CORALL - EXPERT SYSTEM FOR DIAGNOSIS OF CORROSION DAMAGES IN THERMAL POWER GENERATING STATIONS

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CORALL - EXPERTNÝ SYSTÉM NA DIAGNOSTIKOVANIE KORÓZNYCH POŠKODENÍ V TEPELNÝCH ELEKTRÁRŇACH

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Abstrakt

Programový balík expertného systému CORALL bol vyvinutý pre personál elektrární ako pomôcka pri odhaľovaní príčin korózneho poškodenia zariadení tepelných elektrární. Jeho poslaním je asistovať pri úsilí ľudí rozpoznať a identifikovať základnú príčinu skúmaného poškodenia. Program usmerňuje užívateľa k identifikovaniu najpravdepodobnejšieho mechanizmu poškodenia kladením jednoduchých otázok takých ako typ elektrárne, miesto poškodenia, typ paliva, typ kovu a vizuálne hodnotenie poškodeného komponentu.

Po prvý krát sú desaťročia zhromažďované vedomosti a skúsenosti staviteľov a operátorov elektrární k dispozícii vo forme, ktorá je prístupná prostredníctvom mikropočítača. Takto môže byť v krátkom čase diagnostikovaný mechanizmus poškodenia so spoľahlivosťou porovnateľnou so spoľahlivosťou záverov najlepších expertov pôsobiacich v oblasti korózie. Systém CORALL je založený na spoľahlivých verejne publikovaných informáciach akceptovaných expertami z oblasti analýzy korózneho poškodenia v tepelných elektrárňach.

Programový balík expertného systému CORALL je navrhnutý tak, aby bol prístupný i pre užívateľov bez predchádzajúcich skúseností s používaním počítačov a bez požiadaviek na znalosti z programovania počítačov.

Abstract

CORALL expert system package was developed for use by electric utility and power plant personnel during investigation into the cause of thermal power plant corrosion damage. It is intended to assist their efforts to recognize and identify a basic cause of the damage under investigation. The program guides the user to the most likely damage mechanism by asking simple questions, answers to which can be obtained by determining the type of power plant, damage location, type of fuel, type of metal and from visual inspection of the damaged component.

For the first time, decades of accumulated knowledge, expertise and experience of the builders and operators of power generating stations are available in a microcomputer accessible form. In a matter of seconds, a damage mechanism can be diagnosed with the same confidence as the best corrosion damage analysis specialists. CORALL is based on the reliable information published in the public domain and accepted by the practising experts in the area of thermal power plant corrosion damage analysis.

The CORALL expert system package is designed for ease of use and no previous computer experience or computer programming knowledge is required.

INTRODUCTION

Expert systems are computer programs that use knowledge and inference procedures to mimic the deductive reasoning used by human experts. An expert system is a form of artificial intelligence which can be used for diagnosis, monitoring, analyzing, consulting, designing, and many other applications.

Thermal power generating stations consist of many complex systems. Due to rising costs of equipment downtime, replacement materials and maintenance personnel, it is necessary to improve efficiency of the process equipment problem analysis and resolution. The use of expert systems can in a significant way contribute toward this objective.

Since the degradation of primary equipment components due to corrosion is the single largest source of forced outages in thermal power generating stations, it is advantageous to have an expert system which can assist in recognizing and identifying basic causes of corrosion damage. It is essential to correctly identify the damage mechanism/cause so the root cause for a failure can be established and proper ameliorative measures taken.

The correct identification of damage mechanisms/causes is a complex process which may include many individuals, institutions, etc. Technical specialists in metallurgy, chemistry, combustion and power plant design frequently cooperate with the station staff in a failure investigation. These individuals rely on personal experience and a large amount of reports, theories, studies, private communications and investigations concerning the different failure modes and mechanisms. As a result of many years of serious effort by the utility companies and manufacturers to mitigate the problem of failures due to corrosion, information exists which make possible correct identification of all routine failure mechanisms which occur in currently operating systems. It is believed that proper dissemination of this knowledge and future findings will contribute to fewer incidents of failures.

An expert system package, CORALL, was developed for use by electric utility and power plant personnel to assist their efforts to recognize and identify a basic damage mechanism during investigations into the cause of corrosion damages. The program guides the user to the most likely damage mechanism by asking simple questions, answers to which can be obtained by determining the type of plant, type of fuel, failure location, type of metal, and from visual inspection of the damaged component. The CORALL expert system package is designed for ease of use, and no previous computer experience or computer programming knowledge is required.

This paper begins by discussing the primary corrosion damage mechanisms which occur at thermal power stations, then it moves on to describe expert systems in general which leads to a discussion of the CORALL expert system package. Finally, an example of a diagnostic session with CORALL is presented and concluding remarks are given.

CORROSION PROCESSES IN THERMAL POWER GENERATING STATIONS

There are three types of fossil-fired power plants. The most common plant is the pulverized coal-fired steam power plant, which may be used either as a baseload plant (where it runs continuously at capacity except for scheduled maintenance outages) or for intermediate loads between the steady baseload and higher loads needed daily. Gas combustion turbines are used for peak loads that occur for an hour or two each day. Combined cycle plants consisting of gas combustion and steam turbines are generally intended for baseload service, although they must also be capable of sustaining intermediate-load service.

The fossil-fired plants are fuelled by natural gas, oil, and coal. Natural gas is generally clean and does not constitute a corrosion threat, unless firing is substoichiometric for reducing NO_X emissions. Oil can be corrosive to boilers if it contains vanadium and alkali metal impurities: these produce liquid vanadium oxides or alkali sulfates, both of which are highly corrosive to boiler tubes in the combustion chamber or hot-gas passages. Coal can also contain such impurities as sulfides and chlorides which can be extremely corrosive.

Each component at the complex power plant system possesses its unique corrosion problems due to: attack by service environment (high temperature, aggressive gases and liquids, erosion, vibration, mechanical stresses, etc.), human error, and incorrect and inconsistent application of ameliorative measures.

Steam Power Plant

Consists of three heat transport circuits: fuel-air, water-steam, and condenser cooling. In the fuel-air stream, the fossil fuel is burned in air, transfers its heat to a series of heat exchangers, is cleaned of particulate matter, may be scrubbed of sulfur oxides, and exits through the stack. In the water-steam circuit, clean feedwater is converted into superheated steam in a boiler, which expands through a series of turbines, converting its heat into mechanical energy, and is condensed, conditioned, pumped, and heated as feedwater back into the boiler. In the condenser-cooling stream, cold water is passed through the condenser and can be recirculated if a cooling tower is used or is returned back to the source of the cooling water.

The power plant equipment is usually divided into: boiler (steam generator) and auxiliaries. The fuels are combusted in a boiler constructed of water walls consisting of vertical or spiral steel tubes, welded together. The boiler feedwater raises in the water walls and is heated by the combusted fuel. The generated steam is separated from the boiler water which is returned to the bottom of the water walls through downcomers. The saturated steam is superheated by passing through banks of tubes exposed to the flue-gas stream. In supercritical boilers, the boiler pressure is above the critical point, and the liquid becomes superheated vapour without undergoing a phase change. The feedwater is conditioned to be slightly alkaline, but the fluid in the boiler may become acidic or caustic, depending on the nature of impurities and/or treatment chemicals, and presence of corrosion deposits and flow interruptions. If acidic conditions develop, the corrosion of steel boiler tubes is very rapid and the hydrogen evolved in the process is absorbed by the steel and causes hydrogen embrittlement. Under caustic conditions in deposits, the metal wastage of the steel boiler tubes is also very rapid and leads to caustic gauging. Overheating and excessive internal scaling in water walls may occur if boiling undergoes departure from nucleate boiling conditions.

The superheaters and reheaters are subject to steam oxidation with subsequent scale exfoliation from steam exposed surfaces. Hot corrosion and fly-ash erosion can become problems on the fireside surfaces.

The superheated steam leaves the boiler through heavy wall pipes and enters the high-pressure stage of turbine generator where it expands. Then it returns to the boiler for reheating before entering the intermediate-pressure turbine stage for a second expansion. After one or two expansions and reheatings, the steam enters the low-pressure stage of the turbine.

The dry steam is non-corrosive in the high or intermediate-pressure turbines except when condensation of solid sodium hydroxide (NaOH) occurs. However, when expansion of the steam in the low-pressure turbine reaches the point of initial condensation, high concentration of chloride and sulfate salt solutions may deposit. The concentration of these salts in steam condensate may be a million times higher than in the steam. Thus, the permissible impurity levels in the feedwater must be maintained in parts per billion in order to protect the low-pressure turbine. The condensate solution is often acidic as a result of evaporation of ammonia (NH_3) from the feed-water treatment process. In addition, during shutdowns, oxygen and carbon dioxide (CO_2) may dissolve in the acidic deposits on the turbine blades, leading to pitting with resulting loss of up to 90% fatigue strength. Measures which can be taken include: using blades designed to be strong enough to operate with pitted surfaces, periodic blade cleaning, maintaining the steam purity to avoid corrosive salt deposition, using more corrosion resistant low-pressure turbine blade materials (such as titanium alloys), or protecting 12% Cr steel blades with corrosion-resistant coatings.

Corrosion damage which can occur in the condenser include: sulfide-contaminated cooling water (seawater or brackish water) attacking copper-base tubes or tubesheets, pitting or crevice corrosion under deposits or barnacles or between tubes and tubesheets. However, the primary concern with condensers is in leakage of seawater or contaminated cooling water into the water-steam circuit which operates below atmospheric pressure. This in-leakage results in accelerated corrosion of boiler tubes and turbine components.

In the flue-gas handling equipment, it is important to maintain the flue gas temperature above its dew point in order to avoid the deposition of sulfuric acid (H_2SO_4). Accelerated corrosion can also occur at areas where the hot flue-gas contacts cold surfaces.

Corrosion processes which occur in the steam power plants are summarized in Tables 1 and 2.

Gas Combustion Turbines

Consist of compressor, combustion chamber and turbine generator. The inlet air is compressed in a compressor, reacted with fuel in a combustion chamber, and directed at stationary airfoil vanes and through rotor blades or buckets constituting the turbine stage. Thus, the entire fuel and air input passes through the gas turbine. Any corrosive impurities present in either fuel or air will affect the high-temperature components, primarily the combustor, nozzle diaphragm, and turbine. Although the principal threats are oxidation and hot corrosion, the compressor components are susceptible to general and pitting corrosion due to condensation.

Corrosion processes which occur in the gas combustion turbines are summarized in Table 3.

Tab.1 Corrosion processes which occur in boilers

Combined Cycle Power Plant

Consists of gas turbine and a steam power plant. The gas turbine is used as a high-temperature topping cycle whose exhaust gas enters a boiler, which raises steam to operate the steam turbine and generator. To a large extent, corrosion problems in the combined cycle are simply the sum of the corrosion problems in the gas turbine and the steam power plant. Control of impurities in the inlet air and fuels reduces the corrosion damage.

EXPERT SYSTEMS

General Description

An expert system is a type of artificial intelligence program that emulates the interaction a user might have with a human expert on a subject area. Expert systems can be developed for any problem that involves a selection from among a definable group of choices where the decision is based on logical rules. The rules can involve relative probabilities of a choice being correct. Any area where there is a person or group of persons that have special expertise needed by others is a possible area for expert systems. Anything from identification of biological specimens, to automating complex regulations, to aiding customers in selecting from among a group of products, to automated user assistance is possible.

Tab.2 Corrosion processes which occur in steam turbine generators and auxiliary equipment

Expert systems deal with knowledge rather than data and the files they use are often referred to as knowledge bases. The rules that the program uses are IF-THEN type rules. A rule is made up of a list of IF conditions (normal English sentences) and a list of THEN conditions (more sentences) or statements about the probability of a particular choice being the appropriate solution to the problem. If the computer determines that all of the IF conditions in a rule are true, it adds the rules THEN conditions to what it knows to be true. The computer determines what additional information it needs and how best to get this information. If possible, the program will derive information from other rules rather than asking the user. This ability to derive information allows the program to combine many small pieces of knowledge to arrive at logical conclusions about complex problems.

Tab.3 Corrosion processes which occur in gas combustion turbines

The final goal of an expert system is to select the most appropriate solution to a problem based on the data input by the user. If more than one solution, arranged in order of probability, is possible, the program could provide a list of the possible solutions

Benefits and Risks

Expert systems offer the following benefits:

The knowledge about a limited domain is captured in the detail required for machine logic processing; a good knowledge representation will identify areas where the knowledge is uncertain or incomplete; areas for further research become clearly defined and the experiments to be performed are readily apparent (sharpening the expert).

Human experts can be distracted or rushed and led to incorrect or inconsistent deductions; the expert system will always apply the same logic and give consistent results; the results will be correct if the rules are; when the expert system cannot arrive at a conclusion, it refers the user to the human expert (best knowledge base always gives best conclusion).

All conclusions reached by the expert system are justified by inspectable rules; the human expert is freed from remembering all the details of the justification: this is a great time saver in areas where justification is repeatedly requested for slightly different inputs; in cases of disagreement among experts, the knowledge base challenges other experts to point out errors or to generate a correct rulebase (public thinking tool).

With appropriate help facilities, an expert system can become an excellent tutor for transferring knowledge from an expert to his successor; this provides a company with some measure of protection against loss of expertise through attrition (preservation of knowledge).

Non-specialists have access to expert knowledge if the expert is not available; problems that are well understood can be solved by anyone who has access to the expert system, this frees the expert from repeatedly executing the same task so that he can concentrate his efforts on acquiring new knowledge (efficient use of manpower).

The risks involved in expert systems are the same as those associated with any computer program. The conclusions arrived at by an expert system may be wrong if the rules are incorrectly written and/or when the data entered by the user is wrong. Although CORALL is designed to guard against misinterpretation, conclusions should be treated like any conclusions of a single expert. A second opinion is recommended if an incorrect conclusion entails great risks.

The Expert System Shell Used

A program used to build an expert system is usually called an expert system shell. EXSYS(1), one of the many shells available, was used to create the expert system described in this paper. EXSYS is a generalized expert system development package. Expert systems can be developed with EXSYS for any problem that involves a selection from among a definable group of choices where the decision is based on logical rules. The rules can involve relative probabilities of a choice being correct.

Expert systems developed with EXSYS will ask the user questions relevant to a subject. The user answers by selecting one or more answers from a list by entering a numeric value. The computer will continue to ask questions until it has reached a conclusion. The conclusion may be the selection of a single solution or a list of possible solutions arranged in order of likelihood. The computer can explain, in English, how it arrived at its conclusion and why.

Expert system shells, such as EXSYS, coupled with the advance in micro-computer technology means that expert systems can be effectively built, installed on personal computers, and used by all who may need the assistance at low costs.

CORALL EXPERT SYSTEM PACKAGE - DIAGNOSIS OF CORROSION DAMAGE IN THERMAL POWER GENERATING STATIONS

The CORALL expert system package was developed for use by electric utility and power plant personnel during investigations into the cause of corrosion damage. It is intended to assist their efforts to recognize and identify a basic damage mechanism that can produce the type of damage under investigation.

The acceptance of an expert system depends on the credibility of its knowledge base. In the conceptual design of CORALL, two criteria were established for selecting the main source for the factual portion of the knowledge base. The facts should have been: (I) published in public domain so that their reliability could be judged; and (ii) accepted by the practising experts in the area of corrosion damage analysis.

The "Corrosion in Fossil Fuel Power Plants" review section in the ASM Metals Handbook [1], and the "Manual for Investigation and Correction of Boiler Tube Failures" by the Electric Power Research Institute (EPRI) [2], met both criteria and were chosen to be the factual framework for CORALL.

The CORALL knowledge base was constructed around basic corrosion damage mechanisms, described in Section 2, which can independently or jointly bring a failure into being. The damage mechanisms can be determined, with a high degree of certainty, from plant type, location of the damage, type of fuel used, type of metal used, and characteristic appearance parameters. The relationships between corrosion damage mechanisms and these factors are well established with very little ambiguity.

This knowledge is organized into a decision tree structure incorporating the facts from the EPRI Manual and the ASM Metals Handbook and heuristic components contributed by the developers of CORALL. The facts are expressed in the form of production rules using the EXSYS expert system development package. CORALL combines three separate expert systems: COREXYS, CORAUX, and CORGAS to provide a corrosion damage diagnostic system for all types of fossil fuel power plants. The COREXYS expert system aids investigations into the cause of boiler tube failures, CORAUX contains information on causes of corrosion damages in steam turbine generators and auxiliary equipment, and CORGAS helps in determining the cause of corrosion damages in gas combustion turbines.

Use of CORALL expert system package does not eliminate the need for a thorough metallurgical analysis during the failure investigation since such an analysis is essential in many cases to confirm or ascertain the responsible damage mechanisms.

EXAMPLE OF A DIAGNOSTIC SESSION

For the purpose of demonstrating a diagnostic session with the CORALL expert system, a boiler tube failure [4] in the following Figure 1 was chosen.

Fig.1

This tube failure occurred in a superheater convection circuit of a pulverized coal fired boiler and is characterized by the following parameters, determined through a visual observation:

significant tube deformation in the form of metal elongation and reduction in wall cross-section,

rupture shape is fish-mouth like in appearance,

rupture edge is thin, knife-like,

considerable swelling and increase in tube's diameter.

Beginning at the main menu,

The user selects #2 (steam power plant). CORALL then wants to determine the equipment that has been damaged.

The component under investigation is a boiler tube, the user selects #1. At this point the COREXYS expert system is invoked.

The user knows that the boiler tube failure location is superheater in convection circuits and enters # 8 and ENTER.

Then the system requests information on the shape of the tube rupture on the fourth screen.

From visual observation the user can easily establish that the rupture shape is a fish-mouth like opening and enters #2 and ENTER.

The system automatically determines what to ask next to diagnose the tube failure mechanism. In this case information regarding the rupture edge is required.

Since the tube rupture edge is thin and knife-like, the user enters 2 and presses ENTER.

Based on the provided information, the system performs a diagnosis and determines the boiler tube failure mechanism and displays a summary on screen six.

If your computer has graphics capabilities, COREXYS will then display screen seven.

Screen No.7

Fig.2 Short-term overheating

Hit any key to continue and a one line summary of the conclusion is shown. At this point enter 1 and press ENTER. The rule used to determine the conclusion is displayed in screen eight.

SUMMARY

A rule-based system, to assist thermal power plant staff in recognizing and identifying basic causes of equipment corrosion damage, was developed. This micro-computer based software package is an essential tool for efficient analysis and resolution of equipment problems through correct determination of the failure mechanism which is necessary to establish root cause of the failure. The program allows consistent application of ameliorative measures to effectively mitigate routinely occurring equipment problems. The English version of CORALL expert system is available from Ontario Hydro Technologies. Thermal Power Research Institute in Xian, China, distributes the Chinese version of the package.

REFERENCES

[1] EXSYS is an Expert System Development Package, available from EXSYS Inc. P.O. Box 75158, Contr. 14 Albuquerque, NM 87194, USA.

[2] Metals Handbook, p. 985-1008, Vol. 13, 1987 American Society for Metals (ASM).

[3] Electric Power Research Institute: “Manual for Investigation and Correction of Boiler Tube Failures”, CS-3945, Project No. 1890-1, prepared by Southwestern Research Institute, G.A. Gambling and R.M. Arrowwood Jr., April, 1985.

[4] Canadian Electrical Association: “Analysis and Prevention of Boiler Tube Failures”, 83-273G-31, prepared by Ontario Hydro, R.B. Dooley and H.J. Westwood, November, 1983.