhauls.

These models will be used to predict the parameters in the proposed System 2 based on the operating data of System 1.

TABLE 8. REGRESSION ON STRESSORS: LINEAR PARAMETERS

Model Parameter	Constant hazard rate		Three-parameter model		
	MTTF	Fail rate	A	B	C
$\sigma_{Response}$	317.0	0.210	0.064	0.246	2.14
Coefficients of:					
Mean	1094.0	1.033	0.0720	0.693	2.82
Temperature	—	—	—	−0.00504	0.107
Pressure	7.96	—	—	—	—
Efficiency	—	0.0112	—	—	—
Motor utilization	21.4	−0.0151	—	−0.0168	−0.108
Pump utilization	−13.3	—	0.00214	—	0.0784
Motor power	—	—	−0.00488	0.0219	−0.163

Repair Distributions

Data must also be collected for the time required to make the repairs. These data are then used in a model of the repair distribution for which parameters are estimated in the same way that they were estimated for the failure distributions. Four models were used in this study: the normal, log-normal, Erlang, and Weibull. Of these distributions only the Erlang distribution, the parameters of which are shown in Table 9, was sufficiently general to describe all of the available data.

Estimation of Future Behavior

The models which have been built summarize previous experience with specific components. Unless there is reason to believe that the performance of the components is changing, the performance of these same components in the future should follow the same distributions. Thus, for work during operations the maximum likelihood estimate should be used as a prediction of the future behavior.

During design, there is an additional factor in the extrapolation of the estimates. Previous experience must be searched for equipment with similar physics of failure to use as a base for extrapolation; see King (1969) for a discussion of the physics of failure in this regard. The importance of different operating conditions is indicated by the regression on the failure models for the pumps. These correlations aid in making a reasonable extrapolation.

At this time no theories for predicting or even extrapolating the behavior of new equipment exist; thus the best technique is to use analogous equipment for which data are available. This technique is demonstrated by extrapolating parameters obtained in System 1 for System 2.

The gas blowers of System 2 are presumed to be quite similar to those used in System 1, the Savannah River process. The failure rates included 23% attributed to motor failures. It is expected that the turbine drives will have a significantly higher failure rate than that. It is assumed that the failure rate for the turbines is equal to that for the compressors being driven and that these are equal to observed blower failure rates corrected for the motor failures. This gives a MTTF (mean time to failure) for the combined turbine and blower used in stages 1 and 2 of 430 days. The MTTF for GB-3 is 666 days, as in System 1. The expected time for wear-out to begin is two years or greater. This time to wear-out may be modified by information on preventive maintenance which should be supplied for the individual blower.

The heat exchangers are similar to the exchangers in System 1. The temperature profiles and flows are also similar; however, the area of the heat exchangers is somewhat different. The System 1 liquid heaters had areas of 1,500 and 442 sq.ft. with MTTF of 4,000 and 6,200 days respectively. Extrapolating this relation linearly on log-log paper gives an estimate of 2,500 days for the 5,000 sq.ft. heat exchangers. The other exchangers will be estimated conservatively at 2,500 days for MTTF.

Vessels are not expected to fail if adequate preventive maintenance is performed to prevent gross wear-out.

The failure rates and the mean times to wear-out for pumps can be estimated using the regression models. The extension of the linear model to sizes larger than 100 Hp is very risky. Thus, the model will be used for the stage 2 and 3 pumps. For stage 1 pumps, the random region MTTF must be postulated, here at 400 days. This region is consistent with the prevalent general range of failure rates for the process.

The MTTF experienced for S-1 in System 1 was 3,000 days. There is no reason to expect this design to be different. There is no precedent for the failure rates for the gas fired heaters or the high pressure feed pump for GFH-1. It is expected that their failure rate will be reasonably high—300 days for the heaters and 250 days for the heater pump. The effect of errors in this estimate would be to overinvest in capital equipment. Similar estimates may be derived for the mean time to repair. This information is summarized in Table 10.

IV. MAINTENANCE AND DESIGN POLICIES

The failure and protection modes analysis section II and the statistical analysis of failure data section III provide the background necessary for the development of economic maintenance and design policies. In this section, we illustrate how this background information fits into stochastic models of failure and repair to lead to recommendations for system improvements. While certain aspects of failure and repair are best analyzed using established theories of reliability, others involve merely a comparison of a few design alternatives or a combination of theory and empiricism.

TABLE 9. REPAIR DISTRIBUTION PARAMETERS

Parameter	Pump repair	Overhaul	Blower	Gas-liquid HX	Valve
Erlang distribution:					
α	2	82	3	6	2
ρ	12.8	12,900	46.2	122	35.2
Number of observations	31	23	39	34	11

$$f(t) = \rho^{\alpha} t^{\alpha-1} \exp(-\rho t)/(\alpha-1)!$$

TABLE 10. PREDICTED FAILURE AND REPAIR RATES: SYSTEM 2 EXTRAPOLATED FROM DATA OBTAINED FROM OPERATING SYSTEM 1

Equipment	MTTF, days	MTTR (Mean time to repair) days	C	Mean time to wear-out
GB-1, 2	430.0	0.66		
5,000 sq. ft. HX	2500.0	3.0	—	—
3500 ft.^{2} HX	2500.0	3.0	—	—
2000 ft.^{2} HX	2500.0	3.0	—	—
S-1	3000.0	2.5	—	—
GHP-1	250.0	1.0	—	—
GFH-1	300.0	5.0	—	—
GFH-2	300.0	5.0	—	—
GB-3	666.0	0.66	—	—
CTP, HTP, CFP-1	400.0	2.0	—	—
CFP-2	485.0	1.0	−10.0	∞
CTP-2	465.0	1.0	−5.0	∞
HTP-2	415.0	1.0	—	—
CFP-3	930.0	1.0	−3.0	∞
CTP-3	950.0	1.0	+3.85	815 days
HTP-3	765.0	1.0	−2.0	∞

Failure tolerant process design cannot be considered without the simultaneous consideration of maintenance policies. The process must be designed to operate economically in a given maintenance environment and the maintenance system must be designed economically to service a given design. If the engineer has control both over the process design and maintenance system, both must be optimized simultaneously. We make the conjecture that the optimal maintenance policy will be employed for any design. This conjecture establishes a hierarchy of decisions leading to the development of optimal maintenance policies first, to be used later during the design optimizations.

Central to the accuracy of this study are the assumptions necessary to achieve a tractable mathematical model. An impressively large literature exists on the mathematical aspects of failure and repair, some small fraction of which is applicable to the problems that face process engineers. Typically, a mathematically well-established branch of reliability theory rests on assumptions which are only approximately met in practice. To solve a problem at hand, the engineer must use the most pertinent of the existing theories and rely in part on empirical analysis.

Separation of the lifetimes of equipment into three periods, using the limits found in Table 5, is a reasonable method of facilitating this mathematical analysis. Although strategies such as redundancy improve reliability during all three periods, in general the best actions during each period is to modify the repair and startup procedures to reduce the probability of an immediate failure. Examination of components that failed early in life usually show some defect which could have been eliminated by closer attention. The mitigation of failures during the random-failure period requires either more complete understanding of the failure mechanism to reduce the failure rates or added capital investment to reduce the impact of the individual failures. The proper levels of added capital can be determined by the use of stochastic models in which our ignorance of failure detail is quantified. During the period of increasing failure rate, the best action is to determine when it becomes worthwhile to remove the equipment from service for a planned repair rather than wait for an unplanned shutdown. These three periods and their respective strategies are examined separately in more detail.

Wear-In Failures

During the wear-in period, the failure rate is dominated by the parameter A in the model. The failure rate curve looks like Figure 6 which shows a high failure rate during the initial month of operation. As the component grows older, our confidence in its ability to continue operating grows.

Most strategies for mitigating failure during this period are formulated from deterministic analysis of the particular situation. The value of the stochastic model in this case is that it gives a measure of the economic incentive to correct the failure mechanism. If the cause for the higher failure rate could be completely eliminated, then the failure rate would be reduced to that of the random failure period. The difference in the expected number of failures for the two failure probabilities during this period multiplied by the cost of a failure is the maximum amount we should be willing to pay for the added time on stream.

Another strategy for this period is to start up the plant in smaller subunits and to allow a few hours to check out the operations. This model can be helpful in determining the best size of the subunits. If during the first week on-stream there is an expected number of failures E, then it may be worthwhile to break the plant into E subunits for checkout, each of which has a single expected failure. Then the down-time for the E expected failures can overlap during the first week rather than being spread sequentially in bits and pieces over several weeks. The model analysis is of value particularly in selecting the subunits. Strategies during this period cannot be selected by formula; however, selection can be aided by stochastic modeling.

Wear-Out Period

During the wear-out period, the failure rate is dominated by the parameter C in the model. The failure rate curve looks like Figure 4 with an increasing failure rate. At any time the expected number of failures in the next increment of time is greater than at the present time. Preventive maintenance or overhaul strategies are worthwhile only if this increasing rate is present and a planned repair is less costly than allowing the components to fail at random times.

Mathematical reliability theory has several strategies for performing maintenance which are discussed by Barlow and Proschan (1965). These are: 1. Age replacement in which the component is repaired when it reaches a certain age, 2. Block replacement in which all components are repaired at uniform intervals, 3. Random age replacement in which the availability of manpower causes slight variations in the time of repair. Although batch processes might be scheduled by either age or block repair policies, continuous processes will have overhauls by block repair policies. Between major turnarounds times for scheduling would be justified by the combined failure probabilities of several components. Determining these times requires that the analyst return to basic principles described by Barlow and Proschan (1965) and by King (1970).

Random Failure Period

During the random failure period, the parameter B is dominant. Figure 7 shows an example of this period in which the failure rate is constant. Also, during the period from about 5 days to about 420 days, as determined from Table 5, the pump described in Figure 5 is in a random failure period. Even the equipment described in Figures 4 and 6 during much of their lifetimes (the first 380 days and the time beyond the first 44 days respectively) can be described as having a random failure rate. Thus, this type of failure might be expected during most of the plant's lifetime.

Solution Techniques

Without stationary and steady state assumptions, the analyst is limited to small, single component systems which can rarely be isolated in a realistic way. The analysis without these assumptions becomes intractable for large systems. When these two assumptions are reasonable, somewhat larger systems may be modeled and solved analytically. Then the analyst can spend time searching for the optimal system design rather than a solution to the stochastic model for a single design. When these assumptions cannot be accepted and the model can no longer be solved analytically, simulation of the system is an alternative.

The analytic solution of small wearout problems are described in Barlow and Proschan (1965). These are based on a branch of stochastic modeling called *renewal theory* which is described by Cox (1966). A good example of its application to chemical systems was presented by King (1968).

The techniques of simulation are reviewed in Rudd and Watson (1968) and in detail in Shreider (1966). Application to reliability problems is described by Shooman (1968).

The analytic solution to constant failure rate problems offers the best approach if the two assumptions are valid. Using *Queuing theory* described in detail by Moorse (1958) and Karlin (1968), King (1970) has developed models for process systems. The particular attraction of these models is that they are well adapted for use in optimization schemes. In the following example, this approach is illustrated.

Chemical Plant Model

The constant failure rate models are applied to the system for separation of heavy water. In this model, it is assumed that the productivity of the system is proportional to the fraction of time the equipment is operable.

The alternatives considered are the number of repair crews, the spare equipment for each equipment type, the redundant equipment at each service position, and the capacity of the equipment which is installed. Also investigated are changes in the equipment quality, the number of parallel units, modularization, and standardization strategies.

Three types of models are used together for the calculation of the production rate. Because of the Markov property, the repairmen's work load will depend only on the total rate of failure and not on the differences among the components. Thus, the technique is to average the failure and repair rates into a typical component. This queuing model is used to find the work load for the repairman and the average time the component will remain in the shop before repair can begin. This is the average time before one process function was below full capacity. When this assumption was made, a typical approximate value for system thruput in System 2 was 0.9143 whereas the full model found a value of 0.9162. The error was on the order of two parts in a thousand or less for all of the comparisons made with system thruputs above 0.9.

Before the queuing model is formed, the nomenclature, general model, and assumptions are outlined. There are NE equipment types used in the system in NS different positions. These are serviced by NC repair crews. The positions are organized into NUSYS subsystems. Each of these equipment types has a characteristic failure rate f_i and repair rate r_i. There are NO_i extra spares provided for those equipment types for which spares are allowed. The positions are composed of $MOSER_i$ of these components in series to form a subposition; and NU_i out of $NUREQ_i$ of these subpositions to form the position. The positions are grouped in series into subsystems which operate as a single unit without appreciable storage capacity between the positions within the subsystem. The individual subsystem has a $MODULE_i$ out of $MODREQ_i$ type of structure. These subsystems are assumed in the model to be in series in the system. These assumptions give a model which is sufficiently broad to include the usual processing system.

Table 11 shows the grouping of the equipment in Figure 3 into subsystems. Only heat exchangers are in series within a subposition. Because each of the positions with redundancy has a single position in the subsystem, the redundancy is considered to be an increase in the number of modules in the subsystem so that the capacity

TABLE 11. SUBSYSTEMS: SYSTEM 2

Position	Subsystem	Description	Equip. type	$MODREQ_4$	$MOSER_i$	Cost shutdown
1	1	CT, HT-1	20	4	1	1/module
2	1	GB-1	1	4	1	1/module
3	2	CTP-1	10	1	1	5/subsystem
4	3	HRX, CW-1	2	4	6	5/subsystem
5	4	HTP-1	11	1	1	5/subsystem
6	5	SX-1	3	3	4	5/subsystem
7	6	S-1	5	1	1	5/subsystem
8	6	GHP-1	6	1	1	5/subsystem
9	6	GFH-1	7	1	1	5/subsystem
10	7	GFH-2	8	2	1	5/subsystem
11	8	CFP-1	12	1	1	5/subsystem
12	9	CFP-2	13	1	1	1/subsystem
13	10	CTP-2	14	1	1	1/subsystem
14	11	HRX, CW-2	2	1	8	1/subsystem
15	12	HTP-2	15	1	1	1/subsystem
16	13	GB-2	1	1	1	1/module
17	13	CT, HT-2	20	1	1	1/module
18	14	CFP-3	16	1	1	1/subsystem
19	15	CTP-3	17	1	1	1/subsystem
20	16	HRX, CW-3	4	1	4	1/subsystem
21	17	HTP-3	18	1	1	1/subsystem
22	18	GB-3	9	1	1	1/module
23	18	CT, HT-3	21	1	1	1/module
24	19	Remainder	19	1	1	5/module

can be changed during the optimization. The equipment which is used in these positions is shown in Table 12. The failure and repair rates for this equipment was shown in Table 10 and the cost of the equipment was shown in Figure 3.

The heavy water selling price of $28.50/lb. amounts to an annual income of $11,400,000 at 100% production. The fixed cost is set at $1,552,000, and the variable cost set at $1,360,000 by separating the costs mentioned explicitly in Proctor and Thayer. The cost of the equipment is depreciated over a ten-year period. An additional charge of 4% for local taxes and insurance makes the yearly charge 14% of the value of the initial plant. Also a 50% tax on the income from the plant and a 7.5% return on investment after taxes is required.

Some occurrence costs and other costs apply to the alternatives in addition to the capital costs described. The added cost for providing additional repairmen is $52,000/yr. for four shift coverage. A storage charge of $500 is added for each added spare. Occurrence costs are of two types: the cost for making the repair, $300 per failure, and the shutdown loss of a first stage tower pair or the shutdown of stages 2 and 3, $3,400 per failure.

The program which optimizes the system based on this model is detailed by King (1970). This program was used to find the optimal number of redundancies, spares, and crews for the basic design proposed by Proctor and Thayer. The optimal number of units for the alternatives is shown in Table 13. All other equipment was not redundant or spared. There is an increase of $460,000 in the capital for the plant and a predicted increase from 90.8% to 96.1% in the yearly production rate. Also, the venture profit increases from a negative $1,580,000 to a positive $106,000. The venture profit of $106,000 is now the base against which other strategies must be considered.

Strategies for improving the reliability will require changes in the basic information for the system. These changes will require different problems to be run so as to evaluate the redundancy, spare, and crew alternatives under these conditions. These modifications are to standardize equipment, change capacities, and change the modular structure of the subsystems. They are suggested by the description of the expected performance of the system as shown in Table 14.

TABLE 12. POSITIONS: SYSTEM 2

Equipment type	Description	Spares allowed?
1	GB-1, 2	No
2	5000 ft Hx	Yes
3	3500 ft Hx	Yes
4	2000 ft Hx	Yes
5	S-1	No
6	GHP-1	Yes
7	GFH-1	No
8	GFH-2	No
9	GB-3	No
10	CTP-1	Yes
11	HTP-1	Yes
12	CFP-1	Yes
13	CFP-2	Yes
14	CTP-2	Yes
15	HTP-2	Yes
16	CFP-3	Yes
17	CTP-3	Yes
18	HTP-3	Yes
19	Remainder	No
20	CT, HT-1, 2	No
21	CT, HT-3	No

After one looks at the optimal arrangement of the basic system several suggestions can be made. The heat exchangers may be put in multiple banks which can be isolated from each other, instead of in the long series trains proposed for stages 2 and 3. Pumps that are the same size may be standardized or may also have their size reduced and their number increased. The blowers' reliability may be increased if they are supplied from a common header in the first stage so that they are not directly paired with the towers. The extremely failure-prone gas fired heater subsystem may be broken into two parallel sources of heat. These changes are evaluated by making the necessary changes in the system structure and re-optimizing with

TABLE 13. OPTIMAL ALTERNATIVES: SYSTEM 2

Basic Proctor and Thayer proposal for system:
Redundant: CTP-1, HTP-1, GHP-1, CFP-1, CFP-2, CTP-2, HTP-2, CFP-3, CTP-3, HTP-3
Spare: 5,000 sq. ft., 3500 sq. ft., 2000 sq. ft. Heat Exchangers

TABLE 14. EXPECTED PERFORMANCE: SYSTEM 2

Subsystem	Description	Module availability	Shutdown frequency
1	CT, HT-1; GB-1	0.9983	3.66
2	CTP-1	1.00	0.009
3	HRX, CW-1	1.00	3.5×10^{-14}
4	HTP-1	1.00	0.009
5	SX-1	1.00	1.32×10^{-10}
6	GHP, S, GFH-1	0.9828	1.30
7	GFH-2	0.9836	0.0386
8	CFP-1	1.00	0.009
9	CFP-2	1.00	0.0031
10	CTP-2	1.00	0.0034
11	HRX, CW-2	1.00	1.17
12	HTP-2	1.00	0.0042
13	CT, HT, GB-2	0.9983	0.915
14	CFP-3	1.00	0.00084
15	CTP-3	1.00	0.00081
16	HRX, CW-3	1.00	0.584
17	HTP-3	1.00	0.0012
18	CT, HT, GB-3	0.9988	0.6197
19	Remainder	0.9998	0.073
	Overall	0.9611	14.2

TABLE 15. EXAMPLE 2. ALTERNATIVES

Description	Venture worth	Pipe cost
Pump alternatives; GB and HX, basic structure:		
Basic Proctor and Thayer	$106,000	0
Standardized pumps	$148,500	0
Standard ½ size pumps	$327,000	$15,000
Heat exchanger alternatives; GB and pumps, basic structure:		
CW and HRX separated by header	$106,000	>0
Stage 2 & 3 in two banks	$127,000	$ 3,500
GB alternatives; HX and pumps, basic structure:		
½ sized GB	$ 89,000	>0
Common Header for GB	$146,000	$40,000 to 70,000
Policy alternatives:		
Standardized ½ sized pumps, two banks of HX in stages 2 and 3, GB are basic configuration.		
Policy A	$330,000 to 350,000	
Policy C	$460,000 to 480,000	
Policy B	$345,000 to 365,000	

respect to the available variables.

These alternate strategies were evaluated for additional problems using the optimizer to find the optimal redundancy, spare, and crew policy. The results of this work are shown in Table 15. The recommended structure for the system is that: ½ sized pumps be used everywhere except in the third stage where the pumps are common to those of the second stage and share spares, the heat exchangers in stages 2 and 3 should be installed in two banks which can be isolated, and that overhaul policy *C* should be used with the two modules for the stripper subsystem. The details of this recommendation and some of the features of the other strategies are noted below.

When full sized standardized pumps were proposed, there was a shift from the redundancy proposed in the base case shown in Table 13 to a spare of each of the three types of pumps. When the pumps were not standardized, each of the ten pumps required a spare, and the cost of installing that spare in the one place it could be used was more than offset by the savings in the number of shutdowns. When the pumps are standardized into 1000, 100, and 50 horsepower pumps, the spare could be used in several places. The yearly production rate is nearly the same in the two cases; however, the capital cost for the standardized case is less and there are roughly twice as many shutdowns per year. It should be noted that the feed pump for stage 1 and the gas fired heater pump were not considered for standardization because it was expected that they would be of a different basic design than the other process pumps.

When the pumps are standardized and made half size in the first and second stages, the venture worth increases dramatically. In this case, both the advantages of having spares for each size of pump and the ability to maintain flow through the system is preserved. Surprisingly, the total capital required to reach this optimum is $50,000 more for the full sized pumps than for installing half sized pumps.

Two suggestions might be considered for the heat exchangers. In stages 2 and 3, the original proposal was for a strictly-series arrangement of the exchangers, banks of eight and four in series respectively. The alternate proposal is two banks each with four and two in series. This was worthwhile; however, the second suggestion was not. The original proposal for the first stage was to have four banks of six in series in each bank. And it was suggested that it might be worthwhile to make this into two subsystems with four banks of three in series in each. Six banks of two in each bank or some other similar arrangement could also be proposed. But these suggestions did not raise the venture profit any significant amount and required additional capital for pipe changes. Thus the original proposal for stage 1 was accepted.

Also two suggestions for the gas blowers were made. One proposed that half size blowers with a pair for each tower pair would reduce the number of shutdowns and the consequent loss of inventory. However, the added capital required is somewhat greater than the savings would warrant.

The second idea would be to put the blowers on common headers so that the gas to a single pair of towers is not cut off when a blower fails. This reduces the loss in inventory for blower failures also. However, the added value in venture profit would just about pay for the pipe modifications in this case with no consideration to added costs of power or added control problems. Thus, this suggestion is also rejected.

Three overhaul strategies were proposed, which also make a difference in the behavior of the system during the regular operations by providing alternate modes of operating when a failure occurs. The major advantage in overhaul policy *C* is that the subsystem containing the gas fired heater and stripper is made into two modules instead of the single module originally proposed.

V. CONCLUSIONS

We have reviewed current problems in the design and maintenance of failure-tolerant processes with the aim of preparing a review sufficiently general to be accessible to the nonspecialist, but yet sufficiently thorough to be of use as a pattern of analysis applicable to a variety of processing industries.

Central to any quantitative study of process failure is the statistical analysis of operating records. The methods of analysis presented here are original and fit in between the established empirical methods of failure analysis and the more sophisticated numerical optimization procedures.

This paper then summarizes the kind of optimization study which can be made once an adequate system model is available and once failure data have been gleaned from fragmentary operating records.

VI. SELECTED READINGS

The application of mathematical reliability to chemical engineering situations is quite limited. There is, however, substantial literature on deterministic techniques for solving some chemical plant reliability problems. Vast resources on the application of statistics to the failure data, probability techniques for the models, and reliability optimization techniques are quite helpful in developing useful tools for design engineers. Those most directly applicable will be mentioned here. A more thorough list is included in King (1970).

Lenz (1970) has stated a general philosophy similar to that presented here. The specific techniques for implementing his suggestions have been presented by his colleagues Gilmore (1970) and Browning (1969-70). Their techniques mix discussions of production protection and safety.

Also a considerable literature on deterministic methods of analysis exists. The American Institute of Chemical Engineers has sponsored two symposia entitled "Loss Prevention" and "Safety in Air and Ammonia Plants," which are quite useful in analyzing specific systems but are not generally applicable to other processing situations.

Within the field of reliability, there is a substantial literature. The general techniques are not of direct value but many serve to indicate useful approaches. The literature of the field is very competently reviewed monthly by a National Aeronautics and Space Administration publication, "Reliability Abstracts and Technical Reviews." Much of the most significant work appears in four journals: *Operations Research, Institute of Electrical and Electronic Engineers Transactions on Reliability, Technometrics,* and *The Journal of American Statistical Association.* There are three annual meetings on reliability. The "West Coast Reliability Symposium," which is usually concerned with management of reliability in defense contracts, is of little interest to chemical engineers. The "Proceedings of the Annual Reliability and Maintainability Conference" published by the Society of Automotive Engineers usually discuss common problems in Department of Defense, National Aeronautics and Space Administration, and some consumer applications. The "Proceedings of the Annual Symposium on Reliability" published by the Institute of Electrical and Electronic Engineers is generally more theoretically oriented and should be the most useful to chemical engineers. These sources would provide background information in addition to the techniques discussed here.

Finally, the field is sufficiently old to have generated some quite good secondary sources on reliability. The finest text for engineers currently is Shooman (1968). A few known errors in the first printing have been summarized by the author so that the only substantial error is in the maximum likelihood estimates of the parameters of the Weibull distribution on page 475 and following. A monograph by Barlow and Proschan (1965) uses the classic approach and is intended for an audience quite sophisticated in statistical techniques. Ireson (1966) is a handbook for the reliability engineer in the aerospace and defense fields which contains much useful information.

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A Theoretical and Experimental Study of the Centrifugal Molecular Still

DAVID B. GREENBERG

Department of Chemical Engineering
Louisiana State University, Baton Rouge, Louisiana 70803

A mathematical model of the centrifugal molecular still has been derived based on a fully developed profile, but negligible normal and tangential velocity components. Thermal gradients, film thicknesses, and evaporation rates calculated from this mathematical expression correlate well with reported literature values as well as with the present data.

Mean distillation rates were measured for five pure liquids on a centrifugal still with an effective evaporating surface area of 100 sq. cm. These experimentally obtained rates for liquids exhibiting ideal behavior agreed quite well with theoretical values predicted on the basis of simple kinetic theory. In the case of an associated liquid, however, rate measurements were found to be only 35 to 90% of the theoretical value. Although these low values tend to support the concept of an evaporation coefficient as a true molecular property, there was evidence that surface irregularities could have accounted for all or at least part of the discrepancy noted.

Molecular distillation may be defined as distillation which occurs from the surface of a film of liquid under an operating pressure such that residual gas in a vapor space above the liquid may be considered to have a negligible effect on the process. When a low pressure environment and a nearby condensing surface are provided, escaping molecules have a relatively unobstructed path of travel between the evaporating and condensing surfaces. Since the distance separating these surfaces is of the order of magnitude of the mean-free-path of the vaporizing molecules in the residual gas, molecular distillation has been termed "short-path" or "unobstructed-path" distillation.