Nuclear Engineering and Design 110 (1988) 33–46
North-Holland, Amsterdam

APPLICATION OF A POWER PLANT SIMPLIFICATION METHODOLOGY: THE EXAMPLE OF THE CONDENSATE FEEDWATER SYSTEM

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Received June 1988

A novel framework for the systematic simplification of power plant design is described with a focus on the application for the optimization of condensate feedwater system (CFWS) design. The evolution of design complexity of CFWS is reviewed with emphasis upon the underlying optimization process. A new evaluation methodology which includes explicit accounting of human as well as mechanical effects upon system availability is described. The unifying figure of merit for an operating system is taken to be net electricity production cost The evaluation methodology is applied to the comparative analysis of three designs In the illustrative examples, the results illustrate how inclusion in the evaluation of explicit availability related costs leads to optimal configurations. These are different from those of current system design practices in that thermodynamic efficiency and capital cost optimization are not overemphasized. Rather a more complete set of design-dependent variables is taken into account, and other important variables which remain neglected in current practices are identified A critique of the new optimization approach and a discussion of future work areas including improved human performance modeling and different optimization constraints are provided

1. Introduction

A popular prescription for the improvement of central power station performance is "design simplification". However, practical implementation of this advice is impossible without a more precise technical definition of the concept. Further, it must be realized that the motivation to simplify originates from the deficient performance; which is a consequence of suboptimal design. Thus, the goal of simplification, i.e., improved plant performance through redesign, can be achieved only through a systematic consideration of the underlying performance goals of a plant, and the causes of inadequate performance. In general, the performance deficiencies which have led to dissatisfaction with the current generation of power stations have arisen from failure to take into account an adequate set of design-dependent variables in the optimization of designs. Complaints regarding the needless complexity of such plants focus upon a symptom rather than a cause of poor performance.

The translation of the worthwhile vague goal of simplification to tangible engineering design methods with particular emphasis upon nuclear power plants has been a focal activity of the MIT Light Water Reactor (LWR) Innovation Project [1]. The definition of an overall conceptual base [2], the development of a method of design simplification including use of probabilistic performance models and economic analyses [3,4] as well as examination of the implications of this approach to design for new reactor plant [5] have been presented. The purpose of this paper is to describe this project's first application to the design optimization of a particular plant system. This is perhaps the most important aspect of the project's work to date since it provides a concrete test of the method's utility. The system chosen is the condensate feedwater system (CFWS) of a pressurized water reactor (PWR).

The selection of the CFWS is motivated by a number of observations. Historically, it has been an important source of lost plant availability. Due to the nature of its constituent components of thermal-hydra-

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ulic, mechanical and control devices and its multiplicity of mission goals, its refinement provides an adequate challenge to a method which purports to have generic applicability. The current CFWS design configuration is the result of nearly a century of evolution and is that of a mature technology The CFWS is not directly a safety related system These facts imply that it has a significant operational importance and is not over-designed due to external (e.g., safety, regulatory) constraints. The next section provides a synopsis of the evolution of the design complexity of this system. Following that, an overview of the new method of design simplification is presented. Three representative CFWS designs are evaluated using the models of this method and the results are reviewed for both their design effects and implications regarding the value of the method

2. Evolution of design complexity

The CFWS represents one part of the overall, modified Rankine, thermal energy conversion cycle It has three primary missions

(i) to provide sufficient feedwater to the steam generators,
(ii) to heat feedwater in order to improve the thermodynamic efficiency and prevent thermal shock, and
(iii) to maintain proper feedwater chemistry (e g., levels of dissolved O_2, pH, metallic contamination).

The physical boundaries of the system consist of the condenser hotwell, the various steam extraction ports on the main turbine and the steam generator feedwater inlet nozzle. The major components of the CFWS are feedwater pumps, high pressure heaters and associated piping. Minor components include flow control valves, drain pumps and noncondensible gas removal devices

The first tasks of the simplification process are to define a reference design and to acquire detailed knowledge of the components and their operating modes. The CFWS designs of approximately 20 LWR plants [6–24] were reviewed with respect to the number and configuration of major components This exercise advances the goal of reference design definition but does not provide the required detailed knowledge. The latter was obtained through a component-level review of a particular plant which was deemed to be representative of the group. The specific plant selected was Unit 2 of the Beaver Valley Power Station (BVPS-2). A synopsis of the design variability review as well as the particular BVPS-2 configuration is provided in table 1. Considering the large number of plants surveyed, the degree of variation is surprisingly small. A typical system includes redundant feedwater heater trains, multiple partial flow condensate and feedwater pumps and full flow demineralizers Some variation exists in number of levels of redundancy and feedwater pump type (motor- or turbine-driven) and utilization of booster pumps The lack of an open deaerating heater in all plants is noted in contrast to both standard fossil-fueled plant practice and the design of certain European nuclear power plants

Table 1
Current condensate feedwater system design variation

Component	Item	Range of number of components	BVPS-2
Steam generator	Number	2–4	3
Low pressure heater string	Number	2–3	2
Low-pressure heater	Number	3–5 (5) [a]	5
High pressure heater	Number	1–2 (1)	1
Demineralizer	Number	5–9	
	Type	Full flow	Full flow
Condensate pump	Number	2–3 (3)	3
	Type	Motor-driven	Motor-driven
	Capacity	50%	50%
Booster pump	Number	0, 2 or 3 (3)	0
	Type	Motor-driven	N/A
	Capacity	50%	N/A
Feedwater pump	Number	2–3 (2)	3
	Type	Turbine or motor-driven	Motor-driven
	Capacity	50%	50, 50, 30%

[a] Content in ( ) indicates the mode of the distribution.

The BVPS-2 power conversion system is shown schematically in fig. 1. The rationale for the current form of the CFWS as shown in fig 1 is best understood through a stepwise reconstruction of the design evolution of the system. Fig 2a illustrates the simplest possible power conversion system which consists of a feedwater pump, steam generator and turbine-generator set operated in an open configuration This system, while

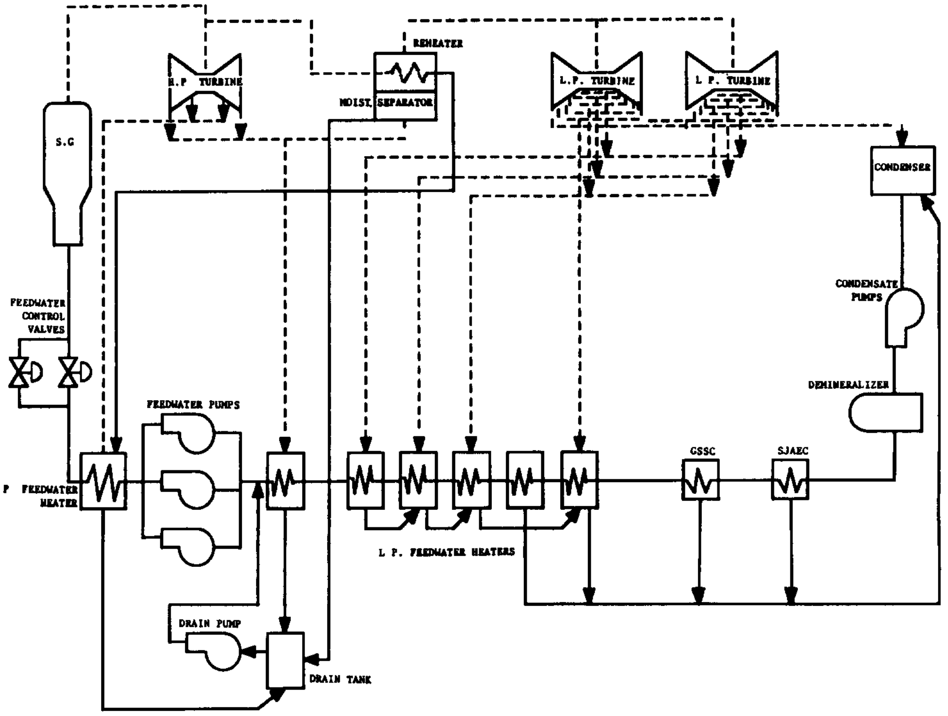


Fig 1 Current BVPS-2 power conversion system design (in two trains), also designated as System 2

admittedly "simple" (in terms of the number of components, for example), suffers from poor thermal efficiency (< 10%, susceptibility to thermal shock, poor water chemistry, and environmental effects due to the discharge of high temperature and potentially radioactive effluent. (Note that the reduction of environmental effects is not a primary system mission goal, but is an overall plant goal which is affected significantly by the system design.) Fig. 2b depicts a system which addresses some of these deficiencies through use of a closed configuration and through the addition of a low pressure condenser. These two alterations also require creation of a second pump category (condensate pump) due to the increased value of the pressure loss around the coolant loop and to the provision for condenser pressure and for removal of noncondensible gases from the system (using vacuum pumps and air ejectors). The thermal efficiency is increased substantially to approximately 28%, and the related environmental effects are reduced. The negative aspects of this design change extend beyond the problems of use of additional imperfect components. They also include introduction of new failure mechanisms (e.g., turbine blade erosion due to use of low quality steam) and new system failure states (e.g., loss of condenser vacuum).

Reduction of water chemistry problems can be addressed through the introduction of a dimineralization (condensate polishing) system while turbine blade erosion can be reduced through the introduction of mid-stage moisture removal (as embodied in the current Moisture Separator Reheaters (MSRs)) Such a system is depicted in fig. 2c. Note again that the introduction of a new failure mechanism (blade erosion) causes the introduction of equipment (MSR) which is not focused primarily upon accomplishment of the original mission goals of the systems. Thermal eficiency and shock considerations lead to the introduction of regenerative heating as embodied in closed (usually tube-in-shell heat exchangers) feedwater heaters. A typical system using five heaters with cascaded drains is shown in fig. 2d. The large number of heaters is noteworthy in that the addition of one stage of regenerative heating can improve cycle efficiency by 2–3% while the addition of a fifth level of heating provides a marginal efficiency improvement of much less than 0.5%. The evolution to maximize the thermal efficiency is evident from the addition of other regenerative devices including turbine-driven (vs. motor-driven) feedwater pumps, steam jet air ejector condensers (SJAEC), turbine gland steam seal condensers (GSSC) and heater drain pumps

Figure 2a The Power Conversion System of Step 1
(Open Cycle System with a Steam Generator Feedwater Pumps, Turbines with a Generator)

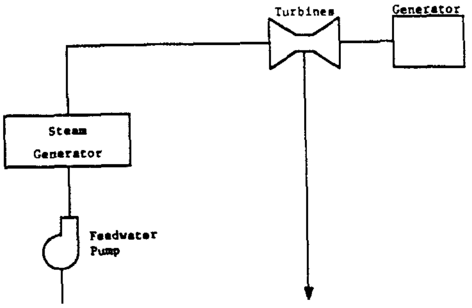


Figure 2b The Power Conversion System of Step 2
(Step One System with a Condenser and Condensate Pump)

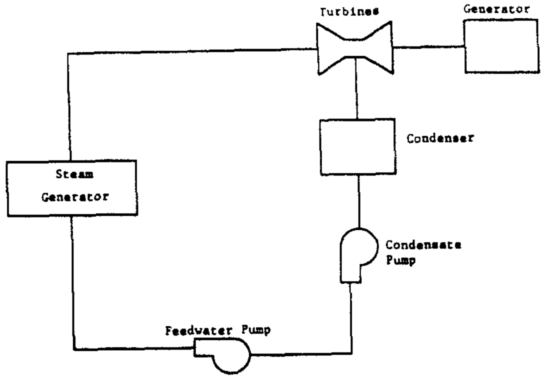


Figure 2c The Power Conversion System of Step 4
(Step Three System with a Condensate Polishing System)

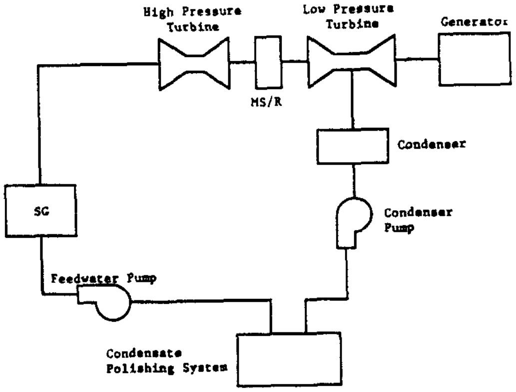
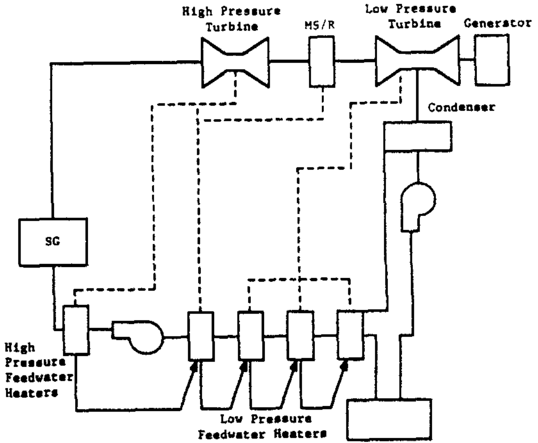


Figure 2d The Power Conversion System of Step 5
(Step Four System with many Feedwater Heaters)



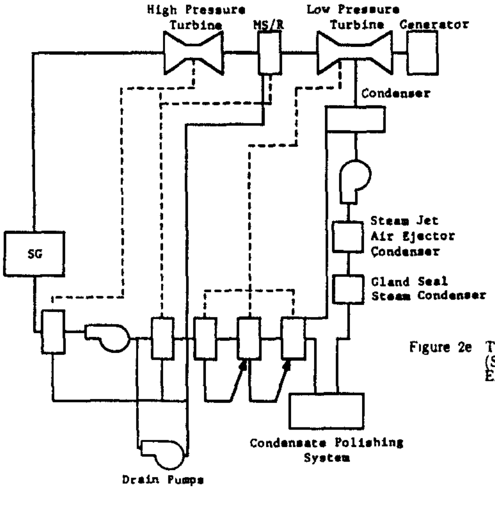


Figure 2e The Power Conversion System of Step 6
(Step Five System with other Minor Heat Exchangers and Drain Pumps)

Fig. 2 Schematic illustration of the design evolution of condensate feedwater systems.

(which have smaller thermodynamic availability effects than the practice of cascading drains). The addition of the last three device categories increases a typical plant electrical output by approximately 0.4%. Such a system is shown in fig. 2e.

When the design evolution of the CFWS is reviewed in this stepwise exercise, it becomes apparent that although the three mission goals are all taken into account the primary influence in the evolving optimization is intrinsically economic. In particular, the modern CFWS design has been determined from the predominant concern for minimizing the sum of capital and fuel costs and less from concern for operating costs. Such costs include those of lost plant availability and component maintenance. This is exemplified as follows.

- in the type and levels of component redundancy employed in current CFWS designs (e.g., heater trains are redundant but feedwater pumps usually are not),
- in the choice of equipment used (no deaerators are used even though water chemistry, e.g, dissolved O_2, would be improved), and
- in the number of heaters used (where the implied increase in unavailability due to an increase in the number of components is not considered to be as important as the thermal gain in efficiency which is achieved).

It is important to note that these observations do not imply a naive design evolution. Rather they illustrate that the underlying optimization criteria which guided past system development are not adequate for current plant economics. It is notable that availability-related economic performance is more difficult to evaluate quantitatively than are those of fuel and capital. This is because the required analysis methods and data bases are the least developed of the entire design process. In order to measure the achievement of system (and plant) mission goals, a unified, implicitly economic evaluation framework is required. The optimization criteria must be stated and understood explicitly from the beginning of the design process. System availability is not a performance characteristic which can be improved easily in completed plants This fact leads to the need for a design evaluation method so that high reliability can be made inherent in a design.

These statements are also valid concerning plant operation and maintenance costs. Such costs have not been treated traditionally as dependent variables in the economic optimization of power station designs. A comprehensive design method should take them into account in addition to availability-related costs. Operation and maintenance costs are not discussed further in this paper. However, this omission is not intended to imply that they should be neglected in formulation of a comprehensive design approach.

3. Design simplification evaluation method

The term "simplification" is included deliberately in the identification of the design refinement method described here. Its use implies that the design optimization exercise is to be a refinement of an existing entity. Two benchmark elements of an evaluation method are a unifying figure of merit and a computational framework for its estimation. For an operational system, the figure of merit must measure economic performance. Given the power plant application, the cost of electricity is chosen as this measure As a contrasting example, the proper figure of merit for a safety system is risk. The computational framework for evaluation of the effects of system simplification upon plant electricity cost is shown schematically in fig. 3

The four major cost categories are those of capital, fuel, replacement power and operation and maintenance. This delineation is not new. However, fig. 3 reflects the fact that the treatment of replacement power and O&M costs in the simplification method is different from standard power plant economic analysis in that the effects of system simplification upon availability and operational costs are computed through a more realistic treatment than has been used previously. In the past such costs were addressed by means of various empirical (and static) cost multipliers upon capital costs. In the simplification method, the capital cost analysis is performed using present worth analysis while the fuel cost computation involves a thermodynamic analysis

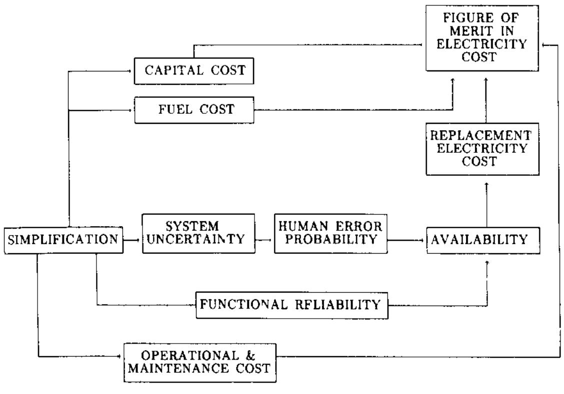


Fig 3 Diagram of impact of system simplification on electricity cost

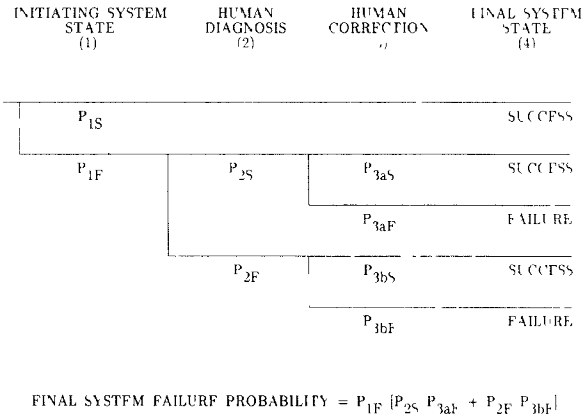


Fig 4 Mitigated failure probability

and uses a fuel cost data base These are standard practices and are not discussed further.

The estimation of availability requires two pieces of information – the mechanical system reliability and the human error probability This requirement reflects the fact that system performance depends upon both mechanical integrity and human operation of a system The art of estimation of the mechanical reliability is the more mature. It benefits from more developed estimation methods and available data bases The tools of probabilistic reliability assessment have advanced to the point of standardization and can produce reasonably accurate estimates of system performance subject to the constraint of availability of adequate information, such as is the case with components having relatively well documented failure and repair characteristics (e.g, pumps, valves, control subsystems) The specific technique which is employed in this evaluation model is that of fault tree analysis [25] of the system at hand The principal limitations on the utilization of these techniques are the treatment of data uncertainty and the inclusion of common cause and common mode failures in the analysis. While these factors are important to note, they are of less concern than the difficulties of human error probability estimates

There are three categories of human errors (1) errors of commission, which involve the misperformance (either manual or cognitive) of a correctly identified action, (2) errors of omission, when the correct act is not identified, and (3) gratuitous errors, where unnecessary acts exacerbate a situation. The current model does not address gratuitous errors but these are recognized as an important area of future work The statistical aspects of manual human actions associated with commission errors have been the subject of most of the literature of "human factors" [26], and reasonably accurate estimates of such error rates can be made However, the

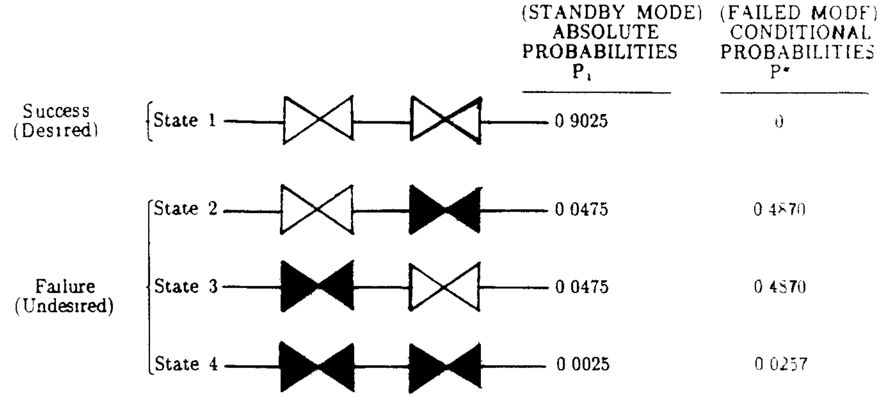


Fig 5 Four possible states of a two-valve system when the probability of a valve open is 0 95

Standby mode

$$H = \text{informational entropy} = P_2 \log_2 \frac{1}{P_1} + P_2 \log_2 \frac{1}{P_2} + P_3 \log_2 \frac{1}{P_3} + P_4 \log_2 \frac{1}{P_4} = 0\ 5727$$

Failed mode

$$H_D = \text{DEPOSS} = P_2{}^* \log_2 \frac{1}{P_2^*} + P_3{}^* \log_2 \frac{1}{P_3{}^*} + P_4{}^* \log_2 \frac{1}{P_4{}^*} = 1\ 147$$

[$P_i{}^*$ conditional probability of system state i when the system is in an undesired state] dependence of cognitive errors such as in system diagnosis upon system design is an area that lacks a substantial conceptual framework of credible empirical data. The necessity for inclusion of this category of model can be appreciated from a review of fig. 4 which depicts the human reliability analysis in an event tree framework.

The ideas discussed in this section are reported more completely in refs. [3] and [29]. In an evaluation of the human contribution to system unavailability emphasis is placed upon the expected fequency of human success in diagnosing the condition of a system which has failed to operate as intended. It is assumed that the system will have a set of possible configurations or states. Among these only one, termed the desired state, will be the state which it is intended that the system occupy at a particular moment. The identity of the desired state may change with the passage of time. In a well-designed system the probability of the desired state will be large and that of any other state, an undesired state, will be small.

These ideas are illustrated in fig. 5, which shows a two-valve hydraulic system. In this example the state where a fluid is permitted to flow, that with both values open, is the desired state. The remaining three states, each of which has at least one valve closed, are all undesired. For this example it is assumed that the probability that a valve will actually be open when it is intended that the valve be open is 0.95. The corresponding state probabilities are shown in fig. 5.

Three alternative conditions are of practical interest for a system, as follows:

- The system is operating as intended.
- The system is in standby status.
- The system has failed to operate as intended, and is, thus, in one of the undesired states.

The respective conditional probabilities of the system state are different for each of these conditions. When the system is operating as intended and a perfect signal indicates this to be the case (e.g., when fluid is seen to be issuing from the system of fig. 5), the conditional probability of the desired state is unity and that of each indesired state is zero. Under this condition the uncertainty of the system is nil as the true condition of the system is known with absolute certainty.

When the system is in standby status the probability assignments of fig. 5 for the standby situation apply. It is seen that the desired state is far more likely than any other. If one were to search for the true system state it would be most efficient to search first for the desired state for this reason. Then if the system were found not to be in that state an efficient search would proceed next to the two single-failure states successively, and after those, finally, to the remaining double-failure state.

When the system is known not to be in the desired stated (e.g., with the example of fig. 5 when fluid does not issue from the piping system) the conditional probability of the desired state is equal to zero. Correspondingly the conditional probabilities of the remaining must be re-normalized such that their sum is equal to unity This renormalization is illustrated in the example of fig. 5 for the failed system situation. It is seen in that example that the number of likely states has doubled, with the conditional probability of each of the single failure states being slightly less than one half. In diagnosing this system the most efficient search would begin with one of these states. However, the probability of not finding the true system state would be 0.55, rather than 0.10 as in the situation where the system is in the first interrogation in standby status.

The uncertainty of a system is quantified by the informational entropy, H, through the relationship:

$$H = -\sum_{i=1}^{n} p_i \log_2 p_i, \tag{1}$$

where n = number of system states, and p_i = probability of the i-th state. For a system known to be in the desired state the value of H is equal to zero, as the system has no uncertainty For the standby and failed system situations of the example of fig. 5, the respective values of the entropy are 0.5727 and 1.147 It is seen that the value for the failed system is approximately double that for the system on standby, reflecting the fact that the number of highly likely states of the former is twice that of the latter. The entropy is used as an indicator of the complexity of the system under consideration.

A postulate of the work reported here, which has been confirmed, is that the number of questions, $\langle \hat{n} \rangle$, which must be asked in order to diagnose a system is a unique function of the system entropy. It has been shown [29] that $\langle \hat{n} \rangle$ obeys the relationship

$$\langle \hat{n} \rangle \simeq \tfrac{1}{2} 2^{H}. \tag{2}$$

This relationship has been shown to hold, at least approximately, without regard for the number of components in the system or the particular values of the state probabilities.

This relationship may be understood by considering the diagnosis of a system of N components for which all possible states have the same probability value. When the number of system states is n the value of p_i is equal to $1/n$. For this system the value of $\langle \hat{n} \rangle$ is equal to

$n/2$ This is because no sequence of searching for the true system state is more efficient than another or than a perfectly random search. For this system the entropy has the value $\log_2 n$, from which the result

$$n = 2^H \tag{3}$$

is obtained, as is that of eq. (2). The system for which the probability of each state has the same value is particularly interesting since it has the least number of possible states of any system having the entropy value H

An especially interesting case is that of the system where all possible states have probabilities of value zero except for the single failure states. The number of possible states is equal to the number of system components For this situation the value of $\langle \hat{n} \rangle$ is given as

$$\langle \hat{n} \rangle = \frac{N}{2} = \frac{1}{2} 2^H \tag{4}$$

The result

$$N = 2^H = N_D, \tag{5}$$

where N_D is termed the diagnostic number of components. The approximations imbedded in eq. (5) apply to well-designed systems which must be diagnosed due to failure but for which the absolute failure probability for each component is small Use of eq (5) permits comparison of dissimilar systems in terms of diagnostic complexity. The approximate equivalent number of system components for a failed system having a conditional entropy value of H is given by N_D. The relative complexity of systems of differing values of H (termed H_D) is indicated by differences in the corresponding values of N_D. The complete definition of H_D is diagnostic entropy for a failed system having a single perfect system signal. It is notable that N_D and $\langle \hat{n} \rangle$ increase exponentially as functions of H.

A concept which is used subsequently in the analysis of system reliability is that of the probability of failure to diagnose a failed system correctly within a limited number, j, of interrogations. When the interrogation of a failed system is performed in the descending order of state probabilities, $P_f(j)$ is seen to obey the relationship

$$P_f(j) = 1 - \sum_{i=1}^{j} p_i. \tag{6}$$

An important aspect of these concepts is that when a group of human subjects was asked to diagnose different failed CFS examples it was seen that the values of $\langle \hat{n} \rangle$, $P_f(3)$ and $P_f(5)$ correlated very well with corresponding results obtained from eqs (2) and (6)

The challenge is to identify a measure of design simplicity which can be correlated with the human error probability. In the work reported here the measure that has been identified as being useful for this purpose is the information entropy, H, [27] subject to the condition that the system is in a failed or undesirable state

The most important aspect of these formulations is that they can be demonstrated empirically (i.e., through actual human performance experiments) that P_f and H_D can be correlated Therefore, the quantification of H_D which involves a mathematical calculation can be used to estimate the human probability of diagnostic success and thus to complete the event tree calculation depicted schematically in fig. 4

4. Application to representative designs

Use of the evaluation method is now demonstrated through a comparative analysis of three candidate CFWS The first is the BVPS-2 system depicted in fig 1 and table 1. Two alternative configurations are constructed by selective modification of the BVPS-2 system One system has less hardware and the other more hardware than the BVPS-2 system. The underlying logic, which is employed in the creation of these two alternatives, reflects the qualitative development history summarized earlier. removal of components which have small effects upon the thermodynamic efficiency, elimination of active components as a general goal, focus upon subsystems which have historically been sources of plant unavailability and exploiting the potential for alternative component utilization

The first alternative, simpler, system is designated as System 1 System 1 has two fewer low pressure heaters and no fifth point heater drain cooler The drains are cascaded down, thus eliminating drain pumps and tanks The three feedwater pumps are changed to variable speed motor-driven pumps and each is rated for 50% of full flow (vs using two 50% and one 30% pumps as with BVPS-2) System 1 is shown schematically in fig. 6. The BVPS-2 system is designated a System 2

The third, more complex, system which is designated System 3 has two condensate pumps, two feedwater pumps, two booster pumps, a drain pump and additional motor-operated valves. System 3 is depicted in fig 7

The major active CFWS components of the three systems are illustrated in figs. 8a through 8c System 1 has 23 active components with four stage of feedwater

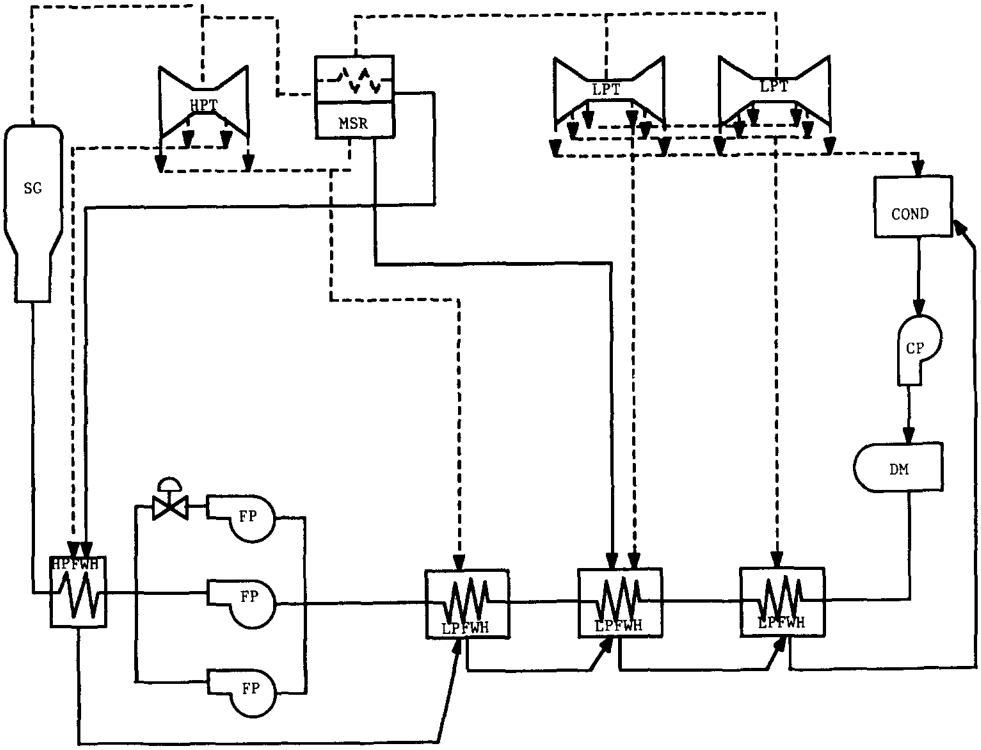


Fig 6 Simplified power conversion system design 1 (in two trains)

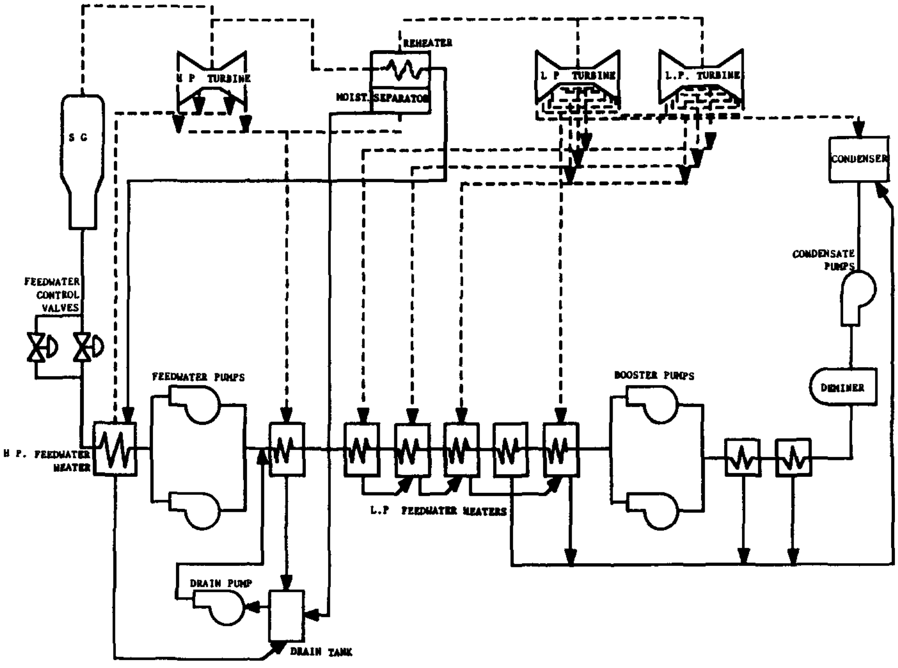


Fig. 7 Complex power conversion system (in two trains), System 3

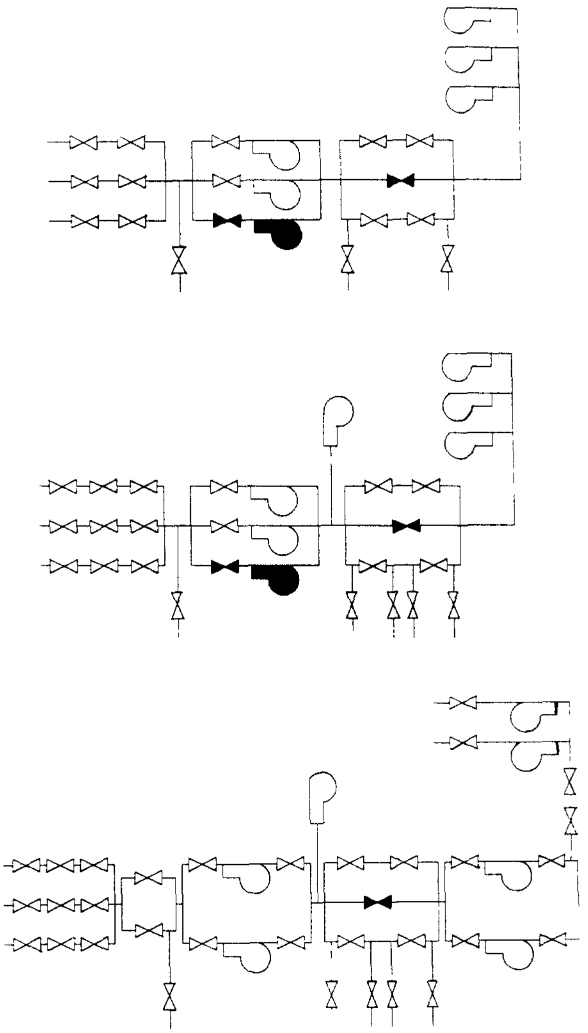


Fig 8 (a, top) Active components configuration of simplified condensate feedwater systems System 1, (b, middle) Active components configuration of medium complexity beaver Valley Power Station-2 condensate feedwater system System 2, (c, bottom) Active components configuration of complex condensate feedwater system System 3

heating. System 2 has 29 active components with six stages of feedwater heating. System 3 has 40 active components with six stages of feedwater heating. The estimation of the human error contribution to system unavailability is based upon use of the concepts outlined previously. The computation of the mechanical or functional reliability contribution, which is performed using fault tree analysis, requires the provision of a component reliability and repair data base. Two alternative data bases are employed for performance of two separate system evaluations The purpose is illustration of the sensitivity of the results of an evaluation to differing uniformity in the expected rates of component failures The data base which is employed in the analysis of Case A utilizes generic industry data for the active components [28] The other data base, employed in the analysis of Case B, is a modification of that of Case A in which the pump failure rates are made uniform These two data bases are listed in table 2 Additional information, including plant power rating, cost data, economic performance factors and additional human error performance attributes, which are required for the overall evaluation methodology calculations are listed in table 3

The calculation of system availability, taking into account both mechanical and human contributions to lost availability, is performed as follows The system is assumed to become unavailable for full power operation due to refueling, shutdowns due to major repairs of long duration and due to transients which take the plant off-line for short durations Each of these classes of outage is characterized by a mean time to failure and a mean time to repair, respectively, as shown in table 2 The human contribution to lost availability arises in transients which lead to forced outages It is assumed that the plant is designed with remotely-activated system recovery features which would permit valves or pumps which were to fail to operate properly to be reset and placed back in service in time to keep the plant running if their failure were detected quickly

Table 2
Reliability data used in sample evaluations

	Item	Case A	Case B
Failure rate (10^{-5}/h)	Feedwater pump	11 90	2 99
	Standby feedpump	2.99	2 99
	Booster pump	2 99	2 99
	Condensate pump	2 99	2 99
	Drain pump	14 50	2 99
	Feedwater control valve	2 00	2 00
	Other motor operated valves	1 66	1 66
	Feedwater heater	$9\ 17\times10^{-2}$	$9\ 17\times10^{-2}$
Mean time to repair (MTTR)	Active component	1 25 days	1 25 days
	Feedwater heater	30 days	30 days
	Refueling	25 days	25 days

Table 3

Other data used in sample evaluation

Item	Data
Power rating	1000 MWe
Replacement electricity cost	40 mills/kWh
Fuel cost	$\$1.8\times10^6$/MTHM
Fuel burnup rate	33000 MWD/MTHM
Price escalation rate	0.09 (yr^{-1})
Discount rate	0.06 (yr^{-1})
Plant lifetime	35 years
Pump cost	$\$5.0\times10^5$
Valve cost	$\$1.0\times10^5$
Feedwater heater cost	$\$1.5\times10^6$
Correction error probability	0.01
Lucky success probability	0.01
Number of interrogations allowed in diagnosis	3

The sequence of events leading to a forced plant outage of either long or short duration is indicated in fig. 4. The outage event sequence consists of the following

- an initial system failure,
- an attempt by the plant operator to diagnose the failure, and
- an attempt to restore the failed components to operation.

The different success and failure paths are indicated in fig. 4.

In system diagnosis it is assumed that the plant operator is trained to search through the system states in the descending order of state probability, and if the analyst cannot identify the true system state in three interrogations that the diagnosis is unsuccessful, the latter assumption is used as a surrogate for the case of the analyst having only a limited amount of time for diagnosis. The probability of successful diagnosis in calculated from eq. (6). Upon successful diagnosis it is assumed that the probability of correcting the system failure is P_{3aS} Upon unsuccessful diagnosis it is also possible, but very unlikely, to correct the failure. The probability value of P_{3bS} is used for this event.

Each branch of fig. 4 then has an associated probability, which is used in combination with mean time to failure data in the calculation of the final system failure rate (FSFR). The initial system failure rate, the rate of events initiating a transient or of refueling, is obtained taking into account only mechanical failure data. It is seen in table 4 that the effects of operator diagnosis is to render FSFR < ISFR, sometimes substantially. Note that the specific human error which appears in this analysis is failure to diagnose and mitigate after three attempts. This is clearly an arbitrary specification based on intuition.

The results of the various evaluations are summarized in tables 4 and 5 which present the three system comparisons based upon Case A and Case B data, respectively. In both comparisons, the diagnostic entropy, H_D, increases with system complexity as is expected. For a given system the absolute values of H_D are higher in Case B due to the greater uniformity among components of the reliability data, but the fractional changes of the value of H_D between systems are the same in both cases. As expected, the variations of P_f and $\langle n \rangle$ reflect that of the entropy The diagnostic number of components, N_D, is noteworthy in that it is substantially lower than the actual number of components in Case A and nearly equal to the actual number of components in Case B. This fact illustrates the point that a system with more uniformly distributed undesired state probabilities is harder to diagnose. Comparison of systems in terms of H_D also provides a measure which can be appreciated in concrete term, i.e., the number of components in a system.

The human effects upon the initial system failure rate (i.e., diagnostic effects other than from actions) are not included in the current model due to a dearth of useful data and the lack of a conceptual framework.

Table 4

Results of the economic evaluation using failure data in Case A

	System 1	System 2	System 3
Number of active components	23	29	40
H_D	4.067	4.304	4.812
N_D	16.792	19.757	28.275
P_f (3)	0.588	0.564	0.639
$\langle \hat{n} \rangle$	8.015	9.392	13.800
ISFR [a] (/yr)	1.419	3.444	8.807
FSFR [b] (/yr)	0.834	1.941	5.624
Availability	0.92448	0.91785	0.90735
[c] Fuel cost saving ($)	-2.01×10^7	0	0
[c] Replacement electricity cost saving ($)	5.03×10^7	0	-7.98×10^7
[c] Capital cost saving ($)	1.0×10^7	0	-1.1×10^7
[c] Total electricity cost saving ($)	4.02×10^7	0	-8.09×10^7

[a] ISFR-Initial System Failure Rate

[b] FSFR = Final System Failure Rate

[c] Net present savings at the start of station operation

Table 5
Results of the economic evaluation using failure date in Case B

	System 1	System 2	System 3
Number of active components	23	29	40
H_D	4 472	4 807	5 278
N_D	22 191	27 992	38.799
P_f (3)	0 810	0 847	0 883
$\langle \hat{n} \rangle$	10 476	13 144	18 345
ISFR [a] (/yr)	1 408	2 409	6 117
FSFR [b] (/yr)	1 139	2.038	5 397
Availability	0 92358	0 91757	0 90799
[c] Fuel cost saving ($)	-2.01×10^7	0	0
[c] Replacement electricity cost saving ($)	$4\ 56\times10^7$	0	-7.28×10^7
[c] Capital cost saving ($)	1.0×10^7	0	$-1\ 1\times10^6$
[c] Total electricity cost saving ($)	3.55×10^7	0	$-7\ 39\times10^7$

[a] ISFR = Initial System Failure Rate
[b] FSFR = Final System Failure Rate
[c] Net present savings at the start of station operation

Such actions represent an area of important future work. Among such human contributors to initial system failure are errors in maintenance, manual errors and cognitive errors in operations and gratuitous error, where needless actions are taken which impair plant operations. Hence, the ISFR values do not reflect a sensitivity to any human performance contributions.

The overall effect of human performance on the FSFR and the system availability is small in the cases studied. This does not represent a failure of the model or imply a general conclusion that human performance attributes are not important. The history of plant operations provides adequate proof of the latter point. The results reflect the characteristic of the systems selected for examination in that the variability of mechanical functional unreliability is a much stronger effect than that of human performance contribution. It is recognized that other systems (especially very high reliability system such as electronic controls) may have quite the opposite sensitivity

Nevertheless, subject to the various limitations and assumptions, the results provide some interesting insights which are unobtainable from existing economic analyses. If the plant optimization criteria were to focus only upon capital, fuel and standard O&M costs, as is the current practice; System 2 (the actual BVPS-2 system) is seen as the optimal choice among the three. This is true for both sets of performance data. However, if the new methodology is employed. System 1 is seen to be more attractive even though its thermodynamic efficiency is lower than that of System 2 and its capital cost savings are relatively small over the plant's operating life System 3 is not preferred under any circumstance

5. Critique and concluding remarks

The evaluation methodology discussed here requires both refinement and application to other systems However, it provides and advancement of the comprehensiveness of the design process. The first area of improvement concerns deficiencies of the conceptual framework Two categories of needed improvement are First, development of models and data for a complete calculation of the figure of merit of the design, such as a better quantification of the influence of human performance upon availability; and, for non-power plant applications, the specification of alternative figures of merit Second, the specification of the new overall evaluation framework for non-operational systems, such as a quantification of risk in evaluation of a safety system.

The next level of refinement of the design methodology is the further development of the various elements of the design evaluation model Experience to-date with operational system analysis indicates that the area of human performance is the most deficient in terms of both theory and supporting data. Some of the more important issues have been mentioned – correlation of system design and performance, identification of proper maintenance errors and gratuitous acts and evaluation of the utility of the event tree concept to this quantification. Use of such improved design methods may lead to changes in the evaluations of the costs of maintenance with replacement of the currently employed cost multiplier methods. Quantification of mechanical reliability remains a developing science, especially in the areas of data uncertainty and applicability

In addition to human error the economic costs of operation and maintenance, of enhanced safety, and of construction schedule disruption, need to be taken into account as design-dependent variables. The economic cost contributions of capital and fuel are adequately addressed with current practices. Development of non-operational system evaluation framework will produce a new set of problem areas

The specific example of the condensate feedwater system is a useful first application, with overall positive results, of the evaluation methodology presented here. The currently unachieved goal of economically optimal large central station power plant performance, as exemplified by the detailed consideration of the CFWS evolution, is seen as resulting from deficiencies in the original specification of plant performance goals and from failure to include all of them as optimization variables in the design process. The inclusion in the evaluation of realistic plant availability and operation and maintenance, is required. The further development and application of methodologies which reflect the complete set of dependent cost factors will provide the technical community with tractable methods for achieving the goal of design simplification and will produce new generations of better performing power plants.

Acknowledgements

The support of this work by the EPRI Advanced Light Water Reactor Program is gratefully acknowledged.

Nomenclature

BVPS-2	Beaver Valley Power Station, Unit 2,
CFWS	Condensate Feedwater System,
FSFR	Final System Failure Rate (per year),
GSSC	Gland Seal Steam Condenser,
H_D	diagnostic entropy for a failed system having a single perfect system signal,
H	information entropy,
ISFR	Initial System Failure Rate (per year),
LWR	Light Water Reactor,
MSR	Moisture Separator Reheater,
N_D	diagnostic number of components,
N	number of system components,
n	number of system states,
$\langle \hat{n} \rangle$	average number of interrogations in system diagnosis,
O&M	Operations and Maintenance,
$P_f(j)$	human error probability to not diagnose successfully after j inquiries,
PWR	Pressurized Water Reactor,
P_i	probability of undesired state i,
SJAEC	Steam Jet Air Ejector Condenser.

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