A SYSTEMATIC METHOD FOR THE CONDITION ASSESSMENT OF CENTRAL HEATING PLANTS IN AIR FORCE LOGISTICS COMMAND

THESIS

Gary J. Starmack, Captain, USAF

AFIT/GEM/DEE/90S-17

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GEM/DEE/90S-17

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Gary J. Starmack, B.S.
Captain, USAF

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Abstract

Air Force Logistics Command (AFLC), faced with decreasing funds and aging utility systems, needed a method to objectively rate its central heating plants. Such an objective rating system would be used to compare heating plants throughout the command to identify potential problem areas and prioritize major repair projects.

This thesis used a Delphi questionnaire to gather opinions from central heating plant experts in order to identify and prioritize components considered most critical to overall plant operation. In addition, the experts suggested measurements which could be used to evaluate component conditions.

By combining expert opinions and readings from technical literature, component model rating schemes were developed for AFLC's steam and high temperature hot water plants. Based on measurements and observations of critical components in the plant, a score between 0 and 100 is assigned to each component (for example, condensate piping, deaerator, etc.), each plant subsystem (distribution system, water treatment system, etc.), and to the plant as a whole. These component model rating schemes and the resultant overall condition index scores will enable AFLC to objectively determine the relative condition of each of its heating plants in order to focus management attention and allocate needed resources to the plants in greatest need of repair.

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I. Introduction

General Issue

According to the Maintenance Engineering Branch of Headquarters Air Force Logistics Command (AFLC), many of the facility infrastructure (F/I) assets of AFLC are deteriorating and are close to failure (1). Facility infrastructure assets are structures or utility systems on an Air Force base which exist to support the mission or missions of the entire base and are placed in the care of the civil engineering organization. Examples of such assets include: pavements, electrical distribution, central heating plants, central chiller plants, liquid fuel distribution, waste-water treatment, and water distribution. Failure of these AFLC infrastructure assets could result in the loss of millions of dollars in production and reduced support capability to critical national defense programs (2). The recent Department of Defense budget reductions have limited the amount of money that can be spent to assure the reliability of these systems into the future. The basic management problem AFLC faces is to determine which critical assets are in the greatest need for repair. Once the state of repair of each asset is determined and prioritized, the limited dollars can then be allocated in an efficient manner.

A utility outage survey was conducted by HQ AFLC in June, 1989 to determine the impact of utility outages on production losses. Each base in the command furnished all their available data on various utility outages but, only in a few instances were records kept on production lost as a result of the outages. The information gathered in this survey gave HQ AFLC only a general impression of the state of its utility systems and no specific inferences on needed rehabilitation work could be drawn (3).

Specific Problem

The specific problem that faces AFLC is the lack of a method to quantify the current state of repair of their facility infrastructure assets. Currently, AFLC uses a qualitative self-assessment system, updated semi-annually, with each base rating its F/I assets as either good, fair, or poor. Without a method to numerically quantify current equipment conditions, projects can not be accurately prioritized for need. Due to the variety of infrastructure assets and their differences in nature, it would be difficult to develop one method to compare all the systems on an absolute scale; therefore, each type of asset must have its own rating system (4).

Research Objectives

This research study devised a method to rate central heating plants (steam and high temperature hot water plants) and their distribution systems on a continuous scale of zero to one hundred by assigning weighted values to each of the vital components of the system. The final product of the study was a component model rating system which facilitates the calculation of an overall condition index value for any central heat plant in AFLC.

Scope and Limitations of Research

This research consisted of a survey of experts using the Delphi technique to determine critical system components, their relative importance, and criteria which is used to assess the heat plant's current condition. Since central heat plants vary from one installation to another with respect to major components and fuel systems, with many equipment combinations possible, this study concerns only the systems encountered in AFLC. Therefore, the surveyed personnel consisted mainly of AFLC maintenance experts since they are knowledgeable of their own systems and would not introduce any components or inspection criteria that was not applicable to AFLC systems. However, it was necessary to have three mechanical engineering experts from outside of AFLC participate in the survey to help balance the number of experts between maintenance and engineering specialties. This study creates a tailor-made rating system to match all of the equipment configurations in the command and may not necessarily be applicable for other central steam plants.

In order to validate the final product, the component models (one for steam and one for high temperature hot water systems) developed from results of a Delphi survey should be operationally tested for a minimum two-year period at all AFLC heat plants. Such tests would allow the correlation of condition index scores with component and system failure rates to determine if the condition indices accurately represent system conditions. However, no operational test was conducted as part of this research. The only indication of the validity of the component models came from a subjective review by the engineers at HQ AFLC/DEMM, the office requesting the development of the model.

Definition of Key Terms

There are some basic terms which will be used throughout this paper that must be defined to understand the work which follows.

The term, central heat plant, refers to a facility which houses a boiler or set of boilers, along with all of the auxiliary equipment necessary to produce steam or high temperature hot water at a controlled rate (equipment such as, fuels, furnaces, controls, and pumps). The heat produced at a central plant is distributed to other buildings in the form of either steam (with pressures typically in the range of 150-250 pounds per square inch) or high temperature hot water (typically 250-350 degrees fahrenheit).

The distribution system consists of the piping which conducts the steam or high temperature hot water to the buildings consuming the heat and the piping which returns the condensed steam or hot water to the central plant. Included in the distribution system are items of auxiliary equipment, such as, pipe, steam traps, and pumps. The distribution system includes only the main piping lines leading to and from each building and the central steam plant and does not include any secondary piping leading to the individual buildings.

Investigative Questions

The specific questions that must be answered to solve this particular problem are:

1). Has any similar rating system been previously developed?

2). What are the variations of equipment types throughout AFLC (coal-fired, gas-fired)?

3). How can these variations be resolved into a single rating system?

4). What are the vital individual components of each utility system?

5). What weight should each component have to influence the overall score?

6). How should the weighting be determined?

7). How can the inspections be carried out in a consistent manner at all locations in AFLC?

Overview of Chapters

This chapter discussed the need for a rating method to assess the current state of repair of utility systems in AFLC, in particular, the central heating utility system. Chapter II will review literature on efforts to establish component model rating systems for heat plants and other mechanical equipment, as well as methods available to predict remaining useful life of boiler components. Chapter III will describe the Delphi methodology used in this study to meet the research objectives and answer the investigative questions. Chapter IV will introduce the component model rating systems for steam and high temperature hot water plants and will detail the steps taken to derive the condition indices. Finally, Chapter V will discuss recommendations for using the model as well as recommendations for further research.

II. Literature Review

Chapter Overview

The purpose of this chapter is to review the available information on rating schemes for steam or high temperature hot water plants or other similar systems, and to gain insight on the current methods used by industry and the government to analyze their mechanical assets. However, a thorough data base review of the Defense Technical Information Center (DTIC), Defense Logistics Studies Information Exchange (DLSIE), and the DIALOG information services did not reveal any published work on rating schemes for central heat plants. Consequently, the researcher reviewed available material on current efforts in the area as well as studies similar in nature.

Government Studies

The Air Force, Army, and Navy have been conducting research in the assessment of conditions for critical mechanical systems. This section of the review will summarize these studies, completed or underway, for boiler system conditions as well as hydroelectric power generation system conditions.

Air Force Logistics Command. In March of 1988, HQ AFLC/DEMM developed a concept paper proposing the formation of a Facility Infrastructure Process Action Team (FIPAT). FIPAT was tasked with improving facility infrastructure (F/I) planning and requirements identification. The team identified 17 major F/I systems requiring attention, including steam production and distribution (5:1-2).

One of the major functions of the FIPAT was to visit the AFLC bases and query the local engineering and maintenance experts on F/I critical system components. The experts were asked to give in their opinion relative weights of importance for each of the 17 infrastructure systems (5:7). The listing of the critical components and their relative importance on a scale of one to one hundred was required as a first step for the development of a component model rating system for each F/I asset (3).

Currently, the only rating system used by AFLC is highly subjective, with each F/I system rated as an overall good, fair, or poor. In the case of central heat plants, no base in AFLC rated itself in the good category. A more objective numerically scored system, on a scale of one to one hundred, is desired to rank each F/I system in order of best to worst.

For central heat plants and their distribution systems, not only is the overall score important, but also the individual scores for each major subsystem of the plant. Low scores will alert management to specific problem areas. The proposed list of critical components and their weight factors gathered during the FIPAT visits were preliminary in nature and a more in-depth study is needed to devise a good assessment system. Such an assessment system could be used to correlate scores for heat plant subsystems and components to rates of deterioration in order to predict failures and thus eliminate costly down time. Currently, no assessment system for any F/I system has been fully developed or implemented (3).

In a letter to HQ USAF/LEEP, dated 5 Mar 1990, HQ AFLC/DEM details its intent to use a new program called Facility Infrastructure Management Aid (FIMA):

> FIMA is a [computer-based] facility management system now under development at HQ AFLC/DEMM. Our purpose is to objectively determine the condition of base facility infrastructure assets, predict their time to failure, and recommend priorities for repair and replacement....It will use expert system technology to advise engineers and craftsmen of impending failures, and diagnose problems before failures occur. It will utilize data that is presently in the Wang [computer system]...as well as vital component data to be added to Wang records....FIMA gives objective, defendable ratings of system condition. These ratings can be used at base, headquarters, and Air Staff level to prioritize requirements....To rate each system, we first define its major components....To assess the condition of these major components, Condition Factors (CFs) are determined. CFs are indicators of the condition of components, which can be used to predict their failure. Each CF is given a numerical value which is used to determine the overall Condition Index (CI) of the system....If all components are not equally important to the functioning of the system, each of the components may be given a different weight. (4).

<u>United States Army Construction Engineering Research Laboratory (USACERL)</u>. A study on heat plant condition assessment is also underway at USACERL. They awarded a contract to Iowa State University in November, 1989 to "Develop evaluation procedures and provide documentation for central heating plants" (6:2). The goals of this contracted study are similar to those of HQ AFLC to develop a quantifiable method for heat plant assessment. The statement of work issued by USACERL explains their study:

> The objective of this delivery order will be to develop a procedure for evaluating the condition of an existing central heating plant, and to estimate the life cycle

> cost for maintaining the status quo. The procedures will provide step by step guidance for this evaluation, and include algorithms for estimating the operating, maintenance and major repair costs involved in continued operation of the plant. (6:2)

According to the contract, the contractor must include the following major subsystems in the evaluation process: water treatment, feedwater system, fuel handling and storage, combustion controls, boiler, air pollution control devices, heat recovery, and physical plant. The evaluation process is to include developing questions to determine the condition of plant equipment based on readily available information on equipment design, age, and maintenance history. In addition, other issues, such as reliability, safety, and compliance with codes will be included in the evaluation. The contractor must then develop a method to rank the condition of the heating plant's major subsystems and estimate their expected remaining lives. The contractor is further required to develop a method to estimate operation and maintenance costs based on the overall condition evaluation results and also to develop a method for estimating major repair and replacement costs. This study is scheduled for completion in November, 1990 (6:1-4).

The above study is primarily for the heating plant alone, not inclusive of the distribution system piping. Some preliminary work has been done by USACERL on the development of condition indices for steam distribution systems. The condition indices are based on a computer analysis of the distribution network.

In addition to miles of pipe in a typical distribution system, other major components are: insulation, valves, joint flanges, manholes, building entry points, expansion joints, pipe supports, sump pumps, and steam traps. Some of these components have methods available to determine their condition and useful life, however, not all methods are quantitative and require experienced engineering judgement. Some condition indicators for the distribution components are: ponding water, burnt grass or steaming ground, endplate drains, water stains, corrosion, condition of insulation, sump operation, air pressure test, ultrasonic testing, thickness testing, infrared surveys, and steam use/flow modeling. One example of a quantitative method of assessing condition would be metal thickness testing. Periodic thickness measurements on a steam drum can be taken and plotted over time. These thickness measurements can be used to determine pressure ratings which could then be used to extrapolate at what point in time the drum thickness will become inadequate to support the steam system pressure. An example of a qualitative method of assessing condition would be conducting a no-load test of the distribution system by producing enough steam to fill the lines when there is no user demand. The amount of steam produced to maintain system pressure will indicate the amount of steam leaks in the system (7:1-5).

The study reports that the ability to track energy losses may be the most important condition indicator for steam distribution systems and there are several methods available to analyze energy loss as this usually represents a large monetary loss.

> Because of the remoteness and limited access of the distribution system, a logical tool to evaluate the system is a computer simulation. Such tools are under development and have been used by USACERL to evaluate energy supply alternatives for Army installations....These computer models are Steam Heat Distribution Program (SHDP) and HEATLOAD. (7:6)

Although these programs are available, there are no formal techniques published on how to effectively use them.

The SHDP program is used to model steam district heating systems. This program calculates the steady state properties during operation of the distribution system. SHDP can evaluate benefits of distribution system modifications, predict energy savings from changes in operating strategies, and predict savings from enhanced maintenance. The HEATLOAD program calculates the daily heating energy consumption for ten typical types of Army facilities based on square feet of facility and heating degree days for the location (7:6-10).

> The entire installation distribution system is entered into SHDP, along with the heat loads for each building calculated from HEATLOAD. SHDP calculates the distribution losses and the total heating requirement for the central heating plant. The distribution losses are compared to the "no-load" load from the plant records....This gives a fairly accurate estimate of the steam trap losses. (7:10)

The SHDP model may be calibrated to the particular heat plant by comparing its load profile to central plant records. This procedure of analysis would be used to determine the most probable causes for system failure, and the components which provide best indication of system condition (7:10).

Army Corps of Engineers. With intentions similar to AFLC and USACERL, the North Pacific Division of the Army Corps of Engineers is working to develop equipment condition indicators for various categories of major hydroelectric equipment. In a survey sent out to various Army engineering branches in December, 1989, the North Pacific Division stated the intent of its study was to create a standard methodology for evaluating the current operating condition of the equipment.

> Our current plan is to prepare a set of specific "condition indicators" for each type of equipment under consideration. Tests or observations will be used to determine the current condition relative to each indicator. A system of point values will be assigned to each indicator....The appropriate weighing of these factors will provide the basis for calculating an overall "condition index"....this "index" figure will be used to estimate the remaining life of equipment (8:1).

The Corps hopes to use the results of this study to compare the condition of similar equipment at different locations and also to adjust useful life predictions for specific equipment based on the trends of condition indices and other observable factors. The Corps also states that this is their first attempt at developing a predictive maintenance program and anticipates refinement of the process "as we gain experience and develop a uniform historical database" (8:1).

In the hydroelectric equipment survey, 13 components were identified and the criteria for analysis ranged from seven to ten indicators for each component. The participants were asked to weigh each indicator listed for each component.

Participants were also asked to add or delete indicators along with an explanation (8:2).

U.S. Navy. The use of a historical database has already proven to be a successful method of boiler maintenance analysis by the U.S. Navy. A study completed in 1979 on destroyer-based 1200 PSI propulsion plant boilers allowed the Navy to revise and reschedule certain preventive maintenance actions to increase operational availability. This particular study was not concerned with developing condition indices, but with reviewing all documented data sources, primarily, the Navy's computerized Maintenance Data System (MDS). The MDS includes all part and labor records, as well as narrative material, describing maintenance actions reported against system components. The MDS identified all maintenance actions reported against the 1200 PSI propulsion systems and allowed the researchers, with the help of other written maintenance records, to establish trends in the deterioration of parts and recommend new maintenance timetables to increase system reliability (9:4-5).

Electric Power Research Institute (EPRI)

EPRI has developed generic guidelines for fossil fuel power plant life extension projects. Although these guidelines are general in nature and deal mainly with the economics of life extension programs, their suggested methodologies can be applied to developing condition indices and rating methods for other systems.

> Life extension can be broadly defined as a utility program that integrates the long range planning function

> with a rigorous program of condition assessment, refurbishment as required, monitoring, and improvement in maintenance and operating procedures....The overall objective [of these guidelines] is to outline the important issues during...a system life extension program. These guidelines are to be used as a general tool to be adapted to the specified needs of each user. (10:S-1)

The guidelines are broken into four specific objective areas: Corporate Planning, Life Assessment Planning, Life Extension implementation, and Refurbishment and Post Refurbishment Issues (10:2-4). Of relevance to this work is the portion on life assessment planning as it directly relates to the methods of assessing plant condition. The article listed five action items under life assessment planning, three of which pertain to condition assessment:

1. List all major systems in the plant and divide the systems into components.
2. Evaluate the historical condition of the unit and its key components, and assess the present operational characteristics using plant data.
3. Choose an equipment ranking procedure.

The EPRI study concluded that by dividing the plant into its major systems and subsequently into components within those systems an ordered evaluation could proceed most logically. Components can further be classified as critical or non-critical. A critical component is one which deserves immediate and future study for life extension while non-critical components are particular to a specific utility and will receive less detailed analysis in the future. A critical component is typically defined as one that has potential to cause an extended outage, pose a threat to personnel safety, or has a long lead time and high cost of replacement (10:3-3 to 3-9).

In evaluating the historical condition of the total system, EPRI recommends the review of past maintenance records, inspection records, availability reports, and failure reports. In addition, interviews with operators and a visual walk-through inspection are recommended. EPRI mentions information discernable during short outages of the boiler:

> ...a variety of visible manifestations can signal the location of damage. Examples are deformed or out of position tubes, unusual fireside deposition patterns, coloration differences, bowing of membrane walls, shiny areas on economizer tubing, and a host of other features that are known to maintenance people. (10:3-11 to 3-12)

In order to choose an equipment ranking procedure mentioned as the third step, EPRI recommends the following:

> The most straightforward ranking methods utilize some form of system that combines one or more attributes by placing a value and weighting factor on each attribute and taking an average or total....More detailed ranking methods could use engineering economics methods, such as, cost-benefit ratio, payback period, net present value, and internal rate of return, but full application of these methods has not been found to be appropriate for life extension planning decisions, particularly for an initial planning study [due to the time required for analysis]. (10:2-20 to 2-25)

These guidelines were designed around a total life extension program which requires in-depth study to accurately predict remaining useful life for any particular component. The guidelines discuss three levels of remaining life determination. The first level makes useful life predictions based on comparing design life with actual historical data. The second level analysis, which is more costly, involves taking physical measurements of component dimensions and performing simple stress analysis of piping and mechanical components. The third, and most costly level, involves advanced analysis, such as, finite element analysis, or radiographic inspection (10:4-1 to 4-34). In an EPRI life extension study done for Niagara Mohawk Power Corporation, all useful life predictions for boiler components were made on the basis of the second and third levels of analysis (11:5-1 to 5-124). These analyses were done after the initial weighing and ranking of the available units, with the ones in the worst condition being selected for further study (11:2-2). For the purpose of this work, a rating scheme along the lines of a first level analysis, developing condition indices, is the desired result. Once problem areas are evidenced by low indices, management may then elect to take further action if necessary, to estimate remaining component life. One such estimating service is already available through Hartford Steam Boiler and Insurance Company.

Hartford Steam Boiler (HSB) Inspection and Insurance Company

One of the services offered by HSB is called the BULS Plus Boiler Condition and Useful Life Studies. These studies will furnish the user with an estimate of remaining life for boiler components. The company does not use any checklists when going through the heating plant, nor do they give any kind of rating or condition index for the components. The study uses nondestructive testing methods, such as ultrasonics and magnetic particle testing, and is applied to only the components that the user requests to be studied (12).

Costs for typical useful life studies on a heating plant producing 30,000 pounds per hour of steam is approximately $5000, and approximately $50,000 for a plant capable of producing 250,000 pounds of steam per hour. The studies require approximately one week's time on site for the inspection team and the final report is usually available within 45 days of the site survey (12).

Since AFLC has several heating plants capable of producing more than 350,000 pounds of steam per hour, such studies would be very expensive and should only be done when and where required. The component model rating system developed in this work could pinpoint the heating plants and major subsystems which are in poor condition and allow AFLC to prioritize their plants which may be in need of further study. Any additional studies could either be done in-house or with a contractor specializing in predicting useful component life.

HSB also publishes a quarterly journal, the Locomotive, which periodically reports statistics on types of boiler failures and their causes. This information gives an overview of the main problems experienced in a boiler and this type of information could prove useful in developing condition indicators and weight factors.

HSB classifies failures only by the type or mode of failure and does not detail which components actually failed. In 1988, the majority of failures were the result of cracking, accounting for 68% of all failures. These cracking failures occur most often in cast iron boilers. The second leading failure type was due to burning or overheating due to low water level, accounting for 13% of the failures. This occurs due to improper operation, leakage, feedwater system failures, or control failures. Other failure types include bulging, breaking, tearing, loosening, and deforming, the largest occurrence of which was 4% for breaking. As for the cause of failures, poor maintenance practice or lack of maintenance was by far the largest contributor to failures, accounting for 54% of all boiler losses. "None of the other known causes [operation, repair, application, construction, design, or external] individually accounts for more than 7% of the losses" (13:185).

An earlier 1985 report listed secondary causes of failure by boiler type. The secondary causes listed were: controls, materials, pressure relief devices, burner and controls, feedwater, low water, thermal shock, and other. For all water tube boilers, the largest of the secondary causes of failure were in the categories called, other, at 37.24%, feedwater at 26.45%, and low water at 15.76% (14:140-141).

These reports indicate that for water tube boilers, feedwater and low water problems, along with maintenance inattention, contributed heavily to most boiler failures. The most frequent types of failures expected for water tube boilers are burning due to low water and cracking.

Rating Systems

Many textbooks and papers on rating systems written for and by managers concern the measurement of concepts such as productivity or quality. These measurements are often done with the use of an objectives matrix. This matrix measures multiple criteria and uses weight factors to obtain a numerical index for overall performance of the entity being examined. This review will not give a detailed description of the objectives matrix technique, but will highlight the basic elements in the matrix which could be adopted in any rating system. The reader is encouraged to review the referenced material for more details on the technique if so desired.

The objectives matrix, originally proposed in 1983, is a reporting form that allows a management team to track their performance against established measures. It also permits weighting and aggregating measures into a composite index of performance for the system as a whole. The main steps in developing the objectives matrix are to select the target system to be measured, choose criteria for measurement, choose the measures or attributes for each criterion, establish transformation curves for each attribute (to relate the measurements to a common scale, typically one to ten), and then assign weights to each attribute (since all do not necessarily have the same importance to the overall score) (15:276-285).

If the system to be measured is complex, multiple matrices may be needed (15:277).

> It is ...reasonable to assume that...larger units can also be represented by an appropriate collection of performance factors. However, figures obtained from measuring the performance of the component units...can not be simply added together....A sophisticated weighting system would be required. (16:648).

The basic steps of targeting a system or systems, selecting measurement criteria, transforming the measures into a standard score, and applying weight factors to each score to calculate an overall index can also be applied to measuring a mechanical system. In the case of a heating plant, many component units would be involved, thus requiring a sophisticated weighting method.

To be sure that an adequate measurement instrument is developed, more than one expert should be responsible for choosing the evaluation criteria. According to two different management texts, it is recommended to use either a face-to-face type meeting (Nominal Group Technique), or the Delphi technique, with all the experienced managers and workers responsible for the system being measured (15:239-240; 16:656-657).

In an overall assessment of the objective matrix technique, Sink summarizes:

> The matrix is a convenient way to report/portray performance measurement data....[But] matrix applications are often fairly crude, subjective, messy, and from a mathematical, statistical, decision science, purist point-of-view not defensible....Overall, however, the process of developing the matrix is quite valuable and serves to explicitly define performance. We believe the general approach, when applied in the context of our general measurement methodology, has much promise for your organization, particularly in traditionally hard to measure areas. (15:285)

The objectives matrix technique was designed as a management tool to measure areas such as the productivity of an organization. Productivity attributes can be periodically measured to determine if problems exist in some part of the process. Problems would be indicated by a decrease in score for any component or for the entire system. In a similar manner, heat plant components may be objectively and periodically measured to determine their current conditions. Any decrease in scores would indicate problems with deteriorating components and systems.

III. Delphi Methodology

This chapter describes the research methodology employed to collect the necessary data to construct the component model rating system for central heat plants in AFLC. The Delphi method was employed to gather information from 13 experts in the field of central heating plant design and maintenance. This survey method allows experts to provide initial written input of their opinions on a particular topic with a chance to revise their inputs once given a summary of all opinions in a second round of questioning. The information collected consisted of expert opinions on which components in a central heating plant are considered the most critical, along with a proposed weighing or ranking of the components in order of importance and suggesting methods to evaluate their current conditions.

Scope and General Description

In order to develop component models for central heating plants, a vast amount of knowledge on heating equipment and its operating characteristics had to be gathered. The most obvious sources of the required information are existing technical literature on central heat plant design and maintenance, and the expert knowledge of experienced designers and maintenance supervisors. A methodical system was required for gathering and evaluating the expert opinions. The Delphi method was employed to obtain the expert knowledge which was incorporated into the development of the central heating plant component models.

The Delphi Method

Background. The Delphi method uses a panel of experts to arrive at a group consensus of opinions on a particular issue. This method is an iterative one which maintains anonymity of the members and provides feedback to each member as to the entire group's opinions. This process is done with questionnaires which are developed and administered by an exercise manager. The iteration of questionnaires and feedback stops once a consensus is reached or when further iterations do not produce any further changes in the panelists answers (17:1). This method is used to achieve expert concurrence for a given application area where no concurrence previously existed (18:4).

Advantages of the Delphi method include its versatility as a data gathering tool and its minimal requirements for time and effort on the part of the participants (18:31). This method is also a relatively efficient way to gather opinions from a group of knowledgeable people. When considering group dynamics in decision making, the Delphi method has several strengths. Insuring the anonymity of the participants is one way of reducing the effect of dominant individuals on arriving at a consensus. The controlled feedback from the exercise manager acts as a way to reduce noise from the responses (the one or two "odd" experts may decide their opinions were in error when reviewing the responses of the entire group). Another strength of this method is the use of statistical group response. This is a way to ensure that the opinion of every member of the group is represented in the final response. The statistic may be the group median, mean, or some other representative number, and will take into account the spread of individual opinions and reduce the pressure on the group for conformity.

The Delphi technique has also been used to elicit and process experts' value judgements. A popular form of value judgements, with which the Delphi can be employed, is the formulation and weighing of major organizational objectives on some scale, typically from 0 to 100 points. The Delphi procedures appear feasible to collect lists of objectives, allocate weights, and statistically aggregate the weights in a manner acceptable to the expert group (19:16,73).

There are also disadvantages of using the Delphi method in research. The main disadvantage of this method lies with the question of replication of results. The results of a Delphi survey should be conducted with a separate panel of experts at a later date to see if the results are the same. This reliability test would obviously require more time. Another weakness of this method is the fact that anonymity of the panelists makes no one accountable for the results of the study. The panelists need not provide any scientific evidence to support their opinions. Another criticism of the method is the inability of the exercise manager to determine the amount of effort each panelist is applying in answering the questionnaire. The differences in effort may be a cause of statistical variations in the answers. The last important weakness of the Delphi method is the fact that the people participating in the panel are not a systematic or random sample of any specifiable population. Some experts will drop out if they disagree strongly with the design and content of the questionnaire; the ones who "stick with it" will have opinions favorable along the lines of the questionnaire and the results won't be representative of the population of experts (18:20-52).

In summary, the Delphi method is best used to solve a problem which can not be solved by analytical techniques but can benefit from subjective judgements on a collective basis (20:4). The research objective of this study, developing component model rating systems for central heating plants, lends itself to a non-analytical solution method due to the large amount of technical information required and a need for experienced-based value judgements to formulate meaningful condition measures. Thus, even with all the criticism of the Delphi method, its ability to gather value judgements on objectives and weights is an excellent tool in the development of a concurrence where none previously existed.

Selection of Experts. The first step in the Delphi process is the selection of the expert participants. The term expert is defined as a person with special skill or knowledge derived from training or experience. For this study, an expert was defined as a senior maintenance supervisor or senior mechanical engineer with at least ten years experience in maintaining or designing central heating plants and their distribution systems. From this operational definition of an expert, 15 names were recommended by the HQ AFLC maintenance engineering branch for participation in the survey.

For a Delphi study, it is recommended that from 10 to 50 experts be included in the survey (21:229). For this work a smaller number of experts was used due to availability.

The selection process was concluded by confirming the participants' expertise with central heating plants by conducting telephone interviews with each one. In addition, the researcher chose to include only those qualifying experts who were willing to volunteer their time to complete the Delphi survey. Two of the proposed experts were eliminated from participation during this process. One of the proposed experts was to retire from service during the study and, therefore, did not volunteer. Another proposed expert was eliminated due to a lack of experience in central heating plant systems. Of the finally accepted 13 participants, six were mechanical engineers, three were heating superintendents, two were mechanical superintendents, and two were heat shop personnel. These personnel are assigned at five different AFLC bases, headquarters AFLC, as well as headquarters Military Airlift Command (MAC), headquarters Tactical Air Command (TAC), and headquarters Air Force Engineering and Services Center (AFESC). The selection of experts outside of AFLC was necessary to include more qualified mechanical engineers into the process.

Round One Questionnaire. The next step included in the Delphi methodology is the development of the first-round survey. The survey is included in Appendix A. It consists of a set of instructions, a sample response, and a questionnaire consisting of 19 pages designed to elicit open-ended responses from each expert on the systems, components, and weights perceived to be the most important to the proper and continued operation of a central heat plant. The open-ended format, requiring a free-form written response, was developed to allow the experts to include as many systems and components as they thought important without constraining or prejudicing their inputs by including lists of candidate systems and components. This open-end input is beneficial to the research in that it allows the widest possible range of responses on proposed systems, components, and criteria to judge component condition.

The sample response included in the survey was used only to demonstrate the expected format of the written responses. It also demonstrated the need to quantify component condition when listing component criteria.

During telephone interviews with the prospective experts, several types of heating plant variations were identified. The variations concerned the type of heating system, steam and high temperature hot water (HTHW), and the type of fuel combusted: coal, oil, gas, and dual fired oil/gas. These equipment variations were listed at the beginning of the questionnaire and each expert was asked to complete the survey based upon the type of system and fuel with which he had the most experience. This was done to reduce the amount of time needed to complete the survey and help ensure the widest possible participation. Had each expert been required to complete one such survey for each heat plant type and fuel type, it was believed that the experts would either drop participation or would not bother to enumerate all the components they felt were critical. Once the questionnaire was developed, it was pretested by a panel of local experts, comprised of four mechanical engineering faculty members of AFIT's School of Civil Engineering, and one engineering management faculty member of AFIT's School of Systems and Logistics for clarity, completeness, and adequacy.

The questionnaires were mailed to all 13 participants with ten experts responding within two months. The three experts who did not reply said that they did not have time to complete the survey due to job requirements. However, they indicated that they would participate in the second round if they had time.

The first round responses were analyzed by first grouping the experts' responses according to the major systems enumerated on the first page of each questionnaire. There were seven major systems identified for steam plants: distribution, water treatment, control, steam generation, combustion/fuel, stacks and breaching/emission control, and electrical. Eight major systems were identified for HTHW plants: distribution, controls, combustion/fuel, HTHW generation, water treatment, emission control, drainage, and pressurization. For each expert's response, the weights given to each major system (on a scale of 1 to 10) were normalized on a relative response scale (from 0 to 1) by taking each major system weight given and dividing it by the sum of all the assigned weights for all major systems (see Appendix C, Tables 1 and 10 for the summary of major system relative responses). The normalization of the weights was necessary since not all experts used the same numerical scale in assigning his weights. The weights given for each component in each major system were also normalized by taking each component weight and dividing it by the sum of all the component weights in that major system (see Appendix C, Tables 2-9 and 11-14 for the results for each system). In the case of the HTHW plant, four of the major systems (water treatment, emission control, drainage, and pressurization) identified by the experts were not accompanied by any component listings, therefore, a normalized weight summary could not be generated for their components.

In some cases, an expert would include a particular component under a major system category different from the majority of experts. For example, one expert listed the burner as a component under the steam generation system, while three other experts listed the burner under the combustion/fuel major system. To remedy this type of situation caused by the open-ended responses, the originally calculated relative weight for the burner component of the "odd" expert was relocated to the combustion/fuel major system. This type of procedure was necessary in order to integrate varied responses into a meaningful summarized structure representative of all the experts' responses.

The written inputs on the condition criteria were summarized for each component and are given in Appendix B. In order for criteria to be included in the summary, at least two experts had to identify the particular component and provide written criteria that could be used to evaluate its condition. Two experts responding to the survey did not give any condition criteria. Criteria for "fair" condition was omitted from the summary to reduce the size of the round two package. For this investigation, the two endpoints, "excellent" and "poor", are sufficient to establish the limits of the criteria.

Round Two Questionnaire. The survey is included as Appendix B of this work. It consisted of a set of instructions, a sample response, a questionnaire asking for component weights, and a summary of responses on condition criteria.

Due to the length of time required for the experts to complete the first round, the second round Delphi package was formatted for quicker participant response. This questionnaire was divided into two sections. Section one required inputs on weights for the major systems and components, and section two required only voluntary comments on the summarized criteria.

In section one of the second round package, a summary of round one responses was included. The summary showed the number of experts who mentioned a particular system or component, and the average normalized weight factor for that system or component (on a scale of 1 to 10). The average normalized weight factor is defined as the average of the relative weights for each system or component normalized on a scale of 1 to 10. For example, the average first round relative response for the steam generation system was 0.24 (from Appendix C, Table 1). Since this was the greatest relative response for the major systems, it was assigned an average normalized weight factor of 10. The average normalized weight factor for the distribution system was assigned a value of 6 by dividing the average relative response for the distribution system (0.15) by 0.24 (the highest response), and multiplying the result by a factor of 10. The result was rounded off to the nearest whole number. Average normalized weight factors were reported to the survey participants in order to relate the average responses in a manner similar to which they were expected to respond. It was expected that confusion would arise if the average relative responses were reported on a scale of 0 to 1 as previously computed.

For most major systems listed, the experts were asked to weigh only 75% of the components. This was done to force the experts into making decisions on which components were truly critical. Consensus on a system or component was defined as a system or component which was weighed by at least 70% of the experts responding to the second round questionnaire. The systems and components for which consensus was reached are included in the final component models.

In section two of the second round package, the experts were asked to comment on the criteria summarized from round one or add new criteria. Responses to this section were not made mandatory in order to decrease the amount of work required to complete the second round questionnaire and to ensure timely response.

Once the questionnaire was developed, it was pretested by a panel of local experts, comprised of four mechanical engineering faculty members of AFIT's School of Civil Engineering for clarity, completeness, and adequacy. The second round packages were sent to all 13 original experts with nine packages returned in a one month period.

The responses of the second round questionnaire were placed into a spreadsheet program to determine which systems and components were selected by consensus as well as to calculate the relative weights for each system and its components. For a system or component to be included in the final component model, it had to be weighed by at least seven experts (at least 70% of the second round participants). Systems and components that did not acquire the 70% consensus rate were discarded. The relative weight responses for the remaining major systems and components were then calculated in the same manner described above for the first round. The average values of the relative responses for each major system and component were used as the final weight factors for the steam and high temperature hot water component models (see Appendix C, Tables 29-39).

In section two of the second round survey, only two experts made comments on the criteria summary. These additional comments added little information and were not included in the development of the final component models.

Summary

This chapter described the methodology used to acquire expert opinions on which heating plant components are critical for proper plant operation and how these components should be evaluated to determine their conditions. A final list of components to be included in the rating system models was decided on the basis of expert consensus. The next chapter will detail the development of the final component models for steam and high temperature hot water plants. The discussion will describe the developed models and the sources of information used to derive each component condition description.

IV. Derivation of Component Models

The purpose of this chapter is to detail the development of the component model rating methods for central steam and high temperature hot water plants. Each component model is broken into several major systems (distribution system, generating system, etc.) with a number of critical components in each system. The condition of each component in the system is described in terms of a numerical value, the condition index. These component condition indices are, for the most part, calculated according to simple linear equations with input variables obtained from plant records or visual inspection. In some cases, a numerical component condition index could only be generated by matching observed characteristics of a component with a criteria list containing corresponding numerical scores. The component condition index scores are then assembled into a score representing the condition of each major system which, in turn, is used in the calculation of the condition index of the overall plant.

The component model rating methods were developed primarily from the results of the Delphi survey. The survey results were used to select which components and systems were to be included as well as to derive the condition indices. For some components, however, insufficient information was available from the Delphi survey to derive numerical representations of condition index. In these cases, telephone interviews with heat plant personnel, review of literature, and the researcher's judgement were exercised to produce a numerical representation of condition.

General Description of the Models

A complete model developed for steam plant systems is presented in Appendix D and the high temperature hot water plant model is in Appendix E. The component models are developed from the results of the Delphi survey discussed in Chapter 3 of this work. All components included had been identified by the panel of experts as the most important components in a steam or high temperature hot water heating system. The weight factors used in the models represent the mean response of the experts. The condition indices were derived from a combination of expert responses, readings from technical literature on central heating plant systems, and the researcher's personal experience with similar systems.

The steam plant component model is broken down into five major systems: distribution, water treatment, control, steam generation, and combustion/fuel. The combustion/fuel system contains descriptions of both coal-fired and dual-fired gas/oil systems. Under each major system is a list of components and condition indices. A condition index is a numerical value between 0 and 100 which describes the current condition of each component. These component indices, when taken as a weighted total, represent the condition of the major system.

The high temperature hot water component model is similar to the steam model but contains only four major systems: distribution, HTHW generation, control, and combustion/fuel. Of these major systems, control and combustion/fuel have components and condition indices identical to that of the steam plant model. The distribution system and the HTHW generation system each contain five components and are somewhat different from the steam model.

Condition Indices. Each component is represented by a condition index. The condition index descriptions include the variables which are to be measured and how the measurements are to be made. The descriptions are listed under each component. Following these descriptions is an equation used to calculate a value of the condition index for the variables measured. For example, consider the distribution system in Appendix D. The steam trap condition index consists of only one equation with the variable being the percentage of failed steam traps:

$$C5 = 133.3 - 6.7\,(\%\text{ of failed steam traps}) \qquad (1)$$

The numerical value of C5 will be the value assigned to the steam trap condition index. But, in the case of the supply piping condition index, two equations are listed. In this case, the supply piping condition index is the total of the numerical values defined by C3 and C4:

$$C3 = 2.5\,(\%\text{ of required steam pressure}) - 200 \qquad (2)$$

where

% of required steam pressure= an average value of the output steam pressure as a percent of the required steam pressure.

$$C4 = 50 - 2.5\,(\text{number of leaks}) \qquad (3)$$

where

number of leaks= the number of steam leaks detected in the last year

For each condition index the limit on the numerical value will range from 0 to 100. A value of 100 would describe a component as being in brand new condition and a value of 0 would describe a failed component. Although the condition index equations could produce a number less than 0 or greater than 100, it should be considered as a bounded function, never greater than 100 or less than 0. For example, if the numerical value of C5 was calculated as 115, it will be assigned the maximum value of 100 and, if the numerical value calculated is -10, it will be assigned the minimum value of 0.

For condition indices containing two equations, the limit on each numerical value will be similarly placed between 0 and 50, thus allowing their sums to be no greater than 100 or no less than 0. This procedure is shown in the worked example in Appendix F.

Total Major System Condition Indices. To calculate the condition index for each major system within the steam plant or HTHW plant, a weighted sum of the individual component condition indices is taken. These index values will also range from 0 to 100. The weighting factors used in these equations are taken from the average values of the Delphi survey responses given in Appendix C. The equations for the major system indices are given in Appendix D and Appendix E. As an example, the total distribution system condition index, CDS, is defined as follows:

$$CDS = 0.2\ (C1 + C2) + 0.23\ (C3 + C4) + 0.2\ (C5) + 0.2\ (C6) + 0.17\ (C7 + C8) \qquad (4)$$

where

C1 + C2= condensate piping condition index
C3 + C4= supply piping condition index
C5= steam trap condition index
C6= condensate pump condition index
C7 + C8= pressure reducing valve condition index

The multiplication factors, or weights, in Eq (4) are taken from Appendix C, Table 30.

Total Plant Condition Index. The overall condition index for the total plant is calculated via a weighted sum of the major system condition indices. This total plant condition index also ranges from 0 to 100. The equation for the total plant condition index for the steam plant model is given as:

$$CSP = 0.17\ CDS + 0.21\ CWT + 0.16\ CCS + 0.24\ CSG + 0.22\ CC/F \qquad (5)$$

where

CSP= total steam plant condition index
CDS= total distribution system condition index
CWT= total water treatment system condition index
CCS= total control system condition index
CSG= total steam generation system condition index
CC/F= total combustion/fuel system condition index

The multiplication factors, or weights, are taken from Appendix C, Table 29.

General Procedure to Derive Condition Indices

The condition indices are derived mainly from a combination of expert responses to the Delphi survey and readings from technical literature on central heating plant systems.

In a letter sent from HQ AFLC/DEMM to HQ USAF/LEEP discussing AFLC's desires to develop facility infrastructure component models, it was mentioned that the overall system numerical rating would be broken down into three condition categories based on score: good, fair, and poor. The range of overall condition indices corresponding to these categories are: 80 to 100 (good), 60 to 79 (fair), and 59 or lower (poor) (4). To match these categories, the Delphi survey collected information on components and evaluation criteria according to the same three categories. The numerical limits given by some of the experts in their proposed evaluation criteria were used as end and midpoints to develop simple linear equations relating the expert's limits to a 0 to 100 scale. For example, the condensate piping condition index was derived by taking experts' inputs on the amount of make-up water used and the iron content of the condensate return water (see Appendix B, Delphi Round Two Questionnaire, Section Two, the first entry). The iron content concept was substantiated by an article in Pulp and Paper stating "Damage to the tubes...may be reduced by keeping the amounts of iron and copper that are returned to the boiler with the condensate at very low levels" (22:151) The use of make-up water percentage as an indicator was substantiated by the multiple responses of experts number 2, 5, and 7. Since two indices representing make-up water and iron content would be added together to produce one condition index, the rating limit for each was placed at 50 points for a "good" score. Expert number 5 suggested that the condensate piping condition could be related to the amount of iron in the condensate return water. For this index a value of 50 is assigned if only .1 PPM of iron was detected and a condition index value of 0 for 1 PPM of iron. Thus, the simple linear equation representing condensate piping condition was derived:

$$C2 = 55.6\ (1 - \text{PPM iron}) \qquad (6)$$

where

PPM iron= 60 day average of iron content in parts per million

Also for condensate piping, expert number 5's input on make-up water percentage was considered as representative of the other experts' inputs. Here a score of 50 is assigned if make-up percentage was 20% and a score of 0 if make-up percentage was 50%. Using these parameters, the second linear equation representing C1 for "mud" or "puff" blowdown was derived:

$$C1 = 83.3 - 1.7\ (\text{make-up\%} - \text{blowdown\%}) \qquad (7)$$

where

make-up%= 60 days average of make-up water percentage
blowdown%= 60 days average of blowdown water percentage

Addition of the numerical values of C1 and C2 result in the condensate piping condition index.

Derivation of Steam Plant Condition Indices

The derivation method described above was applied to all component condition indices. However, in some cases of expert responses, little or no information was given to define limits for the proposed measured variables. In these cases, limits were assigned and condition index equations were derived based upon readings of technical literature, telephone interviews with heat plant personnel, as well as the researcher's personal experience with mechanical systems in general and their maintenance requirements.

Steam Distribution System. The derivation of the condensate piping condition index was discussed above with respect to Eqs (6) and (7). However, a substitute for Eq (7) is necessary for systems which use "continuous" blowdown in lieu of an intermittent "puff" blowdown. This alternate equation representing C1 is given as:

$$C1 = 62.5 - 1.25\,(\text{make-up\%} - \text{blowdown\%}) \qquad (8)$$

To establish the limits for Eq (8), Expert 2's response was used to set the value of C1 at 50 if the difference between make-up and blowdown percentages is ten or less percentage points. Expert 5's response was considered representative of all experts' inputs on the maximum allowable make-up percentage thus, C1 in Eq (8) is assigned a value of 0 if the difference between make-up and blowdown percentages is 50 percentage points or more.

The supply piping condition index was comprised of the two following equations:

$$C3 = 2.5\ (\%\text{ of required steam pressure}) - 200 \qquad (2)$$

and

$$C4 = 50 - 2.5\ (\text{number of leaks}) \qquad (3)$$

The limits proposed by expert 7 were used to set C3 equal to 50 if the output steam pressure meets or exceeds the required pressure and 0 if the output pressure is 80% of the required pressure. For Eq (3), experts 2 and 8 made reference to the numbers of visible steam leaks but did not mention any limits. A review of technical literature revealed no reference to the number of expected leaks in a steam distribution system. To set limits for this index, it was reasoned from experience with large piping distribution networks that 20 leaks per year would be poor and no leaks would be good. Hence, C4 was set to equal 50 for no leaks and 0 for 20 leaks.

A combination of expert response and values mentioned in U.S. Air Force Central Heating Plant Tuneup Workshop, Volume X: Steam and Condensate Systems prepared by USACERL was used to establish the limits for the steam trap condition index, C5, shown below:

$$C5 = 133.3 - 6.7\ (\%\text{ of failed steam traps}) \qquad (1)$$

Expert 5 stated that a poor condition would be represented by having 20% of the system's traps failed. The CERL reference states that a steam trap system would be up to standards if 5% or less of the steam traps have failed (23:57). Therefore, the value of C5 was set to equal 0 if 20% or more of the system traps have failed and 50 if 5% or less of the traps have failed.

The equation for the condensate pump condition index is given as:

$$C6 = 200\,[1 - (\#\text{ of pumps NFO} / \text{total }\#\text{ pumps})] - 100 \qquad (9)$$

where
C6= condensate pump condition index
NFO= not fully operational

A pump is defined as not fully operational if it shows evidence of cavitation, and/or is unable to supply at least 90% of flow and pressure, and/or excessively leaks from seals or valves at a rate of more than 30 drops per minute. This definition was developed from responses by experts 2, 4, 5, and 6 concerning poor conditions for feedwater, water treatment, and condensate pumps. This definition is used throughout this work in reference to all pumps since all the system pumps function in the same manner. Since no other expert input could be practically used to quantify the condensate pumping condition index, and a review of technical literature revealed no references, it was assumed that this index value could be related to the percentage of condensate pumps which were fully operational (the definition of fully operational being converse to the above definition). Having 100% of the condensate pumps in the distribution system "fully operational", the best possible situation, would correspond to a condition index score of 100 for C6. Having only 50% "fully operational" would severely limit emergency back-up capability and decrease heating plant efficiency due to decreased condensate return and increased usage of make-up water. Therefore, a score of 0 was assigned to C6 when only 50% of the condensate pumps are fully operational. Eq (9) is also used to indicate the condition of water treatment and fuel oil pumps.

The pressure reducing valve condition index is represented by summing the values of C7 and C8 shown in the following equations:

$$C7 = 50 - 10\ (\text{PSI of pulsation}) \tag{10}$$

$$C8 = 200\ (\text{actual max pressure drop / design max}) - 150 \tag{11}$$

In Eqs (10) and (11) visual inspections are required to gather the measured variables. The measured variable in Eq (10) is the maximum observed pressure pulsation at the low pressure end of the reducer measured in pounds per square inch (PSI). Expert 6 proposed that no observed pulsation would represent "good" condition, hence a score of 50, and that a 5 PSI pulsation would represent "poor" condition with an associated index score of 0. Eq (11) requires an operability test to acquire the measured variables proposed by expert 1. The magnitude of the obtainable pressure drop of the reducing valve should be compared to the specified product design maximum range. Expert 1 stated that an operability range (actual max pressure drop / design max) of 75% or less would constitute "poor" condition (a C8 score of 0) and a range of 100% would represent "good" condition (a C8 score of 50).

The total steam distribution system condition index, CDS, is calculated by computing a weighted sum of the values C1 through C8. This equation was represented above as Eq (4).

<u>Water Treatment System</u>. The make-up water quality index, C9, was derived from the input of expert 7 and is shown below:

$$C9 = 100 - 66.7\ (\text{PPM hardness}) \tag{12}$$

Expert 7 proposed measuring the hardness of the treated make-up water in parts per million (PPM). According to the limits he listed, the value of C9 was set at 100 if hardness is measured at 0 PPM and 0 if hardness is measured at 1.5 PPM.

The softener condition index is calculated by taking the sum of three indicators, C10, C11, and C12. Three indicators were used in this case due to a wide range of expert response. The index C10 came directly from expert 2's response. A criteria list was developed for scoring this index, in lieu of an equation, assigning index values based on the degree of visible external corrosion (see Appendix D). The index C11 scores the softener on its dependability concerning automatic regeneration of the ion exchange media:

$$C11 = 33 - 11\ (\#\text{ of failures per year}) \qquad (13)$$

Expert 2 did not specify in quantifiable terms how many times the automatic regeneration cycle had to fail before being considered in "poor" condition. Technical literature did not mention any possible limits either. The limits on the number of failures in a one-year period for the regeneration cycle was set at no failures being "good" (a C11 score of 33) and 3 failures being "poor" (a C11 score of 0). These limits were developed from experience with similar softener systems used for small boiler systems and chilled water systems.

The final index for the softener, C12, was derived from the input of expert 4:

$$C12 = 2.2\ (\%\text{ of recommended level}) - 187 \qquad (14)$$

Expert 4 stated that if the internal filter media level was kept at 100% of the manufacturer's recommended level, it should be considered in "good" condition, a C12 score of 33, and a level of 85% or less should be considered "poor" condition, a score of 0.

A combination of expert response and an article in _The Locomotive_ were used to set limits for the deaerator condition index which is a sum of the indicators, C13 and C14 shown below:

$$C13 = 75 - 12.5\ (\text{sat temp of deaerator} - \text{feedwater temp}) \qquad (15)$$

$$C14 = 50 - 2\ (\text{age in years}) \qquad (16)$$

In the article, graphical data displayed that more than 50% of deaerators between 16 and 25 years old showed evidence of corrosion fatigue cracking while no defects were found in deaerators between 0 and 5 years old (24:130). Along the same lines, expert 5 stated that "poor" condition would be reflected in a deaerator over 20 years old. The index score for C14 was set at 50 for a brand new deaerator and 0 for a 25 year old deaerator, according to the article.

Eq (15) was derived from the input of expert 2 who stated that "good" condition (a C13 score of 50) would be reflected by feedwater at a temperature within 2 °F of the saturation temperature associated with the pressure in the deaerator shell. "Poor" condition (a C13 score of 0) is shown by having the feedwater temperature more than 5 °F below the saturation temperature of the deaerator shell.

The limits for the chemical feed system condition index, C15, were obtained from information given by the AFLC industrial water treatment engineer. This special source had to be consulted in this case due to an absence of expert opinion, technical references, and experience. He reported that since the use of phosphates and sulfites differ for each treatment program, the best way to check the functioning of the chemical feed system is to measure the pH of the condensate return water. If the pH is between 7.5 and 8.5, then the amines are being properly fed to the boiler (25). A quadratic relation for C15 is used, giving a score of 100 for a pH of 8 and a score of 0 for a pH outside the suggested range:

$$C15 = 100 - 400\,(pH - 8)^2 \qquad (17)$$

Since a pH lower than 7.5 indicates acetic conditions which will damage piping and a pH of 8.5 or higher is considered excessive and indicates inefficient use of chemicals, a quadratic equation, Eq (17), was derived to indicate the ability of the chemical feed system to maintain proper chemical levels. Figure 1 shows the graph of Eq (17).

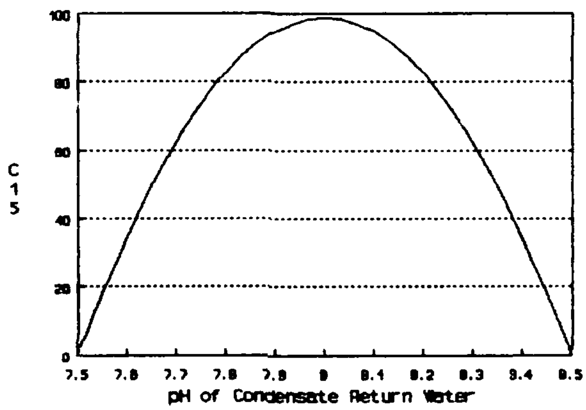

Figure 1. Graph of Equation (17)

The feedwater pumps condition index equation is identical to the condensate pump condition index given as Eq (9) since all system pumps are similar and their conditions can be represented by the same equation.

The water test capability condition index values were derived from input by expert 3, the only expert who provided a written response. The criteria given by expert 3 did not facilitate the derivation of an equation to represent index scores for C17 and C18, so criteria lists were developed to relate existing conditions to an index score. The index C17 relates the training level of water test personnel to a condition score and C18 relates adequacy of lab equipment to a condition score. The water test capability condition index is calculated by summing C17 and C18. The lists may be seen in Appendix D.

The equation for the feedwater condition index, C19, was derived from expert 7's input and is shown below:

$$C19 = 200 - 20000\ (PPM\ O_2) \qquad (18)$$

where

PPM O_2= average oxygen content of boiler feedwater in parts per million

According to expert 2, the lower limit of oxygen content was set at .005 parts per million to correspond to an index score of 100 and .01 parts per million for an index score of 0.

The total water treatment system condition index, CWT, was derived as a weighted sum of the values C9 through C19:

$$\begin{aligned} CWT = {} & 0.17\ (C9) + 0.15\ (C10 + C11 + C12) + 0.13\ (C13 + C14) + \\ & 0.15\ (C15) + 0.11\ (C16) + 0.14\ (C17 + C18) + \\ & 0.15\ (C19) \end{aligned} \qquad (19)$$

where

C9= make-up water quality condition index
C10 + C11 + C12= softener condition index
C13 + C14= deaerator condition index
C15= chemical feed system condition index
C16= feedwater pumps condition index
C17 + C18= water test capability condition index
C19= feedwater condition index

The multiplication factors, or weights, are taken from Appendix C, Table 31.

<u>Control System</u>. The tabular data given by expert number 7 for the air and fuel controls condition indices, C20

and C21, were confirmed by the publication, U.S. Air Force Central Heating Plant Tuneup Workshop, Volume VIII: Combustion Control- Oil/Gas. In this reference, the same tabular information referring to steam pressure tolerance and oxygen tolerance was presented (26:27). Steam pressure tolerance is defined as the percent difference between the actual output steam pressure and the control setpoint steam pressure. The oxygen tolerance was defined as the difference between the maximum and minimum flue gas oxygen levels (each measured as a percentage of flue gas constituents) for any particular fuel firing rate above 33% of maximum boiler capacity. Both defined tolerances are to be kept as close to 0% as possible for proper system operation. A wide tolerance would indicate problems with air and fuel controls. The air controls condition index, C20, is given by the following equation when coal is the fuel:

$$C20 = 100 - 66.7\,(\text{avg}\ \delta\ O_2\%) \tag{20}$$

where

avg δ O_2= the average difference between the maximum and minimum recorded oxygen level (measured as a percentage of flue gas constituents) in the flue gas for the maximum firing rate each day for 30 days of plant operating loads above 33% of plant capacity.

From expert 7's input, an oxygen tolerance of 0% was considered "good" (C20 set equal to 100) and a tolerance of 1.5% was considered "poor" (C20 set equal to 0). In a similar manner, the alternate form of the index C20 used for gas/oil combustion is:

$$C20 = 100 - 100\ (\text{avg}\ \delta\ O_2\%) \qquad (21)$$

The limits on oxygen tolerance in this case are recommended by expert 7 as 0% being "good" and 1% being "poor" with respective index scores of 100 and 0.

The fuel control condition index, C21, is represented by the following equation:

$$C21 = 100 - 20\ (\text{avg steam pressure tolerance}\ \%) \qquad (22)$$

where

avg steam pressure tolerance %= the 30-day average of the percent deviation of actual steam pressure output compared to the setpoint pressure.

As in the case of Eqs (20) and (21), an average of the tolerance values should be taken for a 30-day period to allow a large enough data sample to better estimate the actual mean tolerance value. The limits for Eq (22) came from expert 7 who suggested that 0% tolerance was "good" and 5% was "poor" with respective index values of 100 and 0.

The limits of the condition indices for pressure and temperature indicators, flue gas analyzers, sensors, actuators, and limit controls (indices C22-C26) were all established from the lone opinions of expert number 5 (which were not summarized in Appendix B since no other experts responded during the first Delphi round). Expert number 5 suggested that sensors, actuators, and limit controls all be calibrated to be considered in "good" condition. If only 80% of these components were calibrated, then they should be considered in "poor" condition. Expert 5 did not specifically mention indicators or gas analyzers, however, due to a lack of expert input, the same limits were generalized to these components. From expert 5's input, the following condition index equation for pressure and temperature indicators was derived:

$$C22 = 5\ (\%\ \text{of indicators calibrated}) - 400 \qquad (23)$$

This same equation was used to represent the conditions of indices C23 through C26 in Appendix D.

The total control system condition index, CCS, is shown below:

$$CCS = 0.16\ (C20) + 0.17\ (C21) + 0.14\ (C22) + 0.11\ (C23) + 0.17\ (C24) + 0.12\ (C25) + 0.13\ (C26) \qquad (24)$$

where

C20= air controls condition index
C21= fuel controls condition index
C22= pressure and temperature indicators condition index
C23= gas analyzers condition index
C24= actuators condition index
C25= limit controls condition index
C26= sensors condition index

The multiplication factors, or weights, are taken from Appendix C, Table 33.

Steam Generation System. The equation for the boiler efficiency condition index, C27, was developed as:

$$C27 = 20\ (\%\ \text{efficiency}) - 1500 \qquad (25)$$

where

% efficiency= the average value of overall boiler efficiency for the last 30 days of operation at operating capacity of 50% or more of the boiler capacity

The overall efficiency is a ratio of energy output to energy input and takes into account losses in the combustion process as well as heat losses from equipment. Expert 6 proposed the limits of 80% overall efficiency being "good" and 75% being "poor". The respective index scores assigned to these limits were 100 and 0. Efficiencies are recommended to be measured only at boiler loads of 50% or greater because efficiency is typically load dependent as shown in Figure 2 below.

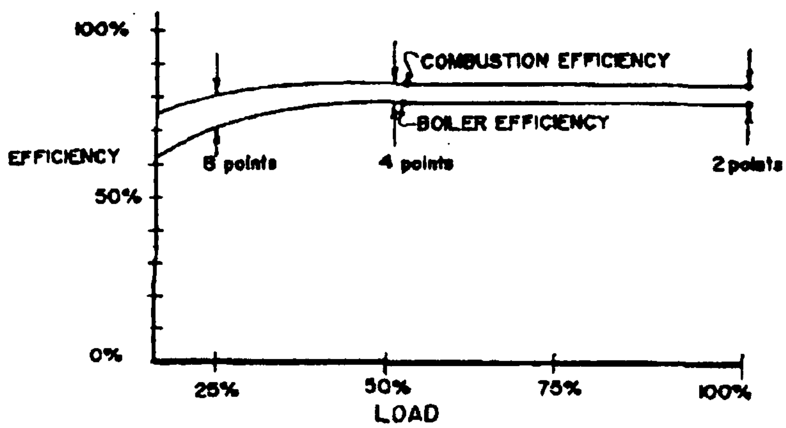

Figure 2. How Combustion and Boiler Efficiencies Change with Load (27:37)

The condition index, C28, reflects the score for casings. A casing is a sheet or plate attached to pressure parts of a boiler for the purpose of supporting insulation or forming a gas-tight closure. Experts 2, 4, 5, and 6 related that casings should not show any damage from cracks or corrosion nor should air be allowed to leak through casings. The limits proposed by experts 4 and 6 related the percentage of casing area which showed damage. More accuracy should result by reporting the actual number of damaged casing sections (penetrated by cracks or corrosion) in a boiler than to estimate the percentage of surface area damaged as proposed by the experts. Without any technical references on the typical number of casing sections in a boiler, but needing to set limits for the condition index equation, eight damaged sections was considered to represent "poor" condition with a C28 value of 0. No damaged sections would represent "good" condition with a score of 100. The casing condition index equation follows:

$$C28 = 100 - 12.5\ (\#\ \text{of penetrated casing sections}) \tag{26}$$

The equation for the boiler tube condition index, C29, is shown below in Eq (27):

$$C29 = 100 - 5\ (\%\ \text{of area sooted}) \tag{27}$$

Expert opinions on tube conditions mentioned visual inspections for soot, corrosion, leaks, and other tube damage with proposed limits relating 15-20% of tubes showing damage to "poor" condition. The publication U.S. Air Force Central Heating Plant Tuneup Workshop, Volume XIII: Operations and Maintenance, stated that if sooting on tubes is excessive, inefficient heat transfer could cause high stack gas temperature and equipment damage. If sooting is excessive, all tubes must be cleaned with mild acid solution requiring a costly procedure of removing boiler plating and insulation (26:62). Since sooting is seen as an indicator of potential damage and increased maintenance costs, Eq (27) was derived to relate the percentage of tubes sooted to tube condition. The limit of 20% of sooted tubes, was used to indicate "poor" condition (a C29 score of 0) and no tubes sooted indicate "good" condition (a C29 score of 100).

The refractory condition index equation, shown below, was derived from a combination of expert responses:

$$C30 = 100 - 3.3\ (\%\ \text{of refractory damaged}) \qquad (28)$$

Experts 1, 4, and 6 related refractory condition to the percentage of refractory which is cracked, chipped or missing. For "poor" condition, the experts suggested limits that ranged from 10% to 30%. For "good" condition, the experts' limits ranged from no damage to 10% refractory damage. The limits for Eq (28) were set at no damage being "good" and 30% damage being "poor" to account for the wide range of opinion.

The steam drum condition index, C31, was derived form input of expert 1. The equation is a follows:

$$C31 = 5\ (\%\ \text{of original design pressure}) - 400 \qquad (29)$$

The measured variable, percentage of original design pressure, is the allowable operating pressure of the drum divided by its original design operating pressure. In the draft report, Energy Supply Alternatives for Picatinny Arsenal, the allowable operating pressure of the drum is related to the thickness for the drum. As the drum walls decrease in thickness, the pressure that the vessel can safely contain also decreases (7:3). Therefore, expert 1's suggestion to relate allowable operating pressure to drum condition with limits of 80% pressure being "poor" and 100% being good were used to derive Eq (29). Allowable operating pressures are assigned periodically by certified boiler inspectors.

The safety devices condition index equation came directly from expert 5's input stating that "good" condition would be represented by no noted deficiencies from the latest boiler inspection and "poor" condition would be indicated by two or more deficiencies. Safety devices include pressure relief valves and low water cut-offs. The equation for safety devices is shown below:

$$C32 = 100 - 50\,(\#\text{ of defective devices}) \tag{30}$$

The total steam generation condition index, CSG, is shown below:

$$CSG = 0.16\,(C27) + 0.12\,(C28) + 0.2\,(C29) + 0.16\,(C30) + 0.17\,(C31) + 0.2\,(C32) \tag{31}$$

where

C27= boiler efficiency condition index
C28= casing condition index
C29= boiler tube condition index
C30= refractory condition index
C31= steam drum condition index
C32= safety device condition index

The multiplication factors, or weights, are taken from Appendix C, Table 32.

Coal Combustion/Fuel System. Fans and dampers were identified by the experts as a critical component for both coal and gas and oil combustion systems. Therefore, the following condition index for fans and dampers is identical for both combustion types.

Expert 5 suggested measuring combustion efficiency and flue gas oxygen to establish the current condition, however, these variables were used in one form or another to indicate conditions for boiler efficiency and air controls. Inputs from experts 2 and 3 were used to describe the physical condition of the fans and dampers in terms of a criteria list relating observed conditions to index scores. The criteria for fans was based on observed vibrations and dampers was based on proper linkage adjustment. These criteria are located in Appendix D and are labeled C33 and C34. Both values are summed to produce the fans and dampers condition index.

The stoker condition index was derived from the comments given by expert 1 relating the stoker condition to the coal feed mechanism's ability to adjust from the lowest to the highest operating capacity. If the stoker can provide full range operation it is considered in "good" condition while 75% of full range is considered "poor". The following equation was developed:

$$C35 = 4\ (\%\ \text{of specified range}) - 300 \qquad (32)$$

The grate condition index was also derived from the inputs of expert 1 which related the grate condition to the percentage of grate area which is cracked. Expert 1 considered 10% or less of the area cracked as "good" condition while 30% or more of the area cracked was considered "poor" condition. The following equation was derived for the grate condition index:

$$C36 = 150 - 5\ (\%\text{ of grate area cracked}) \tag{33}$$

The total coal combustion/fuel system condition index, CC/F, is given below:

$$CC/F\ (\text{Coal}) = 0.3\ (C33 + C34) + 0.34\ (C35) + 0.36\ (C36) \tag{34}$$

where

C33 + C34= fans and dampers condition index
C35= stoker condition index
C36= grate condition index

The multiplication factors, or weights, are taken from Appendix C, Table 35.

Gas and Oil Combustion/Fuel System. The equation for the fuel piping and auxiliaries condition index is given below:

$$C39 = 100 - 25\ (\#\text{ of leaks}) \tag{35}$$

where

\# of leaks= the number of leaks detected in the last year from piping, fittings, valves, and safety valves

Comments from experts 2 and 4 mentioned that leakage was an important factor, however, they did not quantify the limits on the number of leaks. From experience with gas and oil piping lines on smaller boiler systems, the limits were set at no leaks representing "good" condition with an index score of 100 and 4 leaks being "poor" with a score of 0.

Expert number 2's response and technical literature were used to establish the limits on the burner/atomizer condition index, C40. Expert number 2 related that stack gas temperatures exceeding 700°F for gas combustion and 850°F for oil combustion reflect "poor" condition for the burner/atomizer. To set the lower temperature values, not given by expert 2, combustion efficiency curves given in U.S. Air Force Central Heating Plant Tuneup Workshop, Volume XI: Efficiency, and typical minimum flue gas oxygen levels from the USACERL report Reference (26) were used. The typical minimum oxygen level for efficient gas combustion is 4% (26:67). At this level of minimum oxygen and 700°F stack gas temperature, the gas combustion efficiency curve, Figure 3, shows 20% excess air and an efficiency of 74%. By assuming the same minimum oxygen and excess air levels and an efficiency of 80% (considered good by experts 4 and 6 when discussing fuel controls in Appendix B), the corresponding stack gas temperature of 450°F resulted. The same approach was used for oil combustion with a 3% minimum oxygen level. Using Figure 4, at 15% excess air and combustion efficiency of 80%, the resulting stack gas temperature was 625°F. Therefore, 450°F is used as the limit for a "good" score for gas combustion and 625°F as the limit for a good score for oil combustion. The equations for the burner/atomizer condition index are given below. Eq (36) is used for gas combustion and Eq (37) for oil combustion:

$$C40 = 280 - 0.4\,(\text{stack gas temp °F}) \quad (36)$$

$$C40 = 377.8 - 0.44\,(\text{stack gas temp °F}) \quad (37)$$

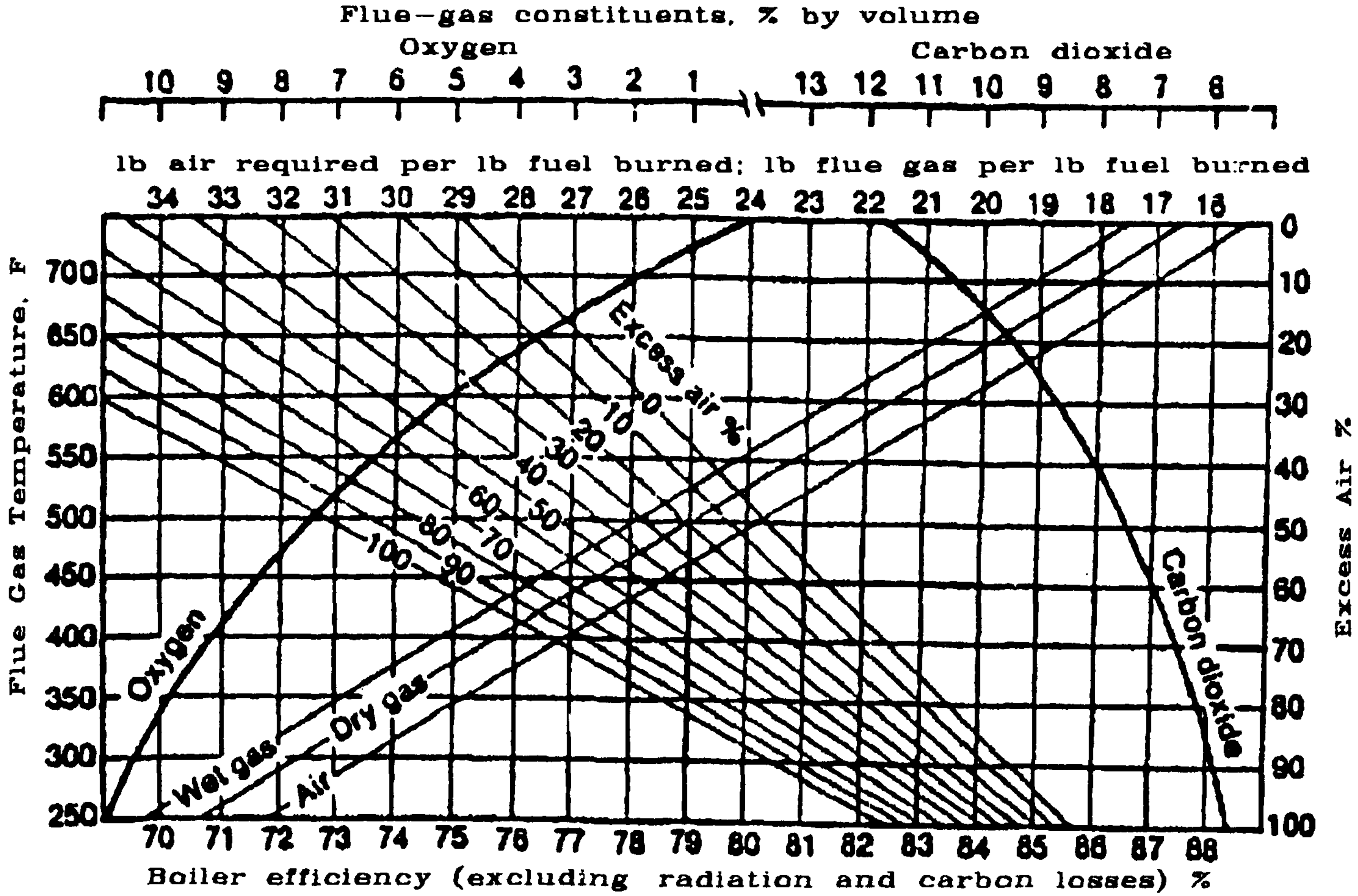

Figure 3. Boiler Efficiency Curve for Gas Combustion (27:90)

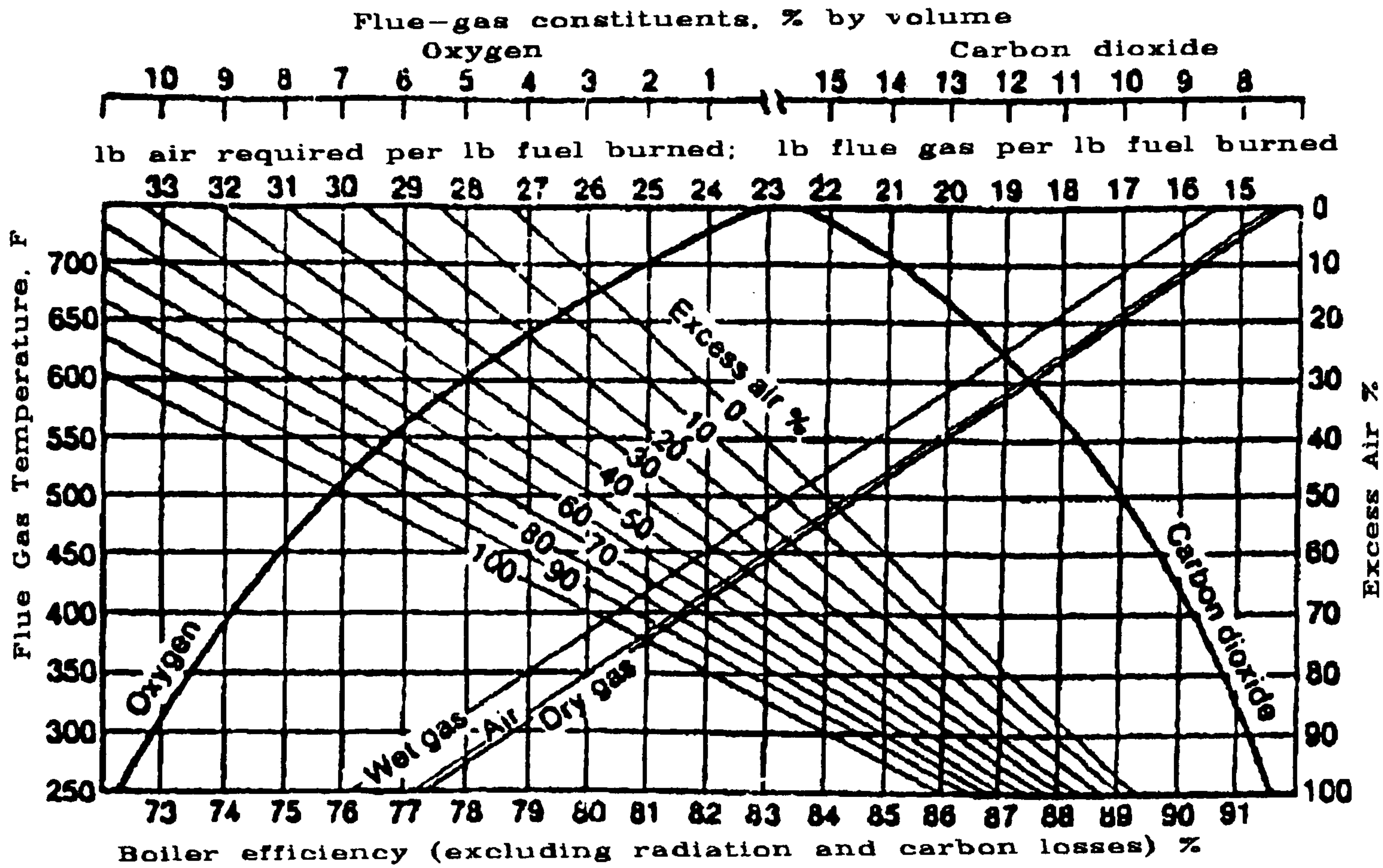

Figure 4. Boiler Efficiency Curve for Oil Combustion (27:90)

The bulk storage oil tank condition index, consisting of the indices C41 and C42, was derived from the comments of experts 2 and 3. Expert 2 related that a good storage tank would not have its usable capacity reduced due to leaks, however, no limits on capacity were suggested. With a void of technical reference on the subject and in an effort to quantify tank condition based on usable capacity, limits were set relating 100% tank capacity as "good" condition (a C41 score of 50) and 50% tank capacity as "poor" condition (a C41 score of 0). The derived relation is shown below:

$$C41 = (\%\ \text{tank capacity}) - 50 \tag{38}$$

Experts 2 and 3 both mentioned that the tank heating system, heating coil and temperature control, should operate relatively trouble free. However, no limits for heating system criteria were given by the experts. In an effort to quantify limits for this index with a lack of reference on problems with tank heating coils, general experience on heating system coils was used to set the limits relating no coil malfunctions in one year as "good" condition and four coil malfunctions as "poor" condition. The respective index scores for these conditions are 50 and 0. The equation for C42 is shown below:

$$C42 = 50 - 12.5\ (\#\ \text{of malfunctions}) \tag{39}$$

The fuel regulator condition index, C44, was developed with a void of expert opinions on proposed evaluation criteria. As described in the USACERL report Reference (26), the regulator controls fuel flow to the boiler by proportionally opening and closing the fuel valve (26:22). However, a search of technical literature did not reveal any criteria which could be used to judge current regulator condition. Therefore, the equation derived for the stoker condition index, Eq (32), was also applied in this case. The rationale behind this decision is that both components regulate the flow of fuel to the furnace and their conditions should be quantified according to similar criteria. The following equation is proposed for the fuel regulator condition index:

$$C44 = 4\ (\%\ \text{of range}) - 300 \tag{40}$$

In the case of the fuel regulator, the measured variable is the capability of the regulator to move the fuel valve from full open to full closed. As for the stoker condition index, the ability to move the valve over only 75% of the required range is considered "poor" and 100% of the range is considered "good".

The derivation of the flame and flow sensors condition index was also hampered by limited expert opinion on evaluation criteria. Expert 3, the only one providing criteria, related that "good" condition would be represented by no combustion shut downs due to faulty flame and flow sensors, while "fair" condition would be reflected by occasional false shut downs, and "poor" condition indicated by having the sensors jumped-out of the safety system. To quantify this criteria, the following equation for the flame and flow sensors condition index was developed:

$$C45 = 100 - 33.3\ (\#\text{ of false shut downs}) \tag{41}$$

where

# of false shut downs= the number of false shutdowns occurring in the past year

The limits on Eq (41) were set at no false shut downs resulting in a C45 value of 100 and 4 false shut downs giving a score of 0.

The total gas and oil combustion/fuel system condition index, CC/F, is given below:

$$CC/F\ (\text{Gas and Oil}) = 0.16\ (C37 + C38) + 0.19\ (C39) + 0.15\ (C40) + 0.09\ (C41 + C42) + 0.12\ (C43) + 0.15\ (C44) + 0.14\ (C45) \tag{42}$$

where

C37 + C38= fan and damper condition index
C39= fuel piping and auxiliaries condition index
C40= burner/atomizer condition index
C41 + C42= bulk storage oil tanks condition index
C43= oil pump condition index
C44= fuel regulator condition index
C45= flame and flow sensor condition index

The multiplication factors, or weights, are taken from Appendix C, Table 34.

Derivation of HTHW Plant Condition Indices

Most of the condition indices for the HTHW system are identical to the Steam system condition indices, hence, a discussion of these identical items will not be repeated in this section.

The condition indices for two of the major subsystems, combustion/fuel and controls, were made identical for both steam and HTHW plants. The combustion/fuel systems for both steam and HTHW are, in actuality, identical and do not require separate condition indices. However, the control system indices were made identical even though the Delphi survey indicated that control components different from the steam system control components should be included in the HTHW system. This was done because there was not enough written criteria from the experts to derive meaningful condition indices for the identified HTHW control components. In addition, all control components included in the model for the steam system also exist in HTHW control systems. It was concluded that there was no one control component in a HTHW system which is substantially different from the control components of a steam system, hence, separate condition indices would not be required.

As done for steam systems, the following paragraphs will describe the inputs used to derive the condition index equations for the high temperature hot water plant component model given in Appendix E.

<u>Distribution System</u>. Due to an absence of written criteria from the Delphi survey, a telephone interview with a HTHW plant supervisor was used to establish the limits for make-up water percentage for the piping condition index, C1. A make-up rate of 3% was considered poor and 0% make-up was considered good (28). This condition index equation involves the same measured variables as Eq (7) above:

$$C1 = 100 - 33.3\,(\text{make-up\%} - \text{blowdown\%}) \qquad (43)$$

Comments supplied by experts 3 and 10 were used to derive the converters condition index, C3:

$$C3 = 333\,[1 - (\#\text{ of converters NFO} / \text{total }\#\text{ converters})] - 233 \quad (44)$$

where

NFO= not fully operational

A converter is defined as not fully operational if its control valves are inoperable or out of calibration, and/or any of its valves or fittings are leaking at a rate of more than 30 drops per minute, and/or there is evidence of a leaky tube bundle. This definition was developed from the criteria given by the experts, however, no limits were suggested in their criteria. For Eq (44), the limit of 100% of converters being fully operational was considered "good" and 50% fully operational corresponded to "poor" condition. A 50% level was considered "poor" because this would indicate a possible reduction in capability to produce needed steam for the required users.

The balanced flow condition index, C4, was derived by comments from expert 10 and a telephone interview with a HTHW plant supervisor. Expert 10 mentioned that blending valves should be in the full open position but gave no other criteria. In an effort to quantify this index, not having any technical references or similar experience, a telephone interview was conducted. In the interview, a heating supervisor stated that the best single measure of the generation system output being balanced with its required load is the percentage of time that the blending valves are fully open. A good system would have the valves open 100% of the time while a poor system would have them open only 50% or less of the time (29). From these responses, Eq (45) was derived:

$$C4 = 2\ (\%\ \text{time blending valves full open}) - 100 \quad (45)$$

The corrosion control condition index, C5, was derived from expert 5's comments on his suggestion to measure corrosion control efforts in the steam distribution system. Although corrosion control was not a consented item for the steam system, it was for the HTHW system. Expert 5's input was not summarized in Appendix B since he was the only one suggesting such criteria, however, his response on corrosion control measures can be applied in the case of the HTHW distribution system. He suggested that "good" condition would be reflected by having 90% of the underground metal piping protected in accordance with criteria given in AFM 85-5. Having only 75% of the underground piping protected would rate as "poor" condition. Eq (46) was derived from these comments:

$$C5 = 6.67\ (\%\ \text{protected}) - 500 \quad (46)$$

The total distribution system index, CDS, is given below:

$$CDS = 0.17\ (C1) + 0.22\ (C2) + 0.19\ (C3) + 0.24\ (C4) + 0.19\ (C5) \quad (47)$$

where

C1= piping condition index
C2= supply pump condition index

C3= converters condition index
C4= balanced flow condition index
C5= corrosion control condition index

The multiplication factors, or weights, are taken from Appendix C, Table 37.

<u>HTHW Generating System</u>. The condition indices for drums and pressure safety devices are identical to the steam system indices since these components are essentially the same for both systems. The index for casing and tubes for the HTHW system is developed from the same criteria as used for steam systems since equipment for both systems is essentially the same. The HTHW casing and tubes index consists of the indices, C6 and C7:

$$C6 = 50 - 6.25\ (\#\ \text{of penetrated casing sections}) \quad (48)$$

$$C7 = 50 - 2.5\ (\%\ \text{of area sooted}) \quad (49)$$

Eqs (48) and (49) are based on the same criteria as Eqs (26) and (27), however, the slope and intercept constants were changed to reflect the fact that C6 and C7 values only range from 0 to 50 for each since they are summed to arrive at the casing and tubes condition index.

The valving condition index, C9, was derived using the inputs of experts 2, 3, 4, and 5. These experts related that valves should not leak and should properly seat. The responses of experts 2, 4, and 5 were in reference to the steam distribution system valving, but can be generalized to HTHW systems since the desired qualities for each type of valve are essentially the same. The following equation was derived for the valving condition index:

$$C9 = 333\,[1 - (\#\text{ of valves NFO} / \text{total }\#\text{ valves})] - 233 \qquad (50)$$

In Eq (50), not fully operational refers to any generating system valve (boiler isolation, bypass, or blending valves) which does not seat properly or leaks from the bonnet or flange. This definition is taken from expert 3's criteria for HTHW systems. Expert 4's suggestion that no leaking valves would indicate "good" condition, and that "poor" condition be reflected by having 30% or more of the valves leaking, was the basis for establishing the limits on Eq (50).

Since there was no criteria given by the experts on the layup capability condition index, technical references were used to establish criteria. This criteria was taken from suggested layup procedures detailed in two separate references. In the book, <u>Steam/its generation and use</u>, it is recommended that wet storage be accomplished with: water treated to 500 PPM hydrazine to maintain a pH at 10, a maintained pressure of 5 to 10 PSI, and a source of heat to keep the unit warm. Dry storage requires a 5 PSI pressure provided by nitrogen and approximately one pound of moisture absorbent for every 1000 pounds per hour of steam capacity of the boiler (30:36-18 to 36-19). <u>U.S. Air Force Central Heating Plant Tuneup Workshop, Volume XIII: Operations and Maintenance</u> recommends for wet storage: 100 PPM of sulfite be used to maintain pH between 8 and 10, that a slight pressure be maintained on the system, and maintain the bottom boiler drum at 140°F to reduce humidity. For dry storage, desiccant should be placed in the boiler (31:68-69). The index scores for wet and dry storage are dependent on the capability of the heating plant to meet the requirements of the above recommended steps.

The total HTHW generating system condition index, CGS, is shown below:

$$CGS = 0.23\ (C6 + C7) + 0.22\ (C8) + 0.20\ (C9) + 0.22\ (C10) + 0.13\ (C11 + 12) \tag{51}$$

where

C6 + C7= casing and tubes condition index
C8= expansion drums condition index
C9= valving condition index
C10= pressure safety devices condition index
C11 + C12= layup capability condition index

The multiplication factors, or weights, are taken from Appendix C, Table 39.

The final equation in the high temperature hot water component model is the total HTHW plant condition index, CHW, shown below:

$$CHW = 0.23\ CDS + 0.25\ CCS + 0.24\ CGS + 0.28\ CC/F \tag{52}$$

where

CDS= distribution system condition index
CCS= control system condition index
CGS= generating system condition index
CC/F= combustion/fuel system condition index

The multiplication factors, or weights, are taken from Appendix C, Table 36.

V. Recommendations and Conclusions

The component models developed in this work do not take into account multiple like components, such as multiple sets of boilers. Recommendations are made concerning the assignment of a single condition index value for any multiple like components. The models were also developed to facilitate a manual data search (as opposed to a computer-based data search) to obtain the required measured variables. If an computer based expert system is used to gather the required information, a larger sample of data is recommended to be taken.

The developed component models should be considered as a first attempt to quantify heat plant conditions. An operational test and further research and refinement will be required to obtain a reliable and accurate rating system.

Recommendations for Implementation.

The component models identify criteria to measure the condition of critical heating plant components and produce an index value indicating the condition. However, the models do not take into consideration a method to assign a single condition index score which represents the condition of a set of multiple like components. Such a method must be determined before the component models can be utilized.

A heating plant normally maintains data pertaining to water treatment and usage, boiler and combustion efficiency, and maintenance and safety inspections. This data is normally stored in log books and on strip charts which makes it difficult and time consuming to search and summarize over any lengthy period of time. Therefore, the models developed in this work require that data be searched only for a limited number of days, typically 30 days. If these models are combined with a computer-based data search capability, data on measured variables may be easily collected for a historical period greater than 30 days. Hence, for use with a computer-based expert system, the models should be adjusted.

Application with Multiple Like Components. A typical heating plant contains, for example, multiple sets of boilers, drums, fans, and burners. These multiple components may be required for either back-up capability or full operation. In either case, all the multiple components should be considered when calculating the condition index for that particular component since the objective is to obtain an accurate representation of the plant's condition. To examine only the boiler units which are currently operating or only the units which are currently laid up could favorably or unfavorably bias the condition indices for the generation system and result in an inaccurate reflection of the overall plant capability.

For each occurrence of a multiple component, each component should be scored individually according to its condition index criteria and the average value of this index be used to calculate the total system condition index and the overall plant condition index. For example, if there are four boilers, four separate condition indices need to be calculated and averaged for the burner component.

In a case where half of the units of a multiple component are scored at 50 points or less (a "poor" score), the lowest individual score should be used for the total system and overall plant condition index. For example, if the four burners were given condition index scores of 39, 49, 68, and 80, the value of the burner component condition index to be reported and used in the total system and overall index calculations is 39. This action is recommended in order to emphasize possible reductions in plant capability.

It is also recommended to maintain the individual scores of these multiple components over time, even though only the average or low score is actually used. This information could be useful in measuring the rate of individual component degradation.

Required Data. Air Force forms which keep track of hourly and daily data on operating conditions and water quality are convenient sources for calculating average values of the required measured parameters. The number of days over which the data should be averaged were recommended in the description of the condition indices for the component models. The number of days of recorded data to be included were typically limited to between thirty and sixty since no computer-based expert system currently exists to sample the data. Under a manual system, a practical limit needs to be placed on the amount of data to be searched and averaged to minimize errors and increase compliance with the condition index calculation procedures. Once an expert system is in place, and the required data is available in a computer data base, the required parameters should be averaged for the previous year at the specified plant operating capacities. For example, in the case of the condensate piping condition index, a computer based expert system could calculate the average daily value of the make-up water percentage for the last calendar year only considering the make-up water percentages for days when the plant capacity was greater than 50%. Such a search done manually would be impractical.

In addition, a maintenance log procedure must be established at each plant (if one is not already established) to track information on maintenance actions with pumps, traps, converters, and other critical components listed in the models. Such logs would be needed to gather data necessary to compute the component condition indices.

Recommendations for Further Research

Although component models were developed to gage the condition of steam and high temperature hot water plants, these models should only be considered as a starting point for further research in the area. Two primary avenues of approach recommended for further research are: a second Delphi survey utilizing a different set of experts, and an operational test of the component models.

A Second Delphi Survey. As mentioned by Sackman in a review of the Delphi technique, a second Delphi survey, identical to the first, should be conducted with a different panel of experts in order to validate the results of the first survey (18:24). Although an identical survey is recommended by Sackman, from results of this study the information on critical components and their weights should not significantly change from one survey to another. Therefore, a Delphi survey should be conducted to gather detailed evaluation criteria on the identified components which are more objective or quantifiable in nature than the criteria gathered in this research. The limits on all the criteria used the models should be set by the experts, not by the researcher as was required for some component indices in this study.

Operational Test of the Models. As with any new management tool, there is a tendency to put it into immediate use, however, field testing for management tools is just as important as that for new hardware (32:49). Hence, the component models should be operationally tested at all AFLC heating plants over a period of at least two years with condition indices calculated at least twice each year. Such an operational test would produce data on the consistency and reliability of the calculated indices. To test the model's reliability, component index values should be compared to component failure rates to see if a strong correlation exists. Such a correlation would indicate that the component models are useful tools to indicate actual condition and make predictions for remaining useful life of components or major systems. No correlation would indicate that the model is not effective in assessing current heat plant conditions and further research is required.

Conclusions

The component model rating systems developed in this thesis represent a first attempt at quantifying the operating condition of central heating plants. Further Delphi research and operational testing are recommended to validate the models' capability to represent the condition of central heating plants. The reader is also cautioned that it will be difficult, if not impossible, to distinguish between poor maintenance practice and actual plant condition as reasons for low condition index scores. Poor operations and maintenance practices in a plant of relatively good condition and good operations and maintenance practices in a plant of poor condition may result in identically low condition index scores. The main reason, either poor physical condition or poor maintenance, can not be detected by this component model. One avenue warranting further research is the analysis of the influence of a plant's preventive maintenance program on plant condition. However, application of these models will direct management attention to the plants in greatest need of care. Once they are identified, resources can then be allocated (staff assistance visits from headquarters and/or contracted useful life studies) to begin proper corrective action.

Appendix A: Round One Delphi Package

AFIT/LSG 21 Feb 90

Central Heat Plant Questionnaire

Delphi Participant:

1. Thank you for agreeing to participate in this AFIT survey. The intent of this research is to devise an inspection-type rating system for central heating plants which will help the Major Command and the local bases pinpoint and document problem areas using a relative numerical scale. When this rating system is developed, it is intended that the individual inspections would be performed by each local base using their own personnel and resources.

2. You have been selected to participate in this research because your experience and proficiency with central heat plant maintenance and/or design qualify you as an expert. You will be participating in this research with approximately 12 other selected experts using a technique called the "Delphi" method.

3. The Delphi method is designed to achieve a consensus opinion among experts on a particular subject. The basic philosophy of the method is "two heads are better than one". After you answer this first set of questions (the first round), I will return to you a summary of all the responses

to allow you a chance to revise your responses and comment on other participants opinions. All responses are confidential and no individuals or organizations will be identified. This confidentiality is to insure your honest opinions while eliminating fear of retribution and pressure from fellow experts. I anticipate that only two rounds of questioning will be needed to achieve a group consensus and complete this research.

4. Attached to this letter is the first round questionnaire, including a set of instructions, and a sample response. Your prompt response during each round will insure the successful completion of this study within the time constraints established by AFIT. Therefore, please complete this survey within 14 days of receipt. If you have any questions about this survey, please call to leave me a message at AV 785-4437/5435. Thank you for taking time to share your expertise.

GARY J. STARMACK, Capt, USAF

Graduate Engineering Mgt Student

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1. Instructions
2. Sample Response
3. Questionnaire
4. Return Envelope

INSTRUCTIONS

1. Definition of Terms:

A. Central Heating Plant: A facility which contains two or more boilers which produce steam or high temperature hot water for distribution to other facilities for the purpose of space heating or process requirements. A central heating plant is manned and operated on a 24-hour per day basis. The entire primary piping distribution network is considered as part of the plant.

B. System: A major division or function of the central plant system which can be considered a system in itself. Examples of central heating plant systems could include the distribution system, controls system, electrical system, steam generation system, etc..

C. System Component: A major part or an individual piece of equipment which is contained in a system. Examples of system components could include: piping, pumps, and traps for the distribution system, and drums, boiler tubes, and superheater headers for the steam generation system.

D. Weighting Factor: A number between 1 and 10 (inclusive) will be used to indicate the relative importance of a specific system or a specific system component. A highly critical system or component will be given a larger number than a less critical one.

E. Evaluation Criteria: Methods and/or rules which should be used when inspecting system components to determine their current condition. The criteria suggested for the components could range from a simple visual inspection to perhaps a more complicated "equation-type" analysis. In all cases, the criteria should be specific and the methods required for accomplishing the evaluation should be within the capabilities of the squadron or be easily obtained through contracting.

2. Specific Instructions:

A. On the first sheet of the questionnaire, please indicate the type of system with which you feel the most competent. Do so by circling the type of heating plant and combustion system, and then answer the questionnaire in conjunction with the specified system.

B. The questionnaire is formatted for short-answer, written responses. It is structured to accept six systems and five components from each system. You may, however, choose to include more or fewer categories than preprinted on the questionnaire. If you think that only five systems need to be listed, then leave the "F" entries blank on the first and subsequent sheets. If, on the other hand, you think you need more systems, add them to the questionnaire (attach additional pages or write on the back of the given pages) and label them in a manner consistent with the rest of the questionnaire (G,H, etc.). The same logic applies to the questions concerning components and criteria (more or fewer answers can be given than the preprinted format allows for).

3. General Comments:

A. A partial sample response is included in this package as a guide for the format of your responses. There are no restrictions on the weighting factors for any item (the numbers don't have to total to any specific amount) except that, for simplicity, each number should be between 1 and 10. The weighting factors for any item are "relative", meaning that a "10" is twice as important as a "5". If, for example, you list four items for a particular section and weight each one as "10", this means that you consider each item to have equal importance (the same would be true if you gave each item a "6"). Therefore, it is best to begin assigning weighting factors for each item by first assigning at least one "10" and then assigning proportionately lower numbers to the lesser important items.

B. Every component in the heating plant is needed for proper operation, so when selecting the most important components, please consider the following: availability of spares, potential to cause full or partial outage, potential for reliability or performance deterioration, and effect on boiler system life.

C. Your participation and honest responses are key to the success of this research. Remember that no thought or opinion is too trivial because one participant's "brainstorm" could provide the impetus for other participants' opinions in the next round of questioning.

THANK YOU FOR YOUR PARTICIPATION !

CENTRAL HEAT PLANT QUESTIONNAIRE

HEAT PLANT TYPE:	**FIRING:**
Steam	*Coal*
High Temp Hot Water	*Fuel Oil*
	Gas
(circle one)	(circle all that apply if dual fired)

In your opinion, what are the most important systems of the central heat plant?
What weighting factor would you assign to each?

SYSTEM	***WEIGHTING FACTOR***
A: Distribution System	**A:** 6
B: Control System	**B:** 4
C: Combustion/Fuel System	**C:** 10
D: Boiler/Steam Generation System	**D:** 10
E: Water Treatment System	**E:** 4
F:	**F:**

CENTRAL HEAT PLANT QUESTIONNAIRE

SYSTEM A — *For **SYSTEM A** list the most critical components and a weighting factor for each. (more than 5 may be listed)*

COMPONENT	*WEIGHTING FACTOR*
A1: Supply Piping	A1: 10
A2: V ves	A2: 3
A3: Condensate Piping	A3: 8
A4:	A4:
A5:	A5:

*For each component in **SYSTEM A**, list the evaluation criteria you would use to establish the condition of each component. For each criteria, assign a definition for excellent, fair and poor condition*

COMPONENT A1 Criteria: Supply Piping - Visual inspection for exterior rust, weatherproofing and insulation

Excellent: No rust on exposed piping, 95% of weatherproofing and insulation in new condition

Fair: 15% of exposed piping rusted, 75-95% of weatherproofing and insulation in new condition

Poor: 25% of exposed piping rusted, and less than 75% of weatherproofing and insulation in new condition

SAMPLE

CENTRAL HEAT PLANT QUESTIONNAIRE

HEAT PLANT TYPE:	**FIRING:**
Steam	*Coal*
High Temp Hot Water	*Fuel Oil*
	Gas
(circle one)	(circle all that apply if dual fired)

In your opinion, what are the most important systems of the central heat plant?

What weighting factor would you assign to each

SYSTEM	***WEIGHTING FACTOR***
A:	**A:** ________
B:	**B:** ________
C:	**C:** ________
D:	**D:** ________
E:	**E:** ________
F:	**F:** ________

CENTRAL HEAT PLANT QUESTIONNAIRE

SYSTEM A

*For **SYSTEM A** list the most critical components and a weighting factor for each. (more than 5 may be listed)*

COMPONENT	***WEIGHTING FACTOR***
A1:	**A1:** ________
A2:	**A2:** ________
A3:	**A3:** ________
A4:	**A4:** ________
A5:	**A5:** ________

*For each component in **SYSTEM A**, list the evaluation criteria you would use to establish the condition of each component. For each criteria, assign a definition for excellent, fair and poor condition*

COMPONENT A1 Criteria: ______________________________

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

SYSTEM A *Components (continued)*

COMPONENT A2 Criteria: ____________________

Exellent:

Fair:

Poor:

COMPONENT A3 Criteria: ____________________

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

***SYSTEM A** Components (continued)*

COMPONENT A4 Criteria: ______________________________

____

____

Exellent:

Fair:

Poor:

COMPONENT A5 Criteria: ______________________________

____

____

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

SYSTEM B

*For **SYSTEM B** list the most critical components and a weignting factor for each. (more than 5 may be listed)*

COMPONENT	***WEIGHTING FACTOR***
B1:	**B1:** ______
B2:	**B2:** ______
B3:	**B3:** ______
B4:	**B4:** ______
B5:	**B5:** ______

*For each component in **SYSTEM B**, list the evaluation criteria you would use to establish the condition of each component. For each criteria, assign a definition for excellent, fair and poor condition*

COMPONENT B1 Criteria: ______________________________

____

____

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

***SYSTEM B** Components (continued)*

COMPONENT B2 Criteria: ____________________

__Exellent:__

__Fair:__

__Poor:__

COMPONENT B3 Criteria: ____________________

__Excellent:__

__Fair:__

__Poor:__

CENTRAL HEAT PLANT QUESTIONNAIRE

***SYSTEM B** Components (continued)*

COMPONENT B4 Criteria: ______________________________

____

____

Exellent:

Fair:

Poor:

COMPONENT B5 Criteria: ______________________________

____

____

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

SYSTEM C — *For **SYSTEM C** list the most critical components and a weighting factor for each. (more than 5 may be listed)*

COMPONENT	***WEIGHTING FACTOR***
C1:	**C1:** ______
C2:	**C2:** ______
C3:	**C3:** ______
C4:	**C4:** ______
C5:	**C5:** ______

*For each component in **SYSTEM C**, list the evaluation criteria you would use to establish the condition of each component. For each criteria, assign a definition for excellent, fair and poor condition*

COMPONENT C1 Criteria: ______________________

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

***SYSTEM C** Components (continued)*

COMPONENT C2 Criteria: ______________________

____

____

Exellent:

Fair:

Poor:

COMPONENT C3 Criteria: ______________________

____

____

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

***SYSTEM C** Components (continued)*

COMPONENT C4 Criteria: ______________________________

____

____

Exellent:

Fair:

Poor:

COMPONENT C5 Criteria: ______________________________

____

____

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

SYSTEM D	*For **SYSTEM D** list the most critical components and a weighting factor for each. (more than 5 may be listed)*

COMPONENT	***WEIGHTING FACTOR***
D1:	**D1:** ________
D2:	**D2:** ________
D3:	**D3:** ________
D4:	**D4:** ________
D5:	**D5:** ________

*For each component in **SYSTEM D** list the evaluation criteria you would use to establish the condition of each component. For each criteria, assign a definition for excellent, fair and poor condition*

COMPONENT D1 Criteria: ____

____

____

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

SYSTEM D *Components (continued)*

COMPONENT D2 Criteria: ____________________

____

____

Exellent:

Fair:

Poor:

COMPONENT D3 Criteria: ____________________

____

____

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

***SYSTEM D** Components (continued)*

COMPONENT D4 Criteria: ____________________

____

____

Exellent:

Fair:

Poor:

COMPONENT D5 Criteria: ____________________

____

____

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

SYSTEM E

*For **SYSTEM E** list the most critical components and a weighting factor for each. (more than 5 may be listed)*

COMPONENT	***WEIGHTING FACTOR***
E1:	**E1:** ________
E2:	**E2:** ________
E3:	**E3:** ________
E4:	**E4:** ________
E5:	**E5:** ________

*For each component in **SYSTEM E**, list the evaluation criteria you would use to establish the condition of eacn component. For each criteria, assign a definition for excellent, fair and poor condition*

COMPONENT E1 Criteria: ____________________

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

SYSTEM E *Components (continued)*

COMPONENT E2 Criteria: ____________________

Exellent:

Fair:

Poor:

COMPONENT E3 Criteria: ____________________

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

***SYSTEM E** Components (continued)*

COMPONENT E4 Criteria: ______________________________

____

____

Exellent:

Fair:

Poor:

COMPONENT E5 Criteria: ______________________________

____

____

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

SYSTEM F

*For **SYSTEM F** list the most critical components and a weighting factor for each. (more than 5 may be listed)*

COMPONENT	*WEIGHTING FACTOR*
F1:	F1: ______
F2:	F2: ______
F3:	F3: ______
F4:	F4: ______
F5:	F5: ______

*For each component in **SYSTEM F**, list the evaluation criteria you would use to establish the condition of each component. For each criteria, assign a definition for excellent, fair and poor condition*

COMPONENT F1 Criteria: ______________________________

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

***SYSTEM F** Components (continued)*

COMPONENT F2 Criteria: ______________________

____

____

Exellent:

Fair:

Poor:

COMPONENT F3 Criteria: ______________________

____

____

Excellent:

Fair:

Poor:

CENTRAL HEAT PLANT QUESTIONNAIRE

***SYSTEM F** Components (continued)*

COMPONENT F4 Criteria: ____________________

Exellent:

Fair:

Poor:

COMPONENT F5 Criteria: ____________________

Excellent:

Fair:

Poor:

Appendix B: Round Two Delphi Package

AFIT/LSG 3 May 90

Central Heat Plant Questionnaire

Delphi Participant:

1. Thank you for agreeing to participate in this AFIT survey. As a reminder, this package is the second and final round of research which will be used in developing an inspection-type rating system for central heating plants to help the Major Command and the local bases pinpoint and document problem areas using a relative numerical scale. When this rating system is developed, it is intended that the individual inspections would be performed by each local base using their own personnel and resources.

2. I am very pleased with the results of the first round responses. There were many different components and inspection criteria given. You will notice that this round of questioning is formatted differently and will not require as much time to complete as the first round. This is due to the great effort you put into the previous round.

3. This research method (The Delphi Method) is designed to achieve a consensus opinion among experts on a particular subject. The basic philosophy of the method is "two heads are better than one". I have summarized all round one

responses to allow you a chance to review the other experts' opinions on the important components, their weights, and inspection criteria and to give you another chance to make inputs on the same. All responses are confidential and no individuals or organizations will be identified. This confidentiality is to insure your honest opinions while eliminating fear of retribution and pressure from fellow experts.

4. Attached to this letter is the second round questionnaire, including a set of instructions, and a sample response. Your prompt response during this round will insure the successful completion of this study within the time constraints established by AFIT. Therefore, please complete this survey within 14 days of receipt. If you have any questions about this survey, please call me at AV 785-8989. Thank you again for taking time to share your expertise.

GARY J. STARMACK, Capt, USAF
Graduate Engineering Mgt Student

4 Atch
1. Instructions
2. Sample Response
3. Questionnaire
4. Return Envelope

INSTRUCTIONS

1. Overview of Round Two:

A. This questionnaire is divided into two sections, section one summarizes all experts' opinions on the major systems along with their components and weights, and section two gives the summary of the inspection criteria for the individual components. In order to insure a quick completion of this round of questioning, only the first section needs to be answered.

B. In section one, all inputs for components and weights are summarized. The summary includes information on the total number of experts who identified a particular system or component, the component listing, and the average normalized weight factor for each component. The average normalized weight reflects the average of all experts' responses in terms of a 1-10 scale. The only responses required in section one are assigning weights (1-10) in the space provided for systems and components that you think are the most important.

C. Section two summarizes the evaluation criteria given for components. There are no required responses for this section, however, if time permits, please review these criteria and make any changes or comments to any responses you desire.

D. The summary of systems and components were grouped according to the consensus of participating experts. Hence, some experts will find that a particular system(s) or component(s) may have been included in a different major system category than was originally indicated. Also, three major systems were common to both steam and high temperature hot water plants: Combustion/Fuel System, Water Treatment System, and Stacks & Breaching/Emission Controls. These common systems appear only under the "steam" summary in both sections one and two.

2. Specific Instructions:

A. Section One: All experts are asked to complete all parts of this section (high temperature hot water, steam, coal, gas and oil) regardless of the system you selected in the previous round of questioning done in March. Please indicate a weight (1-10) in the space provided for each major system and each set of components. Only weigh up to the maximum number of choices allowed for each system heading (as indicated in the right-hand column heading for each major system). For example, you can only weigh a maximum of 7 components (you may weigh less than 7 if desired) under the distribution system. A sample response is attached. Feel free to pencil-in additional components if desired.

B. Section Two: If time permits, please review the evaluation criteria summarized in this section. Only the "excellent" and "poor" criteria are summarized for each component. Feel free to make changes, comments, deletions, or additions to any or all given criteria. You may even add evaluation criteria for components listed in section one which are not represented in the section two summary. Remember that the criteria should be as quantitative as possible and use of highly subjective criteria should be minimized. Additional sheets may be attached if desired.

3. General Comments:

A. A partial sample response is included in this package as a guide. There are no restrictions on the weights for any item (the numbers don't have to total to any specific amount) except that, for simplicity, each number should be between 1 and 10. The weights for any item are "relative", meaning that a "10" is twice as important as a "5". If, for example, you list four items for a particular section and weight each one as "10", this means that you consider each item to have equal importance (the same would be true if you gave each item a "6"). Therefore, it is best to begin assigning weights for each item by first assigning at least one "10" and then assigning proportionately lower numbers to the lesser important items.

B. Every component in the heating plant is needed for proper operation, so when selecting the most important components, please consider the following: availability of spares, potential to cause full or partial outage, potential for reliability or performance deterioration, and effect on boiler system life.

C. Your participation and honest responses are key to the success of this research. I highly appreciate all the responses I received in the first round and I look forward to seeing your opinions in this second and final round.

THANK YOU FOR YOUR PARTICIPATION !

SAMPLE

Steam Plant Components(All Fuels Included)

Distribution System:

# of experts agreeing	Component	Avg Normalized Weight Factors	Weight no more than 7 Components (1-10)
6	Condensate Piping	9	10
3	Supply Pipe Insulation	7	___
5	Steam Traps	8	8
4	Condensate Pumps	8	9
7	Supply Piping	9	10
4	Valves	7	5
2	Pits	3	___
1	Cathodic Protection	9	___
1	Regulators	6	___
2	Pressure Reducing	10	___

SECTION ONE

Steam Plant Major Systems

# of Experts agreeing Systems	Major System	Avg Normalized Weight Factor	Weight at least 5 (1-10)
8	Distribution	6	____
8	Water Treatment	8	____
7	Control	7	____
8	Steam Generation	10	____
7	Combustion/Fuels	9*	____
2	Stacks & Breaching/ Emission Control	7	____
1	Electrical	6	____

(* includes responses for coal-fired systems)

Steam Plant Components(All Fuels Included)

Distribution System:

# of experts agreeing	Component	Avg Normalized Weight Factors	Weight no more than 7 Components (1-10)
6	Condensate Piping	9	____
3	Supply Pipe Insulation	7	____
5	Steam Traps	8	____
4	Condensate Pumps	8	____
7	Supply Piping	9	____
4	Valves	7	____
2	Pits	3	____
1	Cathodic Protection	9	____
1	Regulators	6	____
2	Pressure Reducing	10	____

<u>Water Treatment System</u>: Also Includes High Temp Hot Water inputs.

# of experts agreeing	Component	Avg Normalized Weight Factors	Weight no more than 10 Components (1-10)
4	Make-up Water Sys	10	____
5	Feedwater System	9	____
3	Blowdown	6	____
1	Condensate Quality	7	____
1	Conductivity	7	____
6	Softener	9	____
4	Chemical Feed System	8	____
5	Deaerator	9	____
2	Piping	6	____
4	Pumps	10	____
1	Controls	8	____
1	Regulators	8	____
1	Water Test Capability	10	____

Boilers/Steam Generators:

# of experts agreeing	Component	Avg Normalized Weight Factors	Weight no more than 7 Components (1-10)
1	Boiler Efficiency	10	____
5	Casing	7	____
5	Tubes	9	____
5	Refractory	7	____
3	Safety Devices	8	____
2	Drums	10	____
1	Steam Separator	8	____
1	Furnace Section	8	____
1	Air Heater Section	7	____

Controls:

# of experts agreeing	Component	Avg Normalized Weight Factors	Weight no more than 9 Components (1-10)
4	Air Controls	7	____
4	Fuel Controls	10	____
1	Press,Temp Indicators	8	____
1	Stack Gas Analyzers	6	____
1	Fuel,Steam,Water Meters	5	____
1	Maintenance of all Logs	2	____
3	All Sensors	6	____
1	All Transmitters	4	____
3	Central Logic System/ Controllers	7	____
3	All Actuators	10	____
1	All Limit Controls	6	____
1	Feedwater Controls	8	____

Combustion/Fuel System (Gas and Oil): Coal-fired experts also encouraged to respond to this section. Also includes High Temp Hot Water inputs.

# of experts agreeing	Component	Avg Normalized Weight Factors	Weight no more than 7 Components (1-10)
6	Piping, Valves, Safety Devices	10	____
5	Combustion Fans/ Dampers&Linkages	7*	____
4	Burners/Atomizers	7	____
2	Oil Tanks	7	____
2	Oil Pumps and Auxils	8	____
1	Fuel Meters	3	____
1	Fuel Regulators	8	____
1	Diked Storage Area	5	____
1	Combustion Flame & Flow Sensors	6	____

(* includes relative weights from experts responding to coal-fired systems)

Combustion/Fuel System (Coal): Gas/oil experts also encouraged to respond to this section. Also includes High Temp Hot Water inputs.

# of experts agreeing	Component	Avg Normalized Weight Factors	Weight no more than 10 Components (1-10)
5	Combustion Fans/ Dampers&Linkages	7*	____
1	Coal Pile	4	____
2	Coal Handling	8	____
2	Hoppers	6	____
2	Stoker	8	____
2	Grates	9	____
1	Overfire Air	6	____
1	Coal Drive Motors	10	____
2	Belt Conveyers	8	____
1	Bucket Conveyer Chains	10	____
1	Coal Transfer Controls	6	____
1	Superstructure	5	____
1	Scrapper, Side Rails	7	____

(* includes relative weights from experts responding to gas/oil systems)

Stacks & Breaching/Emission Control: Respond only if you weighted this item as a major system at the beginning of this survey or in the High Temp Hot Water Summary which follows. Also includes High Temp Hot Water inputs.

# of experts agreeing	Component	Avg Normalized Weight Factors	Weight any or all Components (1-10)
2	Stacks and Breaching	10	____
2	Waste Heat Recovery	7	____
2	Dust Collection	6	____
1	Electrostatic Precip	7	____
1	Vacuum Operation	7	____
1	Ash Unloader	7	____
2	Opacity Sensors	5	____
2	Oxygen/CO2 Sensors	7	____

Electrical System: Respond only if you weighted this item as a major system at the beginning of this survey.

any # of experts agreeing Components	Component	Avg Normalized Weight Factors	Weight or all (1-10)
1	Back-up Generator	10	____
1	Breakers	9	____
1	Motor Starters	8	____

High Temp Hot Water
Major Systems

ALL EXPERTS ENCOURAGED TO RESPOND

# of experts agreeing	System	Avg Normalized Weight Factors	Weight no more than 5 Systems (1-10)
2	Distribution	8	____
2	Controls	9	____
2	Combustion/Fuel	10	____
2	HTHW Generation	10	____
2	Water Treatment	7	____
1	Emission Control	5	____
1	Drainage System	3	____
1	Pressurization System	8	____

Distribution System:

more # of experts agreeing Components	Component	Avg Normalized Weight Factors	Weight no than 6 (1-10)
1	Piping	7	____
1	Manholes	8	____
1	Valving	7	____
1	Supply Pumps	7	____
2	Converters	8	____
1	Boiler & Flow Balanced	10	____
1	Insulation	8	____
1	Corrosion Control	8	____

Control System:

# of experts agreeing	Component	Avg Normalized Weight Factors	Weight no more than 5 Components (1-10)
2	Central Data/Gauges	7	____
1	Sensors	8	____
2	Master Controller	8	____
1	Boiler Controller	10	____
1	Control Drive Units	8	____
1	Safety Trips	8	____
1	Auto/Manual Stations	7	____

HTHW Generating System:

# of experts agreeing	Component	Avg Normalized Weight Factors	Weight any or all Components (1-10)
2	Casing and Tubes	10	____
1	Drums	9	____
1	Valving	9	____
1	Pressure Components/ Safeties	9	____
1	Lay-up Capability	9	____

Drainage System:

# of experts agreeing	Component	Avg Normalized Weight Factors	Weight any or all Components (1-10)
1	Bleed System	10	____
1	Blow Down	10	____
1	Flash Tanks	6	____
1	Sump Pumps	6	____
1	Clarifier	6	____

Pressurization System:

No individual components listed.

Combustion: Fuel Oil System -Common to Steam Systems.

Combustion: Coal System -Common to Steam Systems.

Water Treatment System: -Common to Steam Systems.

Emission Control System: -Common to Steam Systems.

SECTION TWO

CRITERIA SUMMARY
STEAM

DISTRIBUTION SYSTEM:

CONDENSATE PIPING:

Expert 5- From site survey and corrosion records:
EXCELLENT: Iron content in condensate return less than .1 PPM and percent make-up less than 20% and no leaks visible.

POOR: Iron content greater than 1 PPM and make-up percent greater than 50% with visible leaks.

Expert 7- From the amount of condensate returned:
EXCELLENT: 80-100% returned.

POOR: Less than 70% returned.

Expert 6- From visual inspection for rust and insulation:
EXCELLENT: No rust and 95% of weatherproofing & insulation in new condition.

POOR: 25% of piping shows rust and less than 75% of insulation in new condition.

Expert 4- From visual inspection for rust, insulation, weatherproofing, and internal pitting:
EXCELLENT: No rust with 90% of insulation and weatherproofing in new condition and no internal pitting.

POOR: Less than 70% of insulation in new condition with 15% of pipe internally pitted and more than 30% of pipe shows rust.

Expert 2- From make-up quantity, leak tightness, general inspection:
EXCELLENT: Make-up % more than 10% greater than continuous blowdown, no visible leaks, supports, anchors, and expansion provisions adequate, no apparent corrosion or physical damage in piping.

POOR: Make-up quantity independent of plant load or percentage of make-up (this indicates steam trap leaks), nearly 100% make-up, leaks at gaskets and valve packings, evidence of severe corrosion, severe water hammer in liquid lines.

SUPPLY PIPING:

Expert 4- From visual inspection of rust, insulation and weatherproofing:

EXCELLENT: 95% of insulation in new condition, no external rust.

POOR: Less than 25% of insulation in new condition, 25% of exposed piping rusted.

Expert 6- From visual inspection of exterior rust and condition of insulation:

EXCELLENT: No rust and 95% of weatherproofing & insulation in new condition.

POOR: 25% of piping shows rust and less than 75% of insulation in new condition.

Expert 7- Delivers required steam at desired pressure:

EXCELLENT: 90-100% of required pressure.

POOR: Less than 80% of required pressure.

Expert 2- From make-up quantity, leak tightness, general inspection:

EXCELLENT: Make-up % more than 10% greater than continuous blowdown, no visible leaks, supports, anchors, and expansion provisions adequate, no apparent corrosion or physical damage in piping.

POOR: Make-up quantity independent of plant load or percentage of make-up (this indicates steam trap leaks), nearly 100% make-up, leaks at gaskets and valve packings, evidence of severe corrosion.

Expert 8- Visual inspection, logs:

EXCELLENT: Supply make-up percent less than 15%, very few steam leaks.

POOR: Supply make-up greater than 30%, numerous steam leaks, pipe failures, corrosion.

STEAM TRAPS:

Expert 2- From make-up quantity, visible plumes from condensate unit vents, water hammer, heating equipment temperature, % of failed traps, base is following a trap maintenance program:

EXCELLENT: Make-up not excessive or not constant quantity, no visible plumes for condensate unit vents, heating equipment at normal temperature,no evidence of water hammer or other symptoms of failed-closed traps, traps installed properly, base has trap maintenance and replacement program.

POOR: Large number of failed traps, base has no trap maintenance and replacement program.

Expert 7- The steam is contained until it has given up its latent heat or until it condenses:

EXCELLENT: Trap allows only condensate to pass.

POOR: Less than 70% of the condensate passes.

Expert 5- Operational Test:

EXCELLENT: Less than 10% of traps failed & blowing through.

POOR: Greater than 20% of traps failed.

Expert 1- Operability:

EXCELLENT: Less than 10% of design steam flow blowing to atmosphere, more than 90% of condensate flow captured.

POOR: More than 30% of design steam flow blowing to atmosphere, less than 75% of design condensate flow captured.

CONDENSATE PUMPS:

Expert 6- Visual inspection:

EXCELLENT: Contacts smooth, no seals or check valves leaking.

POOR: contacts corroded, seals and check valves leaking.

Expert 7- Amount of condensate returned:

EXCELLENT: 100%

POOR: Less than 80% returned.

VALVES:

Expert 4- Visual inspection for exterior rust, leaking packing glands, leaking gaskets, and valve body insulation:

EXCELLENT: No leaking packing glands or gaskets, insulation in good condition on 95%.

POOR: More than 30% leaking glands or gaskets, 70% or less of valve body insulation in good condition.

Expert 2- Visual inspection for leaks at gaskets and valve packings:

EXCELLENT: No visible leakage or corrosion.

POOR: Excessive leaks at gaskets and valve packings, evidence of severe corrosion.

Expert 5- Visual inspection for leaks and capability for full shut off:

EXCELLENT: No leaks, all valves provide 100% shut off.

POOR: More than 10% of valves have leaky gaskets and do not provide full shut off.

Expert 1- Vibration Analysis:

EXCELLENT: Less than .0196 in/sec.

POOR: Greater than .0785 in/sec.

PITS:

Expert 5- Visual inspection:

EXCELLENT: Structurally sound, sumps operational, insulation and jacketing in good condition.

POOR: Pits cracked or leaking ground water, less than 75% of sump pumps operational, less than 75% of piping insulated and jacketed.

Expert 2- Visual inspection:

EXCELLENT: Manholes, valve pits, trenches or tunnels free of water, sump pumps and drains operational, manholes properly covered and identified, no uncontrolled movement transmitted to pipes.

POOR: Manholes, pits, and trenches flooded up to pipelines or full of debris, loose manhole covers, sump pumps not working, pipe supports not sound.

SUPPLY PIPE INSULATION:

Expert 2- Visual inspection for high moisture loading or water hammer, heat loss along line, physical condition of insulation and jacketing:

EXCELLENT: No evidence of heat loss along lines, no water hammer or high moisture loading along steam lines, insulation and jacketing in good condition, no exposed insulation, all insulation in place with no missing pieces, valve bodies insulated with wire-on jacketing or full insulation.

POOR: Considerable portions of system with deteriorated or no insulation. In the case of direct buried underground lines under grass, discolored grass or dead zones indicating heat loss, no valve bodies insulated.

Expert 7- Heat loss per unit area:

(The convective/conductive heat loss equation for pipes was given but without criteria limits).

PRESSURE REDUCING VALVES:

Expert 6- Visual inspection for leak through and steady reduced pressure:

EXCELLENT: No pulsation of pressure and no leak through of relief valves.

POOR: Constant pulsation of pressure in excess of 5 pounds and constant leaking of valves.

Expert 1- Operability range:

EXCELLENT: 90-100% of design range.

POOR: Less than 75% of design range.

<u>WATER TREATMENT SYSTEM</u>:

FEEDWATER SYSTEM:

Expert 7- Feedwater Quality:

EXCELLENT: 0 hardness, less than .04 PPM oxygen in deaerating heater, less than .007 PPM in spray/tray deaerator.

POOR: Greater than 1 PPM hardness.

Expert 6- Treatment to control scale and corrosion:
EXCELLENT: Within 90% of desired level of ph, phosphate, sulfite, & conductivity.

POOR: Anything below 80% of desired levels.

Expert 5- Inspection of operating logs:
EXCELLENT: Feedwater quality meets the criteria of AFP 91-41 more than 95% of the time.

POOR: Meets the criteria of AFP 91-41 less than 85% of the time.

Expert 2- Visual inspection of feed and transfer pumps, level and control of low water cut off, leaks of piping, valves and fittings:
EXCELLENT: Boiler feed pumps and other pumps in system operate smoothly without cavitation, packing or seals not leaking excessively (sweating less than 3 drops per minute), pump driver operates properly, if pump is variable speed it responds properly to load or pressure variation, level control does not hunt and maintains proper water level in boiler, low water fuel cutout works.

POOR: Feed pumps cavitating heavily, packing or seals leaking profusely, grinding noise from pump or drive bearings, pump drive overheating or electrical problems noticed, level control hunting or not maintaining proper water level, low water fuel cut out not operating.

Expert 4- Visual inspection of softeners, piping, water controllers, and drum levels:
EXCELLENT: No leaks on 95% of feedwater systems.

POOR: 20 % or more of the system shows leaks.

Expert 10- Chemical Levels, inspect chemical records:
EXCELLENT: Levels within set ranges, testing reagents not outdated and tested within standards.

POOR: Levels more than 15% outside of range, over 10% of reagents outdated.

MAKE-UP WATER:

Expert 5- Inspection of operating logs:
EXCELLENT: Make-up water quality meets the criteria of AFP 91-41 more than 95% of the time.

POOR: Meets AFP 91-41 criteria less than 85% of the time.

Expert 6- Visual inspection of make-up lines, meters, and softening equipment:
EXCELLENT: No leaks, meters correct, softeners within established parameters.

POOR: More than 15% away from parameters.

Expert 7- Hardness:
EXCELLENT: 0 PPM.

POOR: Greater than 1 PPM.

Expert 3- Visual inspection, means to add chemicals:
EXCELLENT: Make-up water system should function properly and have provisions to add chemicals including an oxygen scavenger.

POOR: Inadequate or inappropriate chemicals used, unsafe means of mixing or adding.

SOFTENER:

Expert 2- Effluent hardness and HCO3 concentration, condition of resins, operation of controls, general physical condition, external corrosion, adherence to maintenance program:
EXCELLENT: Hardness and HCO3 concentration less than 1 PPM, resin beads clean and free of iron contamination, alkalizer and softener capable of automatic regeneration and backwash, physical condition and general cleanliness of installation good, equipment free of external corrosion, maintenance procedures adhered to.

POOR: Effluent hardness and HCO3 concentration greater than 10 PPM, effluent quality varies with throughout, automatic regeneration mode does not work and regeneration and backwash are controlled manually, physical condition and cleanliness poor, external corrosion much in evidence.

Expert 4- Internal and external inspection:
EXCELLENT: No leaks and internal filter media at manufacturers recommended level and removes all hardness.

POOR: Shows leaks and filter media below 85% of recommended level and removes hardness to less than 90% of the required amount.

Expert 1- Ability to remove hardness:
EXCELLENT: 90% of original design.

POOR: Less than 75% of original design.

Expert 3- Softener should be regenerated as required, zeolite checked annually and replaced when ineffective, area should be clean:
EXCELLENT: Meets above criteria.

POOR: Area poorly maintained, little planning for salt replenishment, softener effectiveness not checked.

BLOWDOWN:

Expert 5- Inspection of water treatment logs:
EXCELLENT: Blowdown is performed such that boiler water impurities are maintained beneath maximum limits 100% of the year.

POOR: Boiler water impurities are maintained beneath limits 90% of the year.

Expert 2- Type of blowdown equipment and condition:
EXCELLENT: Boilers are equipped with continuous surface blowdown with heat recovery, percent continuous blowdown controlled by dissolved solids or silica, physical condition of equipment and controls good, bottom blow minimized and restricted to sludge removed, blowdown separator or cooler installed on bottom blow drain.

POOR: Surface blowdown not fitted to boiler or not used, bottom blow used to control solids or silica exclusively, surface blowdown equipment inoperative.

DEAERATOR:

Expert 5- Water treatment test:

EXCELLENT: Feedwater oxygen content less than .1 PPM or feedwater temp above 212 degrees F, deaerator less than 10 years old.

POOR: Feedwater oxygen greater than .5 PPM, feedwater temp below 212, deaerator greater than 20 years old.

Expert 2- Deaerator performance, condition, installation and control:

EXCELLENT: Water within 2 degrees F of saturation, steam plume visible from deaerator vent,steam supply maintaining pressure in the deaerator shell, good condition inside and out.

POOR: No visible plume from deaerator vent, water in storage section more than 5 degrees below saturation temp, most trays collapsed or spray nozzles plugged, steam supply erratic or no steam supply at all.

Expert 1- Water treatment test (ability to remove oxygen):

EXCELLENT: 90-100% of original design parameters.

POOR: Less than 75% of original design.

PUMPS:

Expert 5- Visual Inspection:

EXCELLENT: Pumps provide adequate flow and pressure with no packing gland or bearing leaks, records indicate normal maintenance.

POOR: Pumps have major difficulties such as inadequate capacity or cavitation, requires continuous maintenance, excessive leaks.

Expert 4- Internal and external inspection for leaks and wear:

EXCELLENT: No leaks or wear.

POOR: Pump delivers below 90% of required volume and pressure.

Expert 1- Vibration Analysis:

EXCELLENT: Less than .0196 in/sec.

POOR: Greater than .0785 in/sec.

BOILERS/STEAM GENERATORS:

CASINGS:

Expert 4- Visual inspection for cracks, leaks, and rust on boiler casings:

EXCELLENT: No cracks, leaks, or rust.

POOR: More than 10% of casing shows leaks, cracks, or rust.

Expert 5- Visual inspection:

EXCELLENT: No corrosion, protective coating in good condition.

POOR: Rust has penetrated casing.

Expert 6- Visual inspection for leaks:

EXCELLENT: 90-95% of casing without leaks or other visible damage.

POOR: More than 20% of area with leaks or other visible damage.

Expert 2- Casing airtightness:

EXCELLENT: Casing and setting airtight.

POOR: Considerable air leakage through casing and setting as evidenced by higher than normal excess air.

TUBES:

Expert 2- Visual inspection:

EXCELLENT: Tube firesides free of soot, water sides free of scale, no evidence of fireside or water side corrosion.

POOR: Heavy scaling or corrosion on waterside.

Expert 6- Visual inspection for corrosion, scale, leaks, or pitting:

EXCELLENT: No corrosion, scale, pitting, or leaks.

POOR: 10-20% corrosion or pitting, any leaks or blisters.

Expert 5- Latest Type A or B Boiler Inspection:
EXCELLENT: No scale, deposits, or leaks noted.

POOR: Moderate scale or deposits noted, more than one tube leaking or damaged.

Expert 4- Visual inspection for scale or corrosion:
EXCELLENT: 95% of tubes clean and free of scale and corrosion.

POOR: Below 85% of tubes clean and free of scale and corrosion.

REFRACTORY:

Expert 4- Visual inspection for leaks and missing bricks:
EXCELLENT: No leaks, visible cracks, or missing bricks.

POOR: More than 10% of area has leaks, cracks, or missing bricks.

Expert 5- Latest Type A or B Boiler Inspection:
EXCELLENT: No damage to refractory noted.

POOR: Major refractory repairs necessary.

Expert 6- Visual inspection for cracked, chipped, or missing bricks:
EXCELLENT: No more than 5% visible damage.

POOR: More than 15% visible damage.

Expert 2- Visual inspection:
EXCELLENT: Refractory free of cracks or spalling.

POOR: Loose or collapsed refractory.

Expert 1- Visual inspection:
EXCELLENT: Less than 10% refractory missing.

POOR: More than 30% refractory missing.

SAFETY DEVICES:

Expert 5- Latest Operational Boiler Inspection-Type C:
EXCELLENT: All safety devices in good condition and operating properly.

POOR: More than one deficiency noted.

Expert 4- Visual inspection, test by hand:
EXCELLENT: Safety works freely when lifted by hand (no other criteria given).

Expert 1- Operational test:
EXCELLENT: Discharges 100% of steam at MCR without exceeding maximum allowable working pressure by more than 6% (no other criteria given).

DRUMS:

Expert 5- Latest Type-B boiler inspection:
EXCELLENT: No deficiencies noted.

POOR: More than one deficiency noted.

Expert 1- Thickness (defines allowable operating pressure):
EXCELLENT: 90-100% of original design pressure.

POOR: Less than 80% of original design pressure.

CONTROLS:

AIR CONTROLS:

Expert 4- Boiler control, internal calibration, control air, firing rate:
EXCELLENT: No air leaks, calibration within 95% of manufacturer specifications.

POOR: Calibration not within 80% calibration and 10% air leakage.

Expert 6- Air control of FD and ID Fans, pressurization of fireboxes:
EXCELLENT: Within 90% of manufacturer specifications.

POOR: Below 80% of manufacturer specifications.

Expert 2- Oxygen trim system operation, calibration, and maintenance:
EXCELLENT: Oxygen trim system installed and operating properly, operators familiar with system, system in good physical condition.

POOR: System not operable or deactivated by personnel.

Expert 7- Tabular data given but without reference. Table refers to type of fuel and control system and specifies tolerances on steam pressure and exhaust oxygen as a percent of setpoint.

Expert 1- Actual CFM rating of ID and FD fans:

EXCELLENT: 90-100% of design capacity.

POOR: Less than 75% of design capacity.

FUEL CONTROLS:

Expert 7- Tabular data given but without reference. Table refers to type of fuel and control system and specifies tolerances on steam pressure and exhaust oxygen as a percent of setpoint.

Expert 6- Visual inspection of fuel and air control lines and components:

EXCELLENT: 85% of manufacturer specifications.

POOR: Below 80% of manufacturer specifications.

Expert 4- Visual inspection of piping, calibration of oxygen analyzer:

EXCELLENT: No external leaks on gas or fuel oil system, combustion efficiency 80-82%

POOR: Some leaks and below 75% combustion efficiency.

Expert 6- Visual inspection for leaks in piping and components, calibration to manufacturer specifications:

EXCELLENT: 80% overall efficiency, oxygen within specifications.

POOR: 75% overall efficiency or oxygen above 5% of specifications.

COMBUSTION/FUEL SYSTEM:

PIPING, VALVES, SAFETY DEVICES:

Expert 2- Visual inspection:

EXCELLENT: Bulk storage facility clean with no spills or leakage, insulation good, underground fuel piping has working cathodic protection, valves in working order, maintenance schedules met, pressure reducers and safeties installed and working properly.

POOR: Bulk storage physical condition is poor, considerable leakage or gas odor present, no safety devices or improperly installed,no cathodic protection, condition of valves and valve operators questionable, fuel meters inoperative or out of calibration.

Expert 4- Visual inspection of all piping and pumps:

EXCELLENT: No leaks on any system (no other criteria given).

Expert 5- Fuel-metering Valves (latest annual inspection records),Fuel-pressure Safety Valves (latest inspection):

EXCELLENT: No deficiencies noted for metering valves, safety valves operate properly and reliably.

POOR: Metering valves require more than minor repairs, safety valves require frequent adjustments.

Expert 3- Visual inspection:

EXCELLENT: Piping properly insulated and supported.

POOR: Insulation damaged, temperature severely affected, pipeline not properly supported.

COMBUSTION FANS/DAMPERS & LINKAGES:

Expert 5- Latest annual inspection and Boiler logs:

EXCELLENT: Proper adjustment, average combustion efficiency within 2% of optimum or average stack % of oxygen within 0.5% of optimum.

POOR: Avg combustion efficiency 5% off optimum or average stack % oxygen more than 1% from optimum.

Expert 2- Visual inspection:

EXCELLENT: Fans and drives operate free of vibration and bearings not excessively heated, fans drivers and dampers in good physical condition, fan blades free of dust and foreign matter, lubrication program in effect and being followed, dampers and linkages in proper adjustment with no slop, proper draft and furnace pressure being maintained.

POOR: Moderate to severe vibrations of fans and drivers, variable speed drive not operating, dampers inoperative or wired open, heavy dust accumulations on fan blades, air-fuel mixture out of control, furnace pressure out of control, lubrication schedule not followed.

Expert 3- Visual inspection of FD and ID fans:

EXCELLENT: Variable speed fans, fan inlet dampers, or damper trim controls installed to optimize excess air flow through boiler, fans and dampers in good condition without excess noise and vibration.

POOR: Little or no fan speed control, sloppy linkage, corroded fans and housings, breaching corroded/leaking.

BURNERS AND ATOMIZERS:

Expert 5- Visual inspection:

EXCELLENT: Flame pattern is uniform and stack carbon dioxide content is within 1% of optimum, flame color is correct.

POOR: Flame pattern is irregular, flame color is incorrect, stack carbon dioxide content is more than 2% from optimum.

Expert 2-Visual inspection:

EXCELLENT: Flame programmer operates in proper sequence, igniter operates properly, proper fuel-air mixture maintained across boiler operating range, fuel oil delivered to burner at proper pressure and temperature, swirl vanes properly adjusted, burner hardware and auxiliaries in good physical condition.

POOR: Flame programmer does not operate properly, air flow switch fails to lock out ignition sequence or burner operation, fuel-air mixture too lean indicated by carbon monoxide formation or sooting, oil impinging on and igniting on refractory, high stack temperatures at normal firing rates (700 F for gas, 850F for fuel oil).

Expert 3- Visual inspection:

EXCELLENT: Flame is properly shaped for the firebox without impingement on back wall, tips are changed periodically for cleaning.

POOR: Flame impinges on back wall, evidence of improper atomization.

OIL PUMPS AND AUXILIARIES:

Expert 4- Visual inspection:

EXCELLENT: No leaks (no further criteria).

Expert 2- Physical condition of pumps and auxiliaries:

EXCELLENT: Pumps and auxiliaries are available to operate as needed, replacement parts such as strainer baskets are on hand.

POOR: One or more transfer pumps are out of service, gages and other accessories are not operable, dangerous conditions prevail around tanks and equipment.

OIL TANKS:

Expert 3- Visual inspection:

EXCELLENT: Fuel tank should be well insulated (with heating coil for #6 fuel). Tanks should be periodically cleaned to remove sludge and build up on heating coil.

POOR: Tank not clean, fuel shows sludge contamination, coil temperature control malfunctioning.

Expert 2- Visual inspection:

EXCELLENT: Tankage is leak tight. Off-loading pumps are operating, tested, and inspected regularly. Tank heaters and controls (heavy oils) operating, spill reporting and other environmental rules observed.

POOR: Tank capacity reduced because of leakage, one or more transfer pumps out of service, tank heating system inoperable.

Expert 3- Dike Installation:

EXCELLENT: Dike should contain contents of tank plus one foot and should have a drain system for water removal. Construction may be earth covered with 3" impervious clay covered with 6" sand and 8" crushed stone, or covered with 3" of concrete or with 2" impervious asphalt with rubberized coal tar seal.

POOR: Dike not properly sized, incorrect materials, or material condition poor.

GRATES:

Expert 10- Operational check:

EXCELLENT: Overhauled annually, no opacity violations due to malfunctions.

POOR: No criteria given.

Expert 1- Visual inspection for cracks in grate clips:

EXCELLENT: Less than 10% of grate area has cracks.

POOR: More than 30% of grate area has cracks.

STOKER:

Expert 1- Coal feed mechanism ability to adjust from lowest to maximum operating capacity:

EXCELLENT: 90-100% of full range.

POOR: Less than 75% of full range.

Expert 10- Coal feed system operation, maintenance:

EXCELLENT: Overhauled annually, no opacity violations due to stoker malfunction, lubrication on schedule.

CONVEYERS:

Expert 10- Visual inspection for wear and alignment of belts/rollers:

EXCELLENT: Belts in good shape, worn belts scheduled for time to be replaced, belts aligned and no sign of wear due to misalignment, all rollers working.

POOR: No criteria given.

Expert 1- Number of splices on belt conveyers:

EXCELLENT: 0-1 splice.

POOR: 4-5 splices.

EMISSION CONTROL:

DUST COLLECTION EQUIPMENT:

Expert 2- Visual inspection of physical condition, particulate removal performance, gas tightness, adherence to maintenance program:

EXCELLENT: Stack gas particulate loading meets or is less than allowable concentration, dust collection system is free of flue gas leaks, particulate removal system operates properly with no leakage of recovered particulates, physical condition good, maintenance program followed.

POOR: Particulate concentration in stack gas exceeds local standards, dust collection system inoperative or bypassed for long periods, noticeable flue gas leakage, particulate removal system difficult to operate and leaks measurable dust into plant environment, only emergency maintenance performed.

Expert 10- Vacuum operation:

EXCELLENT: Operates with one ash pump, no leaking joints, no visual spills around system piping.

POOR: No criteria given.

Expert 10- Visual inspection of receiver/bag house:

EXCELLENT: No leaking from receiver, no dust from pump exhaust.

POOR: No criteria given.

Expert 10- Visual inspection of ash unloader:
EXCELLENT: Unloader operates without dusting.

POOR: No criteria given.

Criteria Summary
High Temperature Hot Water Systems

DISTRIBUTION SYSTEM:

BALANCED FLOW WITH BOILER:

Expert 10- Monitor on flow recorders:

EXCELLENT: HTHW boiler has range to handle flow going out to system, blending valves should be in full open positions.

POOR: No criteria given.

CONVERTERS:

Expert 3- Visual inspection of utility room converters:

EXCELLENT: Converter and piping/valving to it should be properly insulated, valves not leaking, control valves operable and not leaking, pressure and temperature indicators working.

POOR: Leaks in valving and control valves, insulation deteriorated, broken pressure/temperature indicators.

Expert 10- Visual inspection of converters:

EXCELLENT: No leaking tube bundles.

POOR: No criteria given.

INSULATION:

Expert 10- Visual inspection:

EXCELLENT: All distribution lines with insulation and protective coverings.

POOR: No criteria given.

CORROSION CONTROL/LOCATION:

Expert 10- Visual inspection:

EXCELLENT: Protective covering in place. No way to check underground lines.

POOR: No criteria given.

CONDUIT:

Expert 3- Visual inspection to insure drain plugs and steam vents are open and vent piped outside so steam leakage is visible:

Excellent: No steam visible from vent and no drainage from drain opening.

POOR: Steam continuously venting and hot water dripping from conduit drain. Will not hold a pressure test.

MANHOLES:

Expert 3- Visual inspection:

EXCELLENT: Manholes don't steam during rainy weather, sump pumps operable and insulation intact.

POOR: Manholes steam heavily during wet periods and continue beyond rainy period, sump pumps have high failure rate, insulation is falling off or missing.

VALVES:

Expert 3- Visual inspection:

EXCELLENT: Valves function smoothly without bonnet leaks, no leakage through valve seats during system shut down.

POOR: Stiff operation, steam leaking from bonnet, valve doesn't hold completely during shut down.

SUPPLY PUMPS:

Expert 3- Visual inspection:

EXCELLENT: Pumps operate without: seal leaks, vibration due to improper coupling alignment, and cavitation noises due to improper design or control of flow to the suction.

POOR: Pumps drip heavily and vibrate due to coupling problems, evidence of cavitation.

<u>CONTROLS</u>:

CONTROL DRIVE UNITS:

Expert 10- Visual inspection:

EXCELLENT: All control drive units operational with workable locking devices.

POOR: No criteria given.

SAFETY TRIPS:

Expert 10- Visual inspection:
EXCELLENT: Trip at settings (checked each time air taken off line.

POOR: No criteria given.

AUTO/MANUAL STATIONS:

Expert 10- Visual inspection:
EXCELLENT: Working fully, all gauges operational, no broken covers.

POOR: No criteria given.

CONTROLLERS:

Expert 10- Visual inspection:
EXCELLENT: Entire system operating properly, no opacity violations due to control problems.

POOR: No criteria given.

GAUGES:

Expert 10- Calibration:
EXCELLENT: All gauges working and calibrated on schedule.

POOR: No criteria given.

CENTRAL DATA GATHERING:

Expert 3- Visual inspection:
EXCELLENT: Central data gathering system should read system operating/control parameters, make required calculations and feed back results in visual/graphical form and hard copy for immediate correction or permanent records.

POOR: Data is questionable, operators work from data gathered manually, frequent down time.

SENSORS:

Expert 3- Visual inspection:

EXCELLENT: Sensors sense operating parameters accurately and transmit signals to the central data system.

POOR: Sensors not accurate, operation of the plant is manual with logged data questionable.

MASTER CONTROLLER:

Expert 3- Visual inspection:

EXCELLENT: Master controller properly adjusts individual boiler firing parameters to balance loads between individual boilers.

POOR: Boilers are hand fired.

INDIVIDUAL BOILER CONTROLLER:

Expert 3- Visual inspection:

EXCELLENT: Boiler controllers automatically adjust firing rate to meet system needs as balanced by master controller.

POOR: Sensor systems not calibrated, unit is hand fired.

HTHW GENERATING SYSTEM:

BOILER PRESSURE COMPONENTS:

Expert 10- Hydrostatic test:

EXCELLENT: Boiler inspections are updated and report is satisfactory, boilers shifted for equal operating hours.

POOR: No criteria given.

Expert 3- Visual inspection of boiler tubes, insulation, metal components:

EXCELLENT: Boiler is annually taken down, cleaned, and inspected. Joints in breaching, horizontal sections, and transitions at fans are cleaned to reduce corrosion, stainless steel stacks are installed.

POOR: Boiler has deficiencies identified by Hartford inspector, improper firing rates, and corrosion.

DRUM:

Expert 3- Visual inspection:

EXCELLENT: Drum has sound welds inside and out, is properly insulated, and has all safety devices and gauges functioning properly. Adequate catwalks provided.

POOR: Insulation deteriorated, gauge glasses opaque from dirt build up, temperature and pressure indicators inoperative, insufficient catwalks for maintenance.

VALVES:

Expert 3- Visual inspection:

EXCELLENT: Valves properly located with no bonnet or flange leaks, valves seat properly.

POOR: Inadequate valving, leaks.

<u>DRAINAGE SYSTEM</u>: No criteria given.

Appendix C: Summary of Delphi Survey Responses

TABLE 1

ROUND ONE RELATIVE RESPONSES FOR STEAM PLANT MAJOR SYSTEMS

System	Relative Responses								AVG	SD
Distribution	.05	.08	.29	.16	.18	.16	.10	.14	.15	.07
Water Treatment	.14	.16	.26	.18	.20	.23	.24	.17	.20	.04
Control	.10	.21	.16	.16	.20	.19	.12		.16	.04
Steam Generation	.29	.20	.24	.22	.18	.21	.34	.24	.24	.05
Combustion/Fuels	.24	.20	.14	.22	.21	.24	.28		.22	.04
Emission Controls	.19	.14							.17	.03
Electrical	.14								.14	.00

TABLE 2

ROUND ONE RELATIVE RESPONSES FOR STEAM DISTRIBUTION SYSTEM

Component	Relative Responses							AVG	SD
Condensate piping	.28	.26	.23	.27	.37	.21		.27	.05
Steam Traps	.22	.21	.20	.21	.32			.23	.04
Condensate Pumps	.19	.21	.21	.32				.23	.05
Supply Piping	.17	.26	.40	.27	.33	.21	.30	.28	.07
Pressure Reducing	.24	.36						.30	.06
Pipe Insulation	.14	.30	.15					.20	.07
Valves	.21	.30	.16	.12				.20	.07
Pits	.08	.10						.09	.01
Cathodic Protect	.26							.26	.00
Regulators	.19							.19	.00

TABLE 3

ROUND ONE RELATIVE RESPONSES FOR STEAM WATER TREATMENT SYSTEM

Component	Relative Responses					AVG	SD
Makeup Water Sys	.29	.25	.50			.35	.11
Feedwater Sys	.36	.25	.50	.30	.20	.32	.10
Softner	.40	.26	.29	.33	.28	.31	.05
Chemical Feed Sys	.30	.16	.23			.23	.06
Deaerator	.20	.18	.62	.27	.32	.32	.16
Pumps	.29	.24	.38	.40		.33	.07
WaterTest Abil	.33					.33	.00
Blowdown	.36	.10	.17			.21	.11
Condensate Qalty	.25					.25	.00
Condutivity	.25					.25	.00
Piping	.15	.24				.20	.04
Controls	.26					.26	.00
Regulators	.26					.26	.00

TABLE 4

ROUND ONE RELATIVE RESPONSES FOR STEAM GENERATION SYSTEM

Component	Relative Responses					AVG	SD
Boiler Effcy	1.00					1.00	.00
Casing	.23	.34	.06	.23	.33	.24	.10
Tubes	.25	.26	.34	.33	.31	.30	.04
Refractory	.13	.26	.31	.33	.17	.24	.08
Safety Devices	.25	.26	.35			.29	.04
Drums	.31	.38				.34	.04
Steam Separator	.27					.27	.00
Furnace Section	.28					.28	.00
AirHeater Section	.25					.25	.00

TABLE 5

ROUND ONE RELATIVE RESPONSES FOR STEAM CONTROL SYSTEM

Component	Relative Responses				AVG	SD
Air Controls	.50	.13	.32	.32	.32	.13
Fuel Controls	.50	.32	.32	.50	.41	.09
P,T Indicators	.33				.33	.00
Gas Analyzers	.27				.27	.00
All Sensors	.15	.32	.29		.25	.07
All Actuators	.15	.28	.21		.21	.05
All Limit Cntrols	.24				.24	.00
Fuel,Water Meters	.20				.20	.00
Log Maintenance	.07				.07	.00
All Transmitters	.15				.15	.00
Central Logic Sys	.30	.40	.24		.31	.07
Feedwater Contrls	.36				.36	.00

TABLE 6

ROUND ONE RELATIVE RESPONSES FOR GAS AND OIL COMBUSTION/FUEL SYSTEM

Component	Relative Responses						AVG	SD
Piping/Auxiliaris	.40	.50	.34	.50	.14	.16	.34	.15
Fans/Dampers	.33	.24	.10	.30	.19		.23	.08
Burner/Atomizer	.33	.20	.28	.19			.25	.06
Oil Tanks	.30	.16					.23	.07
Oil Pumps/Auxils	.20	.31					.26	.05
Fuel Regulators	.34	.19					.27	.08
Flame&Flow Sensor	.21						.21	.00
Fuel Meters	.10						.10	.00
Diked Storage	.16						.16	.00

TABLE 7

ROUND ONE RELATIVE RESPONSES FOR COAL COMBUSTION/FUEL SYSTEM

Component	Relative Responses					AVG	SD
Fans/Dampers	.33	.24	.10	.30	.19	.23	.08
Stoker	.21	.33				.27	.06
Grates	.28	.33				.31	.02
Coal Pile	.14					.14	.00
Coal Handling	.21	.34				.28	.06
Hoppers	.19	.18				.18	.01
Overfire Air	.21					.21	.00
Coal Drive Motors	.33					.33	.00
Belt Conveyers	.33	.23				.28	.05
Conveyer Chains	.33					.33	.00
Coal Transfer Cnt	.20					.20	.00
Superstructure	.16					.16	.00
Scrapper, Rails	.23					.23	.00

TABLE 8

ROUND ONE RELATIVE RESPONSES FOR EMISSION CONTROL SYSTEM

Component	Relative Responses		AVG	SD
Stack&Breaching	.50	.19	.34	.16
Waste Heat Recvry	.33	.16	.24	.09
Dust Collection	.17	.25	.21	.04
ElectrostaticPrcp	.25		.25	.00
Vacuum Operation	.25		.25	.00
Ash Unloader	.25		.25	.00
Opacity Sensors	.21	.14	.17	.04
O2/CO2 Sensors	.21	.28	.24	.04

TABLE 9

ROUND ONE RELATIVE RESPONSES FOR ELECTRICAL SYSTEM

Component	Relative Responses	AVG	SD
Back-up Generator	.37	.37	.00
Breakers	.33	.33	.00
Motor Starters	.30	.30	.00

TABLE 10

ROUND ONE RELATIVE RESPONSES FOR HTHW MAJOR SYSTEMS

System	Relative Responses		AVG	SD
Distribution	.18	.09	.14	.04
Controls	.20	.14	.17	.03
Combustion/Fuel	.20	.16	.18	.02
HTHW Generation	.20	.16	.18	.02
Water Treatment	.10	.16	.13	.03
Emission Control	.09		.09	.00
Drainage System	.06		.06	.00
PressurizationSys	.14		.14	.00

TABLE 11

ROUND ONE RELATIVE RESPONSES FOR HTHW DISTRIBUTION SYSTEM

Component	Relative Responses		AVG	SD
Piping	.21		.21	.00
Supply Pumps	.19		.19	.00
Converters	.17	.26	.22	.04
Balanced Flow	.29		.29	.00
Corrosion Control	.23		.23	.00
Manholes	.24		.24	.00
Valving	.19		.19	.00
Insulation	.23		.23	.00

TABLE 12

ROUND ONE RELATIVE RESPONSES FOR HTHW CONTROL SYSTEM

Component	Relative Responses		AVG	SD
Sensors	.22		.22	.00
Master Cntroller	.28	.18	.23	.05
Boiler Cntroller	.28		.28	.00
Safety Trips	.22		.22	.00
Cntrl Data/Gages	.22	.18	.20	.02
Cntl Drive Units	.22		.22	.00
Auto/Man Stations	.20		.20	.00

TABLE 13

ROUND ONE RELATIVE RESPONSES FOR HTHW GENERATION SYSTEM

Component	Relative Responses		AVG	SD
Casing & Tubes	.36	.33	.34	.02
Drums	.32		.32	.00
Valving	.32		.32	.00
Press Cmpts/Safty	.33		.33	.00
Lay-up Capability	.33		.33	.00

TABLE 14

ROUND ONE RELATIVE RESPONSES FOR HTHW DRAINAGE SYSTEM

Component	Relative Responses	AVG	SD
Bleed System	.26	.26	.00
Blowdown	.26	.26	.00
Flash Tanks	.16	.16	.00
Sump Pumps	.16	.16	.00
Clarifier	.16	.16	.00

TABLE 15

ROUND TWO EXPERT RESPONSE SUMMARY FOR STEAM MAJOR SYSTEMS

Total agreed	System	Response by Expert ID Number									AVG	SD	Consensus
		1	2	3	4	5	6	7	8	10			
9	Distribution	6	5	8	7	6	7	9	8	7	7	1.2	YES
9	Water Treatment	7	8	7	9	8	9	9	9	10	8.4	1	YES
8	Control	8	7	8	6	9	6	8	8		7.5	1	YES
9	Steam Generation	10	10	10	10	10	10	10	10	9	9.9	0.3	YES
9	Combustion/Fuels	8	9	9	8	10	8	9	9	9	8.8	0.6	YES
5	Stacks/Emissions		6	7		7		7		10	7.4	1.4	NO
6	Electrical		6	6	6	6	6	7			6.2	0.4	NO

TABLE 16

ROUND TWO EXPERT RESPONSE SUMMARY FOR STEAM DISTRIBUTION SYSTEM

Total agreed	Component	Response by Expert ID Number 1	2	3	4	5	6	7	8	10	AVG	SD	Consensus
8	Condensate piping	6		9	10	9	10	10	10	9	9.1	1.3	YES
5	Supply Pipe Insul				6		6	8	6	8	6.8	1	NO
9	Steam Traps	7	8	9	8	7	8	9	9	8	8.1	0.7	YES
9	Condensate Pumps	7	7	8	10	6	10	8	8	9	8.1	1.3	YES
9	Supply Piping	8	10	7	9	10	9	9	10	9	9	0.9	YES
6	Valves	8	7	9		10			6	7	7.8	1.3	NO
1	Pits		3								3	0	NO
4	Cathod Protection			8		9		9	7		8.3	0.8	NO
5	Regulators	7	9		8	8	8				8	0.6	NO
7	Pressure Reducing	8	9	10	8		3	9		10	8.9	0.8	YES

TABLE 17

ROUND TWO EXPERT RESPONSE SUMMARY FOR STEAM WATER TREATMENT SYSTEM

Total agreed	Component	Response by Expert ID Number 1	2	3	4	5	6	7	8	10	AVG	SD	Consensus
9	Make-up Water Sys	9	10	10	10	8	10	10	10	10	9.7	0.7	YES
9	Feedwater Sys	10	9	8	9	7	9	10	8	10	8.9	1	YES
5	Blowdown	6	8	6		9			6		7	1.3	NO
6	Condensate Qualty		7	7	7	8	7	9			7.5	0.8	NO
2	Conductivity		7					7			7	0	NO
9	Softner	7	8	9	9	10	9	9	9	9	8.8	0.8	YES
9	Chemical Feed Sys	7	9	8	8	10	8	9	9	9	8.6	0.8	YES
8	Deaerator	8	9	9	9	10	9	10	8		9	0.7	YES
4	Piping		6		8	5	8				6.8	1.3	NO
7	Pumps	9	10		10	6	10	7	7		8.4	1.6	YES
6	Controls	7		7	9		9	8		8	8	0.8	NO
0	Regulators										ERR	ERR	NO
8	WaterTest Ability	6		10	10	10	10	10	8	10	9.3	1.4	YES

TABLE 18

ROUND TWO EXPERT RESPONSE SUMMARY FOR STEAM GENERATION SYSTEM

Total agreed	Component	Response by Expert ID Number 1	2	3	4	5	6	7	8	10	AVG	SD	Consensus
7	Boiler Efficiency			10	10	9	10	10	9	10	9.7	0.5	YES
7	Casing	6	7	7	7			7	8	9	7.3	0.9	YES
9	Tubes	9	10	9	9	9	9	9	10	10	9.3	0.5	YES
9	Refractory	7	8	6	8	7	8	7	7	9	7.4	0.8	YES
9	Safety Devices	10	9	8	10	10	10	9	8	10	9.3	0.8	YES
8	Drums	9	10		10	10	10	9	8	9	9.4	0.7	YES
6	Steam Separator	8	7		8	8	8	7			7.7	0.5	NO
5	Furnace Section	7	8			8	8		10		8.2	1	NO
1	AirHeater Section			6							6	0	NO

TABLE 19

ROUND TWO EXPERT RESPONSE SUMMARY FOR STEAM CONTROL SYSTEM

Total agreed	Component	Response by Expert ID Number 1	2	3	4	5	6	7	8	10	AVG	SD	Consensus
8	Air Controls	9	9	10	10	10	10	7	9		9.3	1	YES
8	Fuel Controls	10	10	10	10	10	10	9	10		9.9	0.3	YES
8	P,T Indicators	8	9	7	8	6	8	8		8	7.8	0.8	YES
7	Gas Analyzers	7	7		7		7	6	6	9	7	0.9	YES
4	Fl,Stm,H2O Meters	7	7	7					5		6.5	0.9	NO
1	Log Maintenance								4		4	0	NO
8	All Sensors	7		8	8	8	8	6	7	7	7.4	0.7	YES
6	All Transmitters	7		8	8	8	8			9	8	0.6	NO
3	Logic/Controllers			7		7		7			7	0	NO
8	All Actuators	8		9	10	9	10	9	9	10	9.3	0.7	YES
8	All Limit Cntrols	7	8	6	8	7	8	7	5		7	1	YES
6	Feedwater Cntrols		10		9	9	9	9	8		9	0.6	NO

TABLE 20

ROUND TWO EXPERT RESPONSE SUMMARY FOR GAS AND OIL COMBUSTION/FUEL SYSTEM

Total agreed	Component	Response by Expert ID Number 1	2	3	4	5	6	7	8	10	AVG	SD	Consensus
9	Piping/Auxiliaris	10	10	9	10	10	10	10	10	10	9.9	0.3	YES
9	Fans/Dampers	8	9	9	8	9	8	7	9	8	8.3	0.7	YES
9	Burner/Atomizer	8	9	10	8	8	8	7	9	7	8.2	0.9	YES
7	Oil Tanks	6		7	7	5	7	7	6		6.4	0.7	YES
8	Oil Pumps/Auxils	9	7	8	7	6	7	8	6		7.3	1	YES
2	Fuel Meters	6	5								5.5	0.5	NO
9	Fuel Regulators	9	7	6	9	7	9	8	8	8	7.9	1	YES
0	Diked Storage										0.0	0.0	NO
8	Flame&Flow Sensor		10	8	10	9	10	6	8	8	8.6	1.3	YES

TABLE 21

ROUND TWO EXPERT RESPONSE SUMMARY FOR COAL COMBUSTION/FUEL SYSTEM

Total agreed	Component	Response by Expert ID Number 1	2	3	4	5	6	7	8	10	AVG	SD	Consensus
7	Fans/Dampers	9		8	10	9	10	7	10		9	1.1	YES
2	Coal Pile	6							8		7	1	NO
5	Coal Handling	9		7				8	7	8	7.8	0.7	NO
5	Hoppers	6				6		6	7	5	6	0.6	NO
8	Stoker	10		9	8	8	8	8	8	9	8.5	0.7	YES
8	Grates	7		10	9	9	9	9	9	9	8.9	0.8	YES
4	Overfire Air	8			7	7	7				7.3	0.4	NO
6	Coal Drive Motors				10	10	10	10	7	10	9.5	1.1	NO
5	Belt Conveyers			7		8		8	8	10	8.2	1	NO
4	Bucket Cnv Chains			8		10		10	8		9	1	NO
4	Coal Trans Contrl					6		6	6	9	6.8	1.3	NO
0	Superstructure										0.0	0.0	NO
5	Scrapper,SideRail				7	7	7	7		6	6.8	0.4	NO

TABLE 22

ROUND TWO EXPERT RESPONSE SUMMARY FOR
EMISSION CONTROL SYSTEM

Total agreed	Component	Response by Expert ID Number									AVG	SD	Consensus
		1	2	3	4	5	6	7	8	10			
5	Stacks/Breaching		10			10		10	10	8	9.6	0.8	NO
5	Waste Heat Recvry		7			6		7	4	7	6.2	1.2	NO
4	Dust Collection					7		6	6	7	6.5	0.5	NO
4	ElectrostaticPrcp					8		7	9	10	8.5	1.1	NO
3	Vacuum Operation							7	6	7	6.7	0.5	NO
4	Ash Unloader					8		7	8	7	7.5	0.5	NO
5	Opacity Sensors		8			7		6	6	10	7.4	1.5	NO
5	O2/CO2 Sensors		9			9		7	8	7	8	0.9	NO

TABLE 23

ROUND TWO EXPERT RESPONSE SUMMARY FOR
ELECTRICAL SYSTEM

Total agreed	Component	Response by Expert ID Number									AVG	SD	Consensus
		1	2	3	4	5	6	7	8	10			
5	Back-up Generator				10	10	10	10		10	10	0	NO
5	Breakers				9	8	9	9		10	9	0.6	NO
5	Motor Startors				8	9	8	8		9	8.4	0.5	NO

TABLE 24

ROUND TWO EXPERT RESPONSE SUMMARY FOR HTHW
MAJOR SYSTEMS

Total agreed	System	Response by Expert ID Number									AVG	SD	Consensus
		1	2	3	4	5	6	7	8	10			
9	Distribution	7	8	8	8	8	8	9	8	10	8.2	0.8	YES
9	Controls	8	9	9	9	9	9	9	9	9	8.9	0.3	YES
9	Combustion/Fuel	9	10	9	10	10	10	10	10	10	9.8	0.4	YES
8	HTHW Generation	10	10	10	10	10	10	10		10	10	0	YES
5	Water Treatment	7				8		9	8	10	8.4	1	NO
1	Emission Control								8		8	0	NO
0	Drainage System										0.0	0.0	NO
4	PressurizationSys		8	8	10		10				9	1	NO

TABLE 25

ROUND TWO EXPERT RESPONSE SUMMARY FOR HTHW DISTRIBUTION SYSTEM

Total agreed	Component	Response by Expert ID Number 1	2	3	4	5	6	7	8	10	AVG	SD	Consensus
7	Piping	7	10		8	9	8	7	9		8.3	1	YES
3	Manholes	7		8					5		6.7	1.2	NO
5	Valving	9	8	7		8		7			7.8	0.7	NO
9	Supply Pumps	10	8	8	7	9	7	7	7	7	7.8	1	YES
8	Converters	8	7	9	8	7	8	7		8	7.8	0.7	YES
8	Balanced Flow		9	10	10	10	10	9	10	10	9.8	0.4	YES
6	Insulation			7	8		8	9	8	8	8	0.6	NO
8	Corrosion Control	6	7		8	8	8	9	9	8	7.9	0.9	YES

TABLE 26

ROUND TWO EXPERT RESPONSE SUMMARY FOR HTHW CONTROL SYSTEM

Total agreed	Component	Response by Expert ID Number 1	2	3	4	5	6	7	8	10	AVG	SD	Consensus
5	Cntrl Data/Gages	8	8	7	8		8				7.8	0.4	NO
7	Sensors	8		8	9	8	9	8	8		8.3	0.5	YES
9	Master Cntroller	7	8	9	8	9	8	8	9	8	8.2	0.6	YES
9	Boiler Cntroller	10	10	10	10	10	10	9	10	8	9.7	0.7	YES
5	Cntl Drive Units		7	8		8		9		10	8.4	1	NO
8	Safety Trips	9	9		10	10	10	9	8	10	9.4	0.7	YES
2	Auto/Man Stations								6	10	8	2	NO

TABLE 27

ROUND TWO EXPERT RESPONSE SUMMARY FOR HTHW GENERATION SYSTEM

Total agreed	Component	Response by Expert ID Number 1	2	3	4	5	6	7	8	10	AVG	SD	Consensus
9	Casing & Tubes	9	9	10	10	9	10	10	10	10	9.7	0.5	YES
9	Drums	10	9	8	9	10	9	9	8	10	9.1	0.7	YES
9	Valving	8	8	8	9	8	9	9	7	10	8.4	0.8	YES
9	Press Cmpts/Safty	9	10	9	10	9	10	9	9	10	9.4	0.5	YES
7	Lay-up Capability			7	9	5	9	9	5	10	7.7	1.9	YES

TABLE 28

ROUND TWO EXPERT RESPONSE SUMMARY FOR HTHW DRAINAGE SYSTEM

Total agreed	Component	1	2	3	4	5	6	7	8	10	AVG	SD	Consensus
		Response by Expert ID Number											
6	Bleed System				10	10	10	10	8	10	9.7	0.7	NO
7	Blow Down			10	10	10	10	10	10	9	9.9	0.3	YES
6	Flash Tanks				6	6	6	7	6	6	6.2	0.4	NO
7	Sump Pumps			8	6	6	6	7	7	7	6.7	0.7	YES
6	Clarifier				6	6	6	7	4	6	5.8	0.9	NO

TABLE 29

ROUND TWO RELATIVE RESPONSE ON CONSENTED SYSTEMS FOR STEAM MAJOR SYSTEMS

System	1	2	3	4	5	6	7	8	10	AVG	SD
	Relative Response by Expert ID Number										
Distribution	.15	.13	.19	.17	.14	.17	.20	.18	.20	.17	.02
Water Treatment	.18	.21	.17	.23	.19	.23	.20	.20	.29	.21	.03
Control	.21	.18	.19	.15	.21	.15	.18	.18	.00	.16	.06
Steam Generate	.26	.26	.24	.25	.23	.25	.22	.23	.26	.24	.01
Combustion/Fuel	.21	.23	.21	.20	.23	.20	.20	.20	.26	.22	.02

TABLE 30

ROUND TWO RELATIVE RESPONSE ON CONSENTED COMPONENTS FOR STEAM DISTRIBUTION SYSTEM

Component	1	2	3	4	5	6	7	8	10	AVG	SD
	Relative Response by Expert ID Number										
Condensate pipe	.17	.00	.21	.22	.28	.22	.22	.27	.20	.20	.08
Steam Traps	.19	.24	.21	.18	.22	.18	.20	.24	.18	.20	.02
Condensate Pump	.19	.21	.19	.22	.19	.22	.18	.22	.20	.20	.02
Supply Piping	.22	.29	.16	.20	.31	.20	.20	.27	.20	.23	.05
Pressure Reduc	.22	.26	.23	.18	.00	.18	.20	.00	.22	.17	.09

TABLE 31

ROUND TWO RELATIVE RESPONSE ON CONSENTED COMPONENTS FOR STEAM WATER TREATMENT SYSTEM

Component	Relative Response by Expert ID Number									AVG	SD
	1	2	3	4	5	6	7	8	10		
Makeup Water Sys	.16	.18	.19	.15	.13	.15	.15	.17	.21	.17	.02
Feedwater Sys	.18	.16	.15	.14	.11	.14	.15	.14	.21	.15	.03
Softner	.13	.15	.17	.14	.16	.14	.14	.15	.19	.15	.02
Chem Feed Sys	.13	.16	.15	.12	.16	.12	.14	.15	.19	.15	.02
Deaerator	.14	.16	.17	.14	.16	.14	.15	.14	.00	.13	.05
Pumps	.16	.18	.00	.15	.10	.15	.11	.12	.00	.11	.06
WaterTest Abil	.11	.00	.19	.15	.16	.15	.15	.14	.21	.14	.06

TABLE 32

ROUND TWO RELATIVE RESPONSE ON CONSENTED COMPONENTS FOR STEAM GENERATION SYSTEM

Component	Relative Response by Expert ID Number									AVG	SD
	1	2	3	4	5	6	7	8	10		
Boiler Effcy	.00	.00	.25	.19	.20	.21	.20	.18	.18	.16	.09
Casing	.15	.16	.17	.13	.00	.00	.14	.16	.16	.12	.06
Tubes	.22	.23	.23	.17	.20	.19	.18	.20	.18	.20	.02
Refractory	.17	.18	.15	.15	.16	.17	.14	.14	.16	.16	.01
Safety Devices	.24	.20	.20	.19	.22	.21	.18	.16	.18	.20	.02
Drums	.22	.23	.00	.19	.22	.21	.18	.16	.16	.17	.07

TABLE 33

ROUND TWO RELATIVE RESPONSE ON CONSENTED COMPONENTS FOR STEAM CONTROL SYSTEM

Component	Relative Response by Expert ID Number									AVG	SD
	1	2	3	4	5	6	7	8	10		
Air Controls	.16	.21	.20	.16	.20	.16	.13	.20	.00	.16	.06
Fuel Controls	.18	.23	.20	.16	.20	.16	.17	.22	.00	.17	.06
P,T Indicators	.14	.21	.14	.13	.12	.13	.15	.00	.24	.14	.06
Gas Analyzers	.13	.16	.00	.11	.00	.11	.12	.13	.26	.11	.08
All Sensors	.13	.00	.16	.13	.16	.13	.12	.15	.21	.13	.05
All Actuators	.14	.00	.18	.16	.18	.16	.17	.20	.29	.17	.07
All Limit Cntls	.13	.19	.12	.13	.14	.13	.13	.11	.00	.12	.05

TABLE 34

ROUND TWO RELATIVE RESPONSE ON CONSENTED COMPONENTS
FOR GAS AND OIL COMBUSTION/FUEL SYSTEM

Component	Relative Response by Expert ID Number									AVG	SD
	1	2	3	4	5	6	7	8	10		
Piping/Auxil	.20	.19	.16	.17	.19	.17	.19	.18	.24	.19	.02
Fans/Dampers	.16	.17	.16	.14	.17	.14	.13	.16	.20	.16	.02
Burner/Atomizer	.16	.17	.18	.14	.15	.14	.13	.16	.17	.15	.02
Oil Tanks	.12	.00	.12	.12	.09	.12	.13	.11	.00	.09	.05
Oil Pumps/Auxil	.18	.13	.14	.12	.11	.12	.15	.11	.00	.12	.05
Fuel Regulators	.18	.13	.11	.15	.13	.15	.15	.14	.20	.15	.03
Flame&Flow Sens	.00	.19	.14	.17	.17	.17	.11	.14	.20	.14	.06

TABLE 35

ROUND TWO RELATIVE RESPONSE ON CONSENTED COMPONENTS
FOR COAL COMBUSTION/FUEL SYSTEM

Component	Relative Response by Expert ID Number									AVG	SD
	1	2	3	4	5	6	7	8	10		
Fans/Dampers	.35		.30	.37	.35	.37	.29	.37	.00	.30	.12
Stoker	.38		.33	.30	.31	.30	.33	.30	.50	.34	.07
Grates	.27		.37	.33	.35	.33	.38	.33	.50	.36	.06

TABLE 36

ROUND TWO RELATIVE RESPONSE ON CONSENTED COMPONENTS
FOR HTHW MAJOR SYSTEMS

System	Relative Response by Expert ID Number									AVG	SD
	1	2	3	4	5	6	7	8	10		
Distribution	.21	.22	.22	.22	.22	.22	.24	.30	.26	.23	.03
Controls	.24	.24	.25	.24	.24	.24	.24	.33	.23	.25	.03
Combustion/Fuel	.26	.27	.25	.27	.27	.27	.26	.37	.26	.28	.03
HTHW Generation	.29	.27	.28	.27	.27	.27	.26	.00	.26	.24	.09

TABLE 37

ROUND TWO RELATIVE RESPONSE ON CONSENTED COMPONENTS FOR HTHW DISTRIBUTION SYSTEM

Component	Relative Response by Expert ID Number									AVG	SD
	1	2	3	4	5	6	7	8	10		
Piping	.23	.24	.00	.20	.21	.20	.18	.26	.00	.17	.09
Supply Pumps	.32	.20	.30	.17	.21	.17	.18	.20	.21	.22	.05
Converters	.26	.17	.33	.20	.16	.20	.18	.00	.24	.19	.09
Balanced Flow	.00	.22	.37	.24	.23	.24	.23	.29	.30	.24	.09
Corrosion Cntl	.19	.17	.00	.20	.19	.20	.23	.26	.24	.19	.07

TABLE 38

ROUND TWO RELATIVE RESPONSE ON CONSENTED COMPONENTS FOR HTHW CONTROL SYSTEM

Component	Relative Response by Expert ID Number									AVG	SD
	1	2	3	4	5	6	7	8	10		
Sensors	.24	.00	.30	.24	.22	.24	.24	.23	.00	.19	.10
Master Cntrler	.21	.30	.33	.22	.24	.22	.24	.26	.31	.26	.04
Boiler Cntrler	.29	.37	.37	.27	.27	.27	.26	.29	.31	.30	.04
Safety Trips	.26	.33	.00	.27	.27	.27	.26	.23	.38	.25	.10

TABLE 39

ROUND TWO RELATIVE RESPONSE ON CONSENTED COMPONENTS FOR HTHW GENERATION SYSTEM

Component	Relative Response by Expert ID Number									AVG	SD
	1	2	3	4	5	6	7	8	10		
Casing & Tubes	.25	.25	.24	.21	.22	.21	.22	.26	.20	.23	.02
Drums	.28	.25	.19	.19	.24	.19	.20	.21	.20	.22	.03
Valving	.22	.22	.19	.19	.20	.19	.20	.18	.20	.20	.01
Press Cmpt/Sfty	.25	.28	.21	.21	.22	.21	.20	.23	.20	.22	.02
Lay-up Capablty	.00	.00	.17	.19	.12	.19	.20	.13	.20	.13	.08

Appendix D: Steam Plant Component Model

Distribution System

1. Condensate Piping Condition Index.

C1: Make-up water percentage for systems that use "mud" or "puff" blowdown. Take the daily average values of make-up percent and blowdown percent for the last 60 days at plant capacity above 50%. Sources: AF Forms 1458 and 1459.

C1= 83.3 - 1.7 (make-up% - blowdown%)

or,

C1: Make-up water percentage for systems that use "continuous" blowdown. Take the daily average values of make-up percent and blowdown percent for the last 60 days at plant capacity above 50%. Sources: AF Forms 1458 and 1459.

C1= 62.5 - 1.25 (make-up% - blowdown%)

and,

C2: Iron content of condensate return. Take the average iron content, in PPM, of the condensate return water for the last 60 days, if measured daily, by the water treatment plant. If this measurement is only taken monthly, take the average of the last three month's values. Source: AF Form 1459.

C2= 55.6 (1 - PPM iron)

2. Supply Piping Condition Index.

C3: An average value of the output steam pressure as a percent of required steam pressure for the last 30 days of operation at 50% or greater plant capacity. Sources: AF Form 1458 and engineering design parameters detailing required pressures for various steam flow rates.

C3= 2.5 (% of required steam pressure) - 200

and,

C4: Number of steam leaks detected in last 365 days from fittings and valve packings in the primary distribution system. Source: maintenance logs and AF Form 1879.

C4= 50 - 2.5 (number of leaks)

3. Steam Traps Condition Index.

C5: Percentage of failed steam traps. Source: latest inspection report of steam trap maintenance program.

C5= 133.3 - 6.7 (% of failed steam traps)

4. Condensate Pumps Condition Index.

C6: The percentage of fully operational condensate pumps. Source: visual inspection.

C6= 200 [1 - (# of pumps NFO / total # pumps)] - 100

Definition: Not Fully Operational (NFO)- pump shows evidence of cavitation, and/or is unable to supply at least 90% of flow and pressure, and/or excessively leaks from seals or valves at a rate of more than 30 drops per minute.

5. Pressure Reducing Valve Condition Index.

C7: Maximum observed pressure pulsations at output end, in PSI, when plant is operating at 50% or greater capacity. Source: visual inspection.

C7= 50 - 10 (PSI of pulsation)

and,

C8: Capability of reducer to operate over its design range measured as a percentage of the design range. Source: operational test of pressure reduction range.

C8= 200 (actual max pressure drop / design max) - 150

6. Total Distribution System Condition Index.

CDS= 0.2 (C1 + C2) + 0.23 (C3 + C4) + 0.2 (C5) + 0.2 (C6) + 0.17 (C7 + C8)

Water Treatment System

1. Make-up Water Quality Condition Index.

C9: Daily average value of hardness, in PPM, of make-up water coming from softner for the last 60 days at plant capacity of 50% or greater. Sources: AF Forms 1458 and 1459.

C9= 100 - 66.7 (PPM hardness)

2. <u>Softner Condition Index</u>.

C10: The degree of external corrosion on the softner, piping, and auxiliary devices. Source: visual inspection.

C10= 33 if there is no evidence of corrosion.
C10= 15 if there is some evidence of corrosion.
C10= 0 if the unit and auxiliaries are heavily corroded.
Note: Intermediate numbers can be assigned by judgement.

and,

C11: The number of times automatic regeneration has failed in the last year. Source: maintenance logs.

C11= 33 - 11 (# of failures)

and,

C12: The percentage of the filter media level versus recommended level. Source: visual inspection.

C12= 2.2 (% of recommended level) - 187

3. <u>Deaerator Condition Index</u>.

C13: The difference between the feedwater temperature leaving the deaerator and the water saturation temperature corresponding to the pressure in the deaerator shell. Source: visual inspection and engineering steam tables.

C13= 75 - 12.5 (sat temp of deaerator - feedwater temp)

and,

C14: Age of deaerator in years. Source: maintenance records.

C14= 50 - 2 (age in years)

4. <u>Chemical Feed System Condition Index</u>.

C15: The daily average of the pH of the condensate return water for the last 60 days of plant operation. Source: AF Form 1459.

C15= $100 - 400\,(pH - 8)^2$

5. <u>Feedwater Pumps Condition Index</u>.

C16: The percentage of fully operational feedwater pumps. Source: visual inspection.

C16= 200 [1 - (# of pumps NFO / total # pumps)] - 100

Definition: Not Fully Operational (NFO)- pump shows evidence of cavitation, and/or is unable to supply at least 90% of flow and pressure, and/or excessively leaks from seals or valves at a rate of more than 30 drops per minute.

6. <u>Water Test Capability Condition Index</u>.

C17: Training level of water test personnel. Source: supervisor.

C17= 50 if well trained and experienced in all tests.
C17= 25 if trained or experienced only for some tests.
C17= 0 if personnel are unskilled in water tests.

and,

C18: Adequacy of lab equipment. Source: supervisor.

C18= 50 if lab space is adequate with plenty of reagents and glassware.
C18= 25 if there is lab space with minimal reagents and glassware.
C18= 0 if lab consists of only a sink with less than minimal reagents and glassware.
Note: Intermediate numbers can be assigned by judgement.

7. <u>Feedwater Condition Index</u>.

C19: Oxygen content of boiler feedwater. Take the average oxygen content, in PPM, of the boiler feedwater water for the last 60 days, if measured daily, by the water treatment plant. If this measurement is only taken monthly, take the average of the last 3 month's values. Source: AF Form 1459.

C19= 200 - 20000 (PPM O_2)

8. <u>Total Water Treatment System Condition Index</u>.

$$CWT = 0.17\ (C9) + 0.15\ (C10 + C11 + C12) + 0.13\ (C13 + C14) + 0.15\ (C15) + 0.11\ (C16) + 0.14\ (C17 + C18) + 0.15\ (C19)$$

Control System

1. Air Controls Condition Index.

C20: The average value of the tolerance of oxygen level in the flue gas, calculated by subtracting the recorded minimum oxygen level from the maximum oxygen level, (δ O_2%), for the highest firing rate each day and taking the average of this difference for the last 30 days of operation at plant capacity above 33%. Source: AF Form 1458.

C20= 100 - 66.7 (avg δ O_2%) (For coal Combustion)

or,

C20= 100 - 100 (avg δ O_2%) (For gas or oil combustion)

2. Fuel Controls Condition Index.

C21: The average value of the tolerance of steam pressure as it deviates from setpoint, calculated by finding the maximum percent difference for the highest firing rate each day, (Pressure - Set Point)/Set Point) x 100, and taking the average of this daily percent difference for the last 30 days of operation at plant capacity above 33%. Source: AF Form 1458.

C21= 100 - 20 (avg steam pressure tolerance %)

3. Pressure and Temperature Indicators Condition Index.

C22: Percentage of pressure and temperature indicators calibrated within the last 365 days. Source: maintenance logs.

C22= 5 (% of indicators calibrated) - 400

4. Gas Analyzers Condition Index.

C23: Percentage of oxygen and carbon dioxide analyzers calibrated within the last 365 days. Source:maintenance logs.

C23= 5 (% of analyzers calibrated) - 400

5. All Actuators Condition Index.

C24: Percentage of actuators calibrated within the last 365 days. Source: maintenance logs.

C24= 5 (% of indicators calibrated) - 400

6. <u>Limit Controls Condition Index</u>.

C25: Percentage of limit controls calibrated within the last 365 days. Source: maintenance logs.

C25= 5 (%of limit controls calibrated) - 400

7. <u>All Sensors Condition Index</u>.

C26: Percentage of all temperature, pressure, and flow sensors calibrated within the last 365 days. Source: maintenance logs.

C26= 5 (%of sensors calibrated) - 400

8. <u>Total Control System Condition Index</u>.

CCS= 0.16 (C20) + 0.17 (C21) + 0.14 (C22) + 0.11 (C23) + 0.17 (C24) + 0.12 (C25) + 0.13 (C26)

<u>Steam Generation System</u>

1. <u>Boiler Efficiency Condition Index</u>.

C27: The average value of boiler efficiency for the last 30 days of operation at above 50% of boiler capacity. Source: AF Form 1458.

C27= 20 (% efficiency) - 1500

2. <u>Casing Condition Index</u>.

C28: The number of individual sections of boiler casings which are penetrated by cracks or corrosion. Source: visual inspection.

C28= 100 - 12.5 (# of penetrated casing sections)

3. <u>Boiler Tube Condition Index</u>.

C29: The percentage of the tubes which are sooted. Source: visual inspection.

C29= 100 - 5 (% of tubes sooted)

4. <u>Refractory Condition Index</u>.

C30: The percentage of the refractory bricks which are cracked, chipped, missing, or otherwise damaged. Source: visual inspection.

C30= 100 - 3.3 (% of refractory damaged)

5. Steam Drum Condition Index.

C31: The allowable operating pressure of the steam drum as a percentage of the original design pressure. Source: AF Form 1222 (type "B" inspection).

C31= 5 (% of original design pressure) -400

6. Safety Devices Condition Index.

C32: The number of defective pressure relief valves and low water cut-offs. Source: AF Form 1222 (type "C" inspection).

C32= 100 - 50 (# of defective devices)

7. Total Steam Generation Condition Index.

CSG= 0.16 (C27) + 0.12 (C28) + 0.2 (C29) + 0.16 (C30) + 0.17 (C31) + 0.2 (C32)

Coal Combustion/Fuel System

1. Fans and Dampers Condition Index.

C33: The degree of vibration of FD and ID fans and drives. Source: visual inspection.

C33= 50 if fan and drive operate without noticeable vibration.
C33= 25 if slight vibration is observed.
C33= 0 if severe vibration is observed.
Note: Intermediate numbers can be assigned by judgement.

and,

C34: The adjustment of dampers and linkages. Source: visual inspection.

C34= 50 if dampers and linkages are in proper adjustment without slop.
C34= 25 if linkages are moderately sloppy.
C34= 0 if dampers are inoperable or wired into position.
Note: Intermediate numbers can be assigned by judgement.

2. Stoker Condition Index.

C35: Coal feed mechanism ability to adjust from lowest to highest operating capacity as a percentage of the manufacturer's specified range. Source: operational check.

C35= 4 x (% of specified range) - 300

3. <u>Grate Condition Index</u>.

C36: the percentage of grate area which is cracked. Source: visual inspection.

C36= 150 - 5 (% of grate area cracked)

4. <u>Total Coal Combustion/Fuel Condition Index</u>.

CC/F (Coal)= 0.3 (C33 + C34) + 0.34 (C35) + 0.36 (C36)

<u>Gas and Oil Combustion/Fuel System</u>

1. <u>Fan and Damper Condition Index</u>.

C37: The degree of vibration of FD and ID fans and drives. Source: visual inspection.

C37= 50 if fan and drive operate without noticeable vibration.
C37= 25 if slight vibration is observed.
C37= 0 if severe vibration is observed.
Note: Intermediate numbers can be assigned by judgement.

and,

C38: The adjustment of dampers and linkages. Source: visual inspection.

C38= 50 if dampers and linkages are in proper adjustment without slop.
C38= 25 if linkages are moderately sloppy.
C38= 0 if dampers are inoperable or wired into position.
Note: Intermediate numbers can be assigned by judgement.

2. <u>Fuel Piping and Auxiliaries Condition Index</u>.

C39: The number of leaks detected in the last 365 days from piping, fittings, valves, and safety valves. Source: maintenance logs and AF Form 1879.

C39= 100 - 25 (# of leaks)

3. <u>Burner/Atomizer Condition Index</u>.

C40: Average stack gas temperature (before economizer) for the last 60 days at above 50% boiler capacity. Source: AF Form 1464.

C40= 280 - 0.4 (stack gas temp °F) (For gas combustion) or,

C40= 377.8 - 0.44 (stack gas temp °F) (For oil combustion)

4. Bulk Storage Oil Tanks Condition Index.

C41: Percentage of tank capacity usable without leakage (a leak 75% of the way up the tank would rate at 75% tank capacity). Source: visual inspection.

C41= (% tank capacity) - 50

and,

C42: Number of heater coil or temperature control malfunctions in the last 365 days. Source: maintenance logs and AF Form 1879.

C42= 50 - 12.5 (# of malfunctions)

5. Oil Pump Condition Index.

C43: The percentage of fully operational oil pumps. Source: visual inspection.

C43= 200 [1 - (# of pumps NFO / total # pumps)] - 100

Definition: Not Fully Operational (NFO)- pump shows evidence of cavitation, and/or is unable to supply at least 90% of flow and pressure, and/or excessively leaks from seals or valves at a rate of more than 30 drops per minute.

6. Fuel Regulator Condition Index.

C44: The percentage of the required range that the fuel flow controller is capable of moving the fuel valve from open to closed. Source: operational check.

C44= 4 (% of range) - 300

7. Flame and Flow Sensors.

C45: Number of false shut downs in the last 365 days due to flame and flow sensors. Source: maintenance logs.

C45= 100 - 33.3 (# of false shut downs)

8. Total Gas and Oil Combustion/Fuel System Condition Index.

CC/F (Gas and Oil)= 0.16 (C37 + C38) + 0.19 (C39) + 0.15 (C40) + 0.09 (C41 + C42) + 0.12 (C43) + 0.15 (C44) + 0.14 (C45)

Total Central Steam Plant Condition Index (CSP)

CSP= 0.17 CDS + 0.21 CWT + 0.16 CCS + 0.24 CSG +
0.22 CC/F

Appendix E: HTHW Plant Component Model

Distribution System

1. Piping Condition Index.

C1: Make-up water percentage. Take the daily average values of make-up percent and blowdown percent for the last 60 days at plant capacity above 50%. Sources: AFLC Form 1625.

C1= 100 - 33.3 (make-up% - blowdown%)

2. Supply Pump Condition Index.

C2: The percentage of fully operational supply pumps. Source: visual inspection.

C2= 200 [1 - (# of pumps NFO / total # pumps)] - 100

Definition: Not Fully Operational (NFO)- pump shows evidence of cavitation, and/or is unable to supply at least 90% of flow and pressure, and/or excessively leaks from seals or valves.

3. Converters Condition Index.

C3: The percentage of fully operational converters. Source: visual inspection.

C3= 200 [1 - (# of converters NFO / total # converters)] - 100

Definition: Not Fully Operational (NFO)- Valves or fittings leaking any steam or water, or control valves not operable or out of calibration, or evidence of a leaky tube bundle.

4. Balanced Flow Condition Index.

C4: The percentage of time that the blending valves are in the full open position for the last 365 days. Source: maintenance logs or supervisor evaluation.

C4= 2 (% time blending valves full open) - 100

5. Corrosion Control Condition Index.

C5: The percentage of underground piping protected by a cathodic protection system in accordance with AFM 85-5. Source: engineering data/corrosion control records.

C5= 6.67 (% protected) -500

6. Total Distribution System Condition Index.

$$CDS = 0.17\,(C1) + 0.22\,(C2) + 0.19\,(C3) + 0.24\,(C4) + 0.19\,(C5)$$

HTHW Generating System

1. Casing and Tubes.

C6: The number of individual sections of boiler casings which are penetrated by cracks or corrosion. Source: visual inspection.

C6= 50 - 6.25 (# of penetrated casing sections)

and,

C7: The percentage of the tube surface area which is sooted. Source: visual inspection.

C7= 50 - 2.5 (% of area sooted)

2. Expansion Drums Condition Index.

C8: The allowable operating pressure of the expansion drum as a percentage of the original design pressure. Source: AF Form 1222 (type "B" inspection).

C8= 5 (% of original design pressure) -400

3. Valving Condition Index.

C9: The percentage of boiler isolation, bypass, and blending valves fully operational. Source: visual inspection.

C9= 333 [1 - (# of valves NFO / total # valves)] - 233

Definition: Not Fully Operational (NFO)- Valve does not seat properly, or bonnet or flange is leaking steam or water.

4. Pressure Safety Devices Condition Index.

C10: The number of defective pressure relief valves and low water cut-offs. Source: AF Form 1222 (type "C" inspection).

C10= 100 - 50 (# of defective devices)

5. Layup Capability Condition Index.

C11: Wet storage capability. The plant must be capable of storing a boiler wet with the following four conditions: 1). Stored water to be maintained with a sulfite level of 100 PPM or a hydrazine level of 500 PPM. 2). Stored water to be maintained at a pH between 8 and 10. 3). Boiler to be pressurized to at least 5 PSI throughout storage. 4). Boiler fireside kept adequately heated to reduce humidity. Source: supervisor evaluation.

C11= 16.7 (# of conditions which can be met) - 16.7

and,

C12: Dry storage capability. The plant must be capable of storing a boiler dry with the following two conditions: 1). The plant has, on-hand, at least 1/2 pound of moisture absorbent or desiccant for every 1000 pound per hour plant steam flow capacity. 2). Boiler to be maintained at a minimum of 5 PSI nitrogen pressure. Source: supervisor evaluation.

C12= 25 (# of conditions which can be met)

6. Total HTHW Generating System Condition Index.

CGS= 0.23 (C6 + C7) + 0.22 (C8) + 0.20 (C9) + 0.22 (C10) + 0.13 (C11 + C12)

Control System

1. Air Controls Condition Index.

C13: The average value of the tolerance of oxygen level in the flue gas, calculated by subtracting the recorded minimum oxygen level from the maximum oxygen level, (δ O_2%), for the highest firing rate each day and taking the average of this difference for the last 30 days of operation at plant capacity above 33%. Source: AF Form 1165.

C13= 100 - 66.7 (avg δ O_2%) (For coal Combustion)

or,

C13= 100 - 100 (avg δ O_2%) (For gas or oil combustion)

2. <u>Fuel Controls Condition Index</u>.

C14: The average value of the tolerance of steam pressure as it deviates from setpoint, calculated by finding the maximum percent difference for the highest firing each day, (Pressure - Set Point)/Set Point) x 100, and taking the average of this daily percent difference for the last 30 days of operation at plant capacity above 33%. Source: AFLC Form 1402.

C14= 100 - 20 (avg steam pressure tolerance %)

3. <u>Pressure and Temperature Indicators Condition Index</u>.

C15: Percentage of pressure and temperature indicators calibrated within the last 365 days. Source: maintenance logs.

C15= 5 (% of indicators calibrated) - 400

4. <u>Gas Analyzers Condition Index</u>.

C16: Percentage of oxygen and carbon dioxide analyzers calibrated within the last 365 days. Source: maintenance logs.

C16= 5 (% of analyzers calibrated) - 400

5. <u>All Actuators Condition Index</u>.

C17: Percentage of actuators calibrated within the last 365 days. Source: maintenance logs.

C17= 5 (% of indicators calibrated) - 400

6. <u>Limit Controls Condition Index</u>.

C18: Percentage of limit controls calibrated within the last 365 days. Source: maintenance logs.

C18= 5 (%of limit controls calibrated) - 400

7. <u>All Sensors Condition Index</u>.

C19: Percentage of all temperature, pressure, and flow sensors calibrated within the last 365 days. Source: maintenance logs.

C19= 5 (%of sensors calibrated) - 400

8. Total Control System Condition Index.

CCS= 0.16 (C13) + 0.17 (C14) + 0.14 (C15) + 0.11 (C16) +
0.17 (C17) + 0.12 (C18) + 0.13 (C19)

Coal Combustion/Fuel System

1. Fans and Dampers Condition Index.

C20: The degree of vibration of FD and ID fans and drives. Source: visual inspection.

C20= 50 if fan and drive operate without noticeable vibration.
C20= 25 if slight vibration is observed.
C20= 0 if severe vibration is observed.
Note: Intermediate numbers can be assigned by judgement.

and,

C21: The adjustment of dampers and linkages. Source: visual inspection.

C21= 50 if dampers and linkages are in proper adjustment without slop.
C21= 25 if linkages are moderately sloppy.
C21= 0 if dampers are inoperable or wired into position.
Note: Intermediate numbers can be assigned by judgement.

2. Stoker Condition Index.

C22: Coal feed mechanism ability to adjust from lowest to highest operating capacity as a percentage of the manufacturer's specified range. Source: operational check.

C22= 4 (% of specified range) - 300

3. Grate Condition Index.

C23: the percentage of grate are which is cracked. Source: visual inspection.

C23= 150 - 5 (% of grate area cracked)

4. Total Coal Combustion/Fuel Condition Index.

CC/F (Coal)= 0.3 (C20 + C21) + 0.34 (C22) + 0.36 (C23)

Gas and Oil Combustion/Fuel System

1. Fan and Damper Condition Index.

C24: The degree of vibration of FD and ID fans and drives. Source: visual inspection.

C24= 50 if fan and drive operate without noticeable vibration.
C24= 25 if slight vibration is observed.
C24= 0 if severe vibration is observed.
Note: Intermediate numbers can be assigned by judgement.

and,

C25: The adjustment of dampers and linkages. Source: visual inspection.

C25= 50 if dampers and linkages are in proper adjustment without slop.
C25= 25 if linkages are moderately sloppy.
C25= 0 if dampers are inoperable or wired into position.
Note: Intermediate numbers can be assigned by judgement.

2. Fuel Piping and Auxiliaries Condition Index.

C26: The number of leaks detected in the last 365 days from piping, fittings, valves, and safety valves. Source: maintenance logs and AF Form 1879.

C26= 100 - 25 (# of leaks)

3. Burner/Atomizer Condition Index.

C27: Average stack gas temperature (before economizer) for the last 60 days at above 50% boiler capacity. Source: AFLC Form 1402.

C27= 280 - 0.4 (stack gas temp °F) (For gas combustion)

or,

C27= 377.8 - 0.44 (stack gas temp °F) (For oil combustion)

4. Bulk Storage Oil Tanks Condition Index.

C28: Percentage of tank capacity usable without leakage (a leak 75% of the way up the tank would rate at 75% tank capacity). Source: visual inspection.

C28= (% tank capacity) - 50

and,

C29: Number of heater coil or temperature control malfunctions in the last 365 days. Source: maintenance logs and AF Form 1879.

C29= 50 - 12.5 (# of malfunctions)

5. Oil Pump Condition Index.

C30: The percentage of fully operational oil pumps. Source: visual inspection.

C43= 200 [1 - (# of pumps NFO / total # pumps)] - 100

Definition: Not Fully Operational (NFO)- pump shows evidence of cavitation, and/or is unable to supply at least 90% of flow and pressure, and/or excessively leaks from seals or valves at a rate of more than 30 drops per minute.

6. Fuel Regulator Condition Index.

C31: The percentage of the required range that the fuel flow controller is capable of moving the fuel valve from open to closed. Source: operational check.

C31= 4 (% of range) - 300

7. Flame and Flow Sensors.

C32: Number of false shut downs in the last 365 days due to flame and flow sensors. Source: maintenance logs.

C32= 100 - 33.3 (# of false shut downs)

8. Total Gas and Oil Combustion/Fuel System Condition Index.

CC/F (Gas and Oil)= 0.16 (C24 + C25) + 0.19 (C26) + 0.15 (C27) + 0.09 (C28 + C29) + 0.12 (C30) + 0.15 (C31) + 0.14 (C32)

Total HTHW Plant Condition Index (CHW)

CHW= 0.23 CDS + 0.25 CCS + 0.24 CGS + 0.28 CC/F

Appendix F: Worked Example

This example demonstrates the the use of the condition index equations, the resulting condition index values, as well as how these values are applied in determining overall system condition index. The distribution system index equations are used in this illustrative example.

Condensate Piping Condition Index

Given:

The average "continuous" blowdown for the last 60 days when plant output was above 50% of its capacity= 5.1% (of the total amount of feedwater)

and,

The average make-up amount for the the same period= 23.7%

then according to Eq (8),

C1= 62.5 - 1.25 x (23.7 - 5.1)

C1= 39.3

and,

Given:

The average iron content of the condensate return water from 3 samples taken the last 3 months= .32 parts per million

then according to Eq (6),

C2= 55.6 x (1 - .32)

C2= 37.8

so,

Condensate Piping Condition Index= 39.3 + 37.8 = 77.1

Supply Piping Condition Index

Given:

From the last 30 days of operation at 50% or greater plant operating capacity, the average value of the output steam pressure as a percentage of required pressure= 89.2%

then according to Eq (2),

$$C3= 2.5 \times (89.2) - 200$$

$$C3= 23.0$$

and,

Given:

The number of steam leaks detected in the last 365 days= 12

then according to Eq (3),

$$C4= 50 - 2.5 \times (12)$$

$$C4= 20.0$$

so,

Supply Piping Condition Index= 23.0 + 20.0= 43.0

<u>Steam Trap Condition Index</u>

Given:

The distribution system contains 84 steam traps, and the latest trap maintenance inspection report shows that 11 of them, or 13.1 %, have failed

then according to Eq (1),

$$C5= 133.3 - 6.7 \times (13.1)$$

$$C5= 45.5$$

so,

Steam Trap Condition Index= 45.5

<u>Condensate Pumps Condition Index</u>

Given:

80% of the condensate pumps are currently fully operational

then according to Eq (9),

$$C6= 2 \times (80) - 100$$
$$C6= 60.0$$

so,

Condensate Pump Condition Index= 60.0

Pressure Reducing Valve Condition Index

Given:

The observed maximum pressure pulsation of the reducing valve= 2 PSI

then according to Eq (10),

C7= 50 - 10 x (2)

C7= 30

and,

Given:

The reducing valve is capable of reducing the pressure up to 70% of the design range

then according to Eq (11),

C8= 2 x (70) - 150

C8= -10 which must be set to the minimum allowable value of 0.

C8= 0

so,

Pressure Reducing Valve Condition Index= 30.0 + 0.0= 30.0

Total Distribution System Condition Index

Given the above values for C1 through C8, the total distribution system condition index, CDS, is:

CDS= .2 x (77.1) + .23 x (43.0) + .2 x (45.5) + .2 x (60.0) + .17 x (30.0)

CDS= 51.5

This CDS value would correspond to a "poor" rating.

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Vita

Captain Gary J. Starmack was born in Dhahran, Saudi Arabia on 25 February 1957. He graduated from Samuel Ayer High School in Milpitas, CA in 1975 and attended San Jose State University for 3 years before enlisting in the Air Force. He graduated from San Diego State University, under the Airman Education and Commissioning Program, with the degree of Bachelor of Science in Mechanical Engineering in May 1984. Upon graduating from OTS in August 1984, he was assigned to the 323rd CES at Mather AFB CA. During this assignment, he formed and led the squadron's Heating, Ventilating, and Air Conditioning (HVAC) Evaluation Team to evaluate system conditions and design upgrades for over thirty HVAC systems. He used his extensive knowledge of the base's mechanical systems to formulate Mather's first five-year HVAC improvement plan recommending and prioritizing various repair and upgrade projects. In June 1986, he was assigned as the mechanical design engineer for the 40th CEF at Aviano AB, Italy where he designed 14 oil-fired boiler upgrade projects. In August 1988, he was promoted to Chief, Resources and Requirements and was responsible for approving and prioritizing HVAC system repair projects. After Aviano, he attended AFIT where he earned a Master of Science degree in Engineering Management in September 1990. Upon graduation, Captain Starmack was assigned to HQ TAC, Langley AFB, VA.

Permanent Address: 395 N. Pk. Victoria Dr.
Milpitas, CA 95035

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13. ABSTRACT *(Maximum 200 words)*

Air Force Logistics Command (AFLC), facing decreasing funds and aging utility systems, needed a method to objectively rate its central heating plants. Such a rating system would be used to compare heating plants throughout the command to identify potential problem areas and prioritize major repair projects. This thesis used a Delphi questionnaire to gather opinions from heating plant experts in order to identify and prioritize components considered most critical to overall plant operation. In addition, the experts suggested measurements which could be used to evaluate component conditions. By combining expert opinions and readings from technical literature, component model rating schemes were developed for AFLC's steam and high temperature hot water plants. Based on measurements and observations of critical components in the plant, a score between 0 and 100 is assigned to each component (for example, condensate piping, deaerator, etc.), each plant subsystem (distribution system, water treatment system, etc.), and to the plant as a whole. These component model rating schemes and the resultant overall condition index scores will enable AFLC to focus their management attention and allocate needed resources to the plants in greatest need of repair.

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