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Enabling 48 Month Maintenance Intervals for IRIS

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IRIS (International Reactor Innovative and Secure) is a small, integral, PWR with a planned 48 month interval between maintenance and refueling outages. The long outage interval creates a number of maintenance challenges. Many of these challenges have been identified in an earlier study by Mark Robert Galvin, in his thesis for the Master of Science at Massachusetts Institute of Technology (MIT), entitled *Maintenance Cycle Extension in Advanced Light Water Reactor Plant Design*. Of the issues identified, three were chosen for further investigation by the Tennessee Valley Authority(TVA): 1) Maintenance of main condenser cleanliness, 2) Testing of pressure relief valves, and 3) Maintenance of turbine electro-hydraulic control fluid. These issues are reviewed, recommendations are given, and needed further work is identified.

KEYWORDS: IRIS, maintenance, condenser cleanliness, relief valves, electro-hydraulic controls, turbine control valves

I. Introduction

IRIS (International Reactor Innovative and Secure) is an advanced light water cooled reactor, designed to enhance safety and lower costs by placing the steam generators, coolant pumps, and pressurizer inside the reactor vessel. An overview of the IRIS design is given by Carelli *et al* [1)].

The initial IRIS core is being designed for a 48 month fuel cycle. To achieve a matching interval between maintenance outages, a number of challenges must be addressed. The most important challenges have been identified in an earlier study by Galvin[2,3)]. They include 1) maintenance of main condenser cleanliness, 2) testing of pressure relief valves, 3) maintenance of turbine electro-hydraulic control (EHC) fluid, 4) inspection of steam generator tube integrity, 5) testing of safety system operability, and 6) trip testing of the main turbine generator.

Of these issues, the first three were chosen for investigation by TVA. The remaining issues are being, or will be investigated by other members of the IRIS consortium.

II. Condenser Cleanliness

Condenser cleanliness is an important factor in determining the efficiency of any steam cycle power plant. It is one controllable variable in determining the temperature at which heat is rejected. This may become economically significant in warm climates where air conditioning is common, and peak electrical loads often coincide with peak ambient temperatures and peak prices (or costs) of electricity. Condenser cleanliness may also affect plant capacity during these peak load times.

1. Fouling Mechanisms and Controls

Condenser fouling may be caused by a number of factors, including biological, chemical and physical mechanisms. Fouling can worsen when these mechanisms occur simultaneously. Control of fouling may be tailored to fit the most important local mechanisms.

(1) Macro-fouling

Macro-fouling occurs when water borne debris is trapped against the tube sheet and blocks or partially blocks a number of tubes. Debris may include aquatic plants, tree leaves, limbs, or whole trees, aquatic or terrestrial animals, and man-made materials such as packaging materials, pallets or even small boats. Various styles of trash racks and traveling screens may be used to minimize this problem. The problem then becomes maintaining these racks and screens. This often involves unpleasant labor conditions. Despite best efforts, it is difficult to guarantee no macro-fouling will penetrate to the plant.

If macro-fouling reaches the tubesheet, it must be removed by opening the water box and manually removing the debris. Often, some debris has become attached to the tube sheet, or has blocked the tubes long enough to create other fouling conditions. If so, a variety of tools can and should be used to thoroughly clean the condenser.

Split water boxes are commonly used to allow such activities while generating at half load. Half of the condenser is drained to allow maintenance access. Extending this idea, it is possible to divide a water box into N sections, and allow maintenance while operating at fraction of full load = 1/(N-1). If economically justified, over-sizing the condenser could allow this maintenance at full load. At Sequoyah Nuclear plant, a three part water box allows online cleaning with no power reduction, under most circumstances.

(2) Biological Fouling

Biological fouling is perhaps the most important fouling mechanism. It typically begins with micro-organisms that produce a layer of viscous, yet adhesive material. Macro-biological fouling often follows as clam and mussel larvae find attractive places to settle and grow.

Biological fouling has commonly been addressed by the periodic or continuous use of oxidizing biocides such as chlorine or its derivatives. Because of concerns about potentially carcinogenic byproducts, chlorine use is being reduced or eliminated in many areas. Low doses of chlorine

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are sometimes effective in controlling biofo uling for a few days or even weeks, but do not ensure against biofouling over longer times, especially when macro-fouling is part of the problem.

Automatic scrubbing devices such as sponge balls or brushes have been found effective in controlling biofouling, but again provide little defense against macro-fouling. While both sponge ball and brush systems are effective, the brush systems are more costly to install, and limit the ability to locate small leaks at the tube sheet, since the brush cages are attached to the tube sheet and block direct access.

(3) Physical Fouling

Physical fouling can occur due to suspended solids (sand, silt, sediment) deposition. This problem is usually controlled by designing for water velocities[4)] in the range of 1.8 to 2.4 m/s, depending on the tube material. Lower velocities are recommended with softer tube materials, such as copper, while higher velocities may be used with stainless steels and titanium. If recommended velocities are maintained, sediment alone is not a serious problem; however, macro-fouling can reduce the local water velocity, and micro-fouling may increase the adhesiveness of the sediment. The sponge ball or brush techniques mentioned above can help control sediment as well as micro-biological fouling.

(4) Chemical Fouling

Chemical fouling mechanisms include oxidation and precipitation of dissolved iron or other metal, as well as various corrosion mechanisms. Corrosion is best controlled by the use of resistant materials. Copper alloys were once popular for condenser tubing because of their good heat transfer and inherent biocide properties, but are now being replaced with stainless steel or titanium. These changes are partly motivated by steam cycle chemistry considerations, where copper tends to migrate and cause problems in steam generators or turbines.

The precipitation of metal oxides can be treated as a special case of physical fouling, and addressed with mechanical scouring systems. Corrosion can also be limited by addressing the other fouling mechanisms, which often provide the stagnant, anaerobic conditions favorable to corrosion.

2. Recommendations for Maintaining Condenser Cleanliness

IRIS is being designed for a world wide market, and the following recommendati ons are those that will generally apply. However, allowance must be made for local water quality, ambient temperatures, environmental regulations, flora and fauna.

1) A divided water box should be used that will allow access to the condenser at partial load. Economic optimization studies are recommended to determine the tradeoffs between 2 divisions and 3 or 4, as well as the merits of over-sizing the condenser.

2) Careful attention should be given to the selection of trash racks or screens. Nominally self-cleaning systems are available and should be evaluated against the estimated labor costs involved in manually maintaining these systems. In any case, plans for final handling and disposal of material removed from the racks or screens should be developed.

3) Sponge ball cleaning systems are recommended to maintain cleanliness in the absence of macro-fouling. Biocide treatment may be considered to enhance control of microbiological fouling, if local regulations permit. The use of alternative biocides, such as ozone, should also be considered.

4) Cooling water velocity should be maintained high enough to prevent suspended solids deposition, but low enough to avoid erosion of condenser tubes. Generally this will be between 1.8 and 2.4 m/s.

5) Corrosion resistant condenser tubes are recommended, generally stainless steel or titanium.

6) Condenser heat transfer should be monitored to detect fouling problems before they become severe.

An excellent summary of condenser maintenance recommendations is found in EPRI 1003088[5)].

III. Pressure Relief Valves

Galvin reviewed American Society of Mechanical Engineers (ASME) Code[6)] requirements for overpressure protection, as well as relief valve testing requirement given by ASME OMb-2000[7)]. All Class I Pressure Relief Devices are required to be tested prior to installation, and again within the initial 5 year operating period. Additionally, a minimum of 20% of these valves are to be tested within any 24 months. The routine testing is to determine valve set point, which must be within 3 percent of nominal.

1. Options for Relief Valve Testing

To meet the above requirements, and still allow a 48 month period between maintenance outages, Galvin recommended further evaluation of two options:

- Assisted lift devices (such as those by Furmanite) may be used to facilitate on-line testing.
- The use of a Code compliant, isolation valve with appropriate interlocks, to isolate one relief valve (of a redundant pair) for testing.

Either method requires provisions for access to the relief valves within the containment, and due consideration of personnel safety and working conditions. Ambient temperature will need to be controlled or limited, and provisions should be made to handle leakage of high-temperature, high- pressure steam if the tested valve or isolation valve fails to fully reseal. The IRIS containment is maintained under an inert nitrogen atmosphere, so personnel breathing equipment will be required. System facilities will need to be designed to allow for the ingress and egress of test personnel and equipment and should include adequate radiation shielding to limit test personnel exposures while in the area. This should be feasible, since the core will be shielded with more than 1.5 meters of water and steel, and radiation fields will be low.

Either method will require additional, redundant relief valves. .

(1) Assisted lift testing on-line

Assisted opening (and closing) will minimize valve chatter that can damage the valve seat, and no system overpressure is required. Furthermore, if assisted lift is used to test a pilot-operated valve, only a small flow volume is required through the pilot valve. The main valve does not need to be fully opened at each test, but should be tested at each refueling outage.

This option provides the simplest solution to the problem of long term fuel cycles, but poses the most detrimental process for maintaining the long-term functionality of the relief valve. The major points of consideration for this design and test methodology include access to routinely perform the tests, design of the support system piping to accommodate the testing, and the possible degradation of the relief valve seat areas resulting from the periodic part-stroke lift of the valve.

Access to perform the testing implies space to attach and operate test equipment (dictated by available vendor test equipment), as well as the personnel safety considerations discussed above.

Support system design considerations include the effects of thermal expansion on the valve's attached piping and the ability of the discharge piping and system components to accept and quench the high pressure, high temperature fluids. System design should also include contingency to accommodate some possible continued leakage after the testing is completed. Leakage may occur for a relatively short period of time, or may need to be accommodated and controlled until such time as the valve can be repaired.

Relief valve seat leakage following use of assisted-lift testing devices frequently occurs in practical applications with high pressure and high temperature system components. Extremely robust seat material and obturator facing materials are required in the design of a valve arrangement, where the valve would be periodically opened a small amount, in order to mitigate the effects of high pressure fluid erosion of the seating faces. In some cases, this minor leakage will reduce back to zero over time as the valve's environmental conditions return to normal following the completion of the test actuation, provided the seating surfaces have not been eroded. However, even if the valve seating areas were not damaged during the testing phases, the presence of minor leakage following closure of the valve could result in significant erosion. At a minimum, the assisted-lift test equipment (such as that available from Furmanite) should allow for enhanced re-seating of a leaking valve. .

(2) Code Compliant Isolation Valves

If code compliant isolation valves can be designed, in-place testing of isolated valves can then be done on-line, in the conventional manner, or with assisted lift.

This option will require significant design development, with support from a valve supplier. The design problem could be difficult and expensive, since it requires isolation valve or valves to operate at high temperature and pressure, and may require independent, diverse interlocks, perhaps including instrumentation and controls to open and/or prevent closure of the appropriate valves. The increased complication inherently increases the possibility of failure of the component through increased number of system sub-components and the increased interface with the human element needed to maintain the system.

Boiler and Pressure Vessel Code Case #2254, "Changeover Valves Installed Between Safety Valves or Safety Relief Valves and Boilers," provides direct guidance on possible modified system designs for relief valves and use of in-series isolation valves. However, this Code Case is currently limited to application for boilers fabricated and constructed to the requirements of ASME Section I and for designs whose maximum allowable working pressure does not exceed 800 psi (5.52 MPa). A similar Code Case would have to be developed for application with the IRIS design for operating components with design pressures of 2500 psia (17.24 MPa), if it is not practical to fully meet all of the requirements of NB-7142.

A system design with a common 3-way valve (as originally suggested by Galvin) carries with it a higher possibility of common-mode failure. Any degradation of the common valve affects the operability of all of the redundant relief valves simultaneously and may negate the benefits of redundancy. The use of testing apparatus on the common line header also increases the probability of the introduction of debris which may foul the operation of the 3-way valve or transport it to the other redundant relief valve. However, the use of a system design with individual code compliant isolation valves, perhaps one or two associated with each relief valve, also carries the greater possibility of wear based failures that would result in forced shutdowns for repairs [e.g. more components, more probability of failure]. But the use of individual isolation valve sets would reduce the average use or operation of each individual isolation valve, delay the eventual wear failure of a specific valve's packing, and offset the increased failure probability due to increased numbers of components. Conversely, the use of a 3-way common valve increases the wear on a single valve's packing.

The use of a common 3-way isolation valve will have a more intrusive effect resulting from the thermal expansion of the system piping. Unequal thermal movement of piping arrangements has contributed in current PWR operating units to the occurrence of relief valve seat leakage. Changes in area ventilation characteristics have also resulted in relief valves leaking by their seats.

It should be noted that the use of isolation valves with relief valves to allow for periodic testing, and possible in-service maintenance of the relief valves, increases the element of human error and results in higher risk of associated failures. Provisions for objective verification of the position of the isolation valves, on a continuous and routine basis, must be incorporated into the system design, instrumentation and controls, and plant operating procedures. Use of a continuous monitoring such as an area video camera located in the relief valve vault coupled with physical valve designs such as locked-open valve position features will facilitate meeting the requirements of NB-7142.

Note that the desire to allow for on-line maintenance of the relief valves during plant operation will also require that the design of the individual valve's discharge lines include the capability of being isolated from the common discharge control volume.

2. Recommendations for Relief Valve Testing

Pilot-operated valves are recommended, since they are less prone to valve chatter, and testing does not require repeated opening and closing of the main valve under flow conditions. Thus, two major damage mechanisms are minimized.

It is recommended that designs for redundant pilot-operated relief valve assemblies with provisions to periodically isolate, test, and/or maintain the pilot-valve cartridge be developed for use in the IRIS systems. A significant effort may be required to properly design such a system, but designing a system to isolate pilot valves should be a more tractable problem than isolating the main relief valves.

This option will necessitate the development of the supporting ASME Code Case with provisions and guidelines similar to those shown in ASME Section I code Case #2254. The use of an assisted-lift test device on the pilot valve (or arrangements for test pressurization connections to the isolated pilot valve cartridge) should also be incorporated into this proposed design.

We estimate that submittal of a code case will require about one man-year of effort, and four to six years of elapsed time. This is in addition to the design effort mentioned above.

Such a design would accommodate in-situ testing and minimize the effect of valve seat damage resulting from the periodic part-stroke of the main valve. This design configuration could accommodate removal and repair of the pilot actuator, if it becomes necessary. Any such configuration would also be required to meet the requirements of ASME Section III, paragraph NB-7142. This design configuration can provide for periodic in-service verification of the pilot valve's functionality, but will need to be coupled with assisted-lift device tests of the pilot valve with it actuating the main relief valve assembly during planned outage periods. Such testing could be conducted at the start of the refueling outage immediately following shutdown of the reactor and prior to the full cool down of the system. In this manner, any identified degradation of the valve could be planned and corrected during the refueling outage.

IV. Turbine Electro-Hydraulic Control (EHC) Fluids

1. Problem Definition

Galvin identified sludge build up in EHC fluid as one of the six problems that needed to be resolved to enable a 48 month maintenance outage interval. He suggested a number of potential enhancements to current system, but recommended a cautious "operate and assess" approach to these. The first two are based on the possibility that fluid stagnation in dead zones of the system is a significant causal factor, especially when operating continuously at fixed load. His suggestions were:

- When operating at steady state, automatically generated dithering signals could be used to stroke the controls by imperceptible amounts and disturb low flow regions, without affecting the generator output.
- Ultrasonic transducers could be used for a similar effect, to agitate the fluid.
- Synthetic fluids could be substituted for petroleum-based fluid.

EPRI has sponsored several studies of turbine electro-hydraulic controls (EHC). EPRI TR-107069[8)] included a review of Licensee Event Reports (LERs) filed with the U.S. Nuclear Regulatory Commission. In the period from January 1990 through June 1996, about 50 serious events (mostly reactor trips) were associated with the hydraulic portion of the EHC system. These events were further analyzed to determine root causes if possible, and other contributing factors. Five major contributing factors were identified, starting with the most frequent:

1. Vibration.
2. Electrical failure.
3. Testing procedures.
4. Maintenance or operational errors.
5. Fluid contamination.

Of these, Galvin identified only EHC fluid as being a problem. This problem is characterized by sludge or sediment in the hydraulic fluid, which can then cause malfunctions in actuators or plugging of lines. Many factors influencing fluid degradation were identified in the above mentioned EPRI report. The major contaminants were:

- Air
- Water
- Miscellaneous foreign material, such as dust.
- Incompatible materials, especially elastomers in o-rings and gaskets

Often, these problems are the result of poorly planned or executed maintenance or testing procedures.

Aggravating factors include high temperatures, leakage, inadequate volumes of fluid, and inadequate filtration rates. High temperatures are known to accelerate fluid breakdown. This problem is mitigated by isolating or insulating lines from external heat sources, and by providing adequate cooling. Vibration may cause fatigue damage, especially at pipe or tubing joints. The resulting leaks may contribute to fluid contamination from external sources. An EPRI report[9)] is available to help address problems with piping and tubing.

Entrained air can cause compression-ignition or 'dieseling', and this can result in carbon black from partially burned fluid. This problem is mitigated by designing the system to avoid repeated pressure stress. Instead of using constant speed pumps and continually recycling fluid through a relief valve, a variable displacement pump is recommended. The cause of air entrainment should also be addressed, and the choice of EHC fluids should be reviewed, since some formulas have shorter air release times than others.

All recommended fluids are tri-aryl phosphates, which were developed to insure fire resistance. They are derived from natural feedstock, either coal or petroleum, but are highly processed. A confusing and arcane nomenclature has developed that refers to those with xylenyl groups (originally found in coal tar) as 'natural', and those with phenol groups (from processed petroleum) as 'synthetic'. This is made increasingly obscure since 'natural' fluids are now generally manufactured from the oxidation of hydrocarbons (usually from petroleum) as well. No one formulation is universally recommended. Key characteristics are air release time, hydrolytic stability and bulk oxidation resistance. The best air release times and hydrolytic stability are reported to be with 'natural' formulations, while the best bulk oxidation resistance is with 'synthetic' formulations.

A more recent EPRI publication[10)] is devoted entirely to EHC fluid maintenance. It contains recommendations for fluid selection, storage, make-up, sampling and analysis, condition monitoring, purification, and troubleshooting. Table 11-1 of that report gives a brief summary of recommended fluid test frequencies, along with recommended operational limits.

EPRI staff feels that careful application of the lessons learned in the above report will allow users to avoid problems from sludge buildup, although not all reported cases are well understood.

TVA staff report no problems with sludge in the EHC fluid of our nuclear plants, but did report sludge in the EHC fluid of a fossil (coal-fired) plant. These were resolved by careful attention to procedures recommended by the fluid vendor.

2. Recommendations for Electro-Hydraulic Fluid Maintenance

Careful attention to the recommendations provided in EPRI 1004554, especially the periodic monitoring of fluid properties shown in Table 11-1, should allow users to avoid serious problems. Monthly sampling intervals are suggested for many parameters, but for the first installation of a new design, more frequent sampling is desirable. In addition, we recommend that the design should permit easy changes of all filtration media while on-line.

V. Conclusions

Three challenging areas for maintaining plant availability over a 48 month fuel cycle have been identified, and methods for resolving them are proposed. Much work remains but no insurmountable obstacles appear to exist.

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