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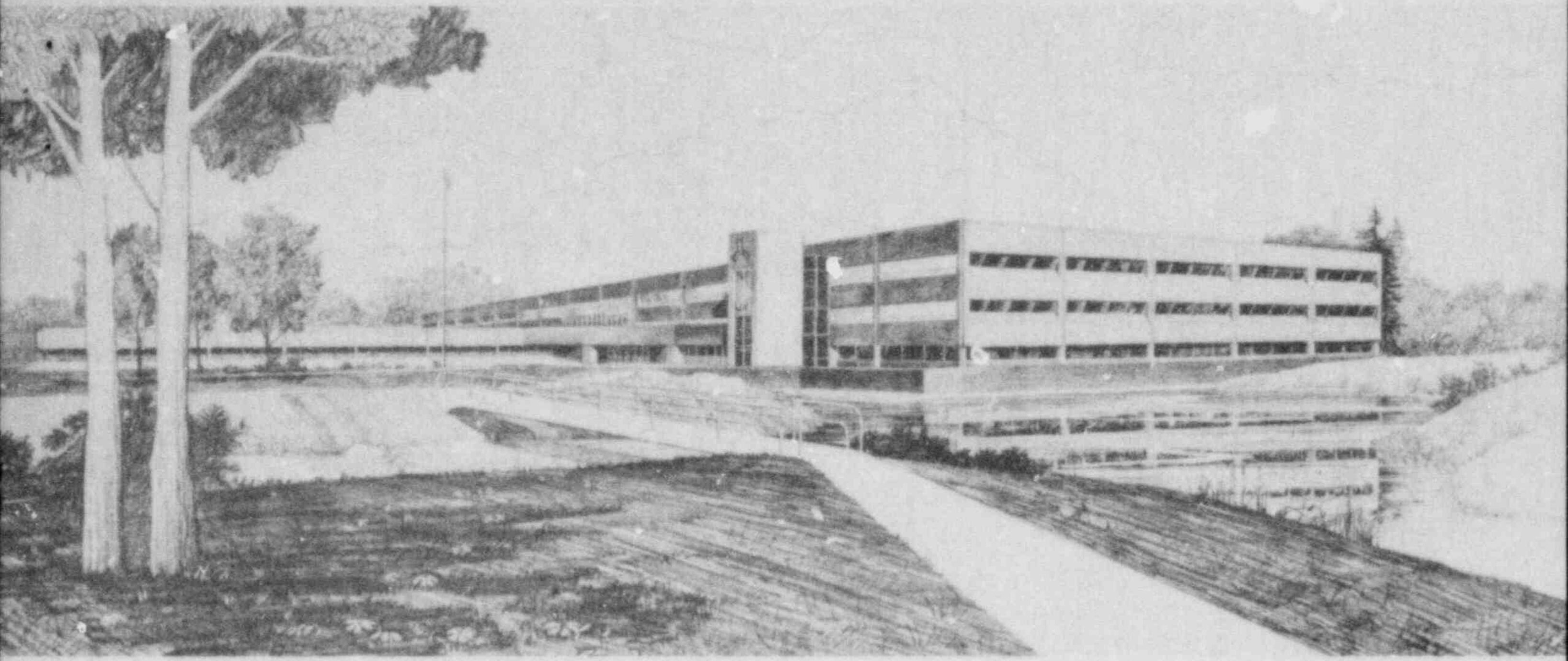

Idaho National Engineering Laboratory
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Assessment of Reactor Coolant Pump Instrumentation in Support of Coolant Inventory Trend Analysis

Alvin E. Arave

September 1984

Prepared for the
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ASSESSMENT OF REACTOR COOLANT PUMP INSTRUMENTATION IN SUPPORT OF COOLANT INVENTORY TREND ANALYSIS

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ABSTRACT

Reactor coolant pump motor power and temperature measurements are used by Babcock & Wilcox (B&W) plant owners to calculate void fraction for trending ICC conditions while the pumps are running. This new measurement technology satisfies NUREG-0737, Item II. F.2, "... licensees shall provide. . .additional instrumentation. . .to supplement existing instrumentation in order to provide an unambiguous, easy-to-interpret indication of inadequate core cooling." In this report, the Nuclear Power Plant Instrument Evaluation (NPPIE) project compares system accuracy, capability, and limitations to measurement requirements using small-break test data and full-scale plant analytical studies. Small-break experimental data show that ICC void fraction calculations are conservative compared to gamma densitometer void fraction measurements in the pipe just upstream of the pumps and liquid level conductivity probes in the reactor vessel. Analytical studies verify that a measure of void fraction at the pumps is conservative relative to the desired coolant inventory trend conditions in the reactor vessel.

FIN No. A6369—Power Plant Instrumentation Evaluation

SUMMARY

The United States nuclear industry is currently in the process of implementing NUREG-0737, Supplement No. 1, *Requirements for Emergency Response Capability (Generic Letter No. 82-33).* The requirements in this document include instrumentation for determining inadequate core cooling (ICC) in pressurized water reactors (PWRs) while the pumps are running. In response to this requirement, the reported detection system uses the reactor coolant pump (RCP) motor current or power measurements, system pressure, and pump inlet temperature to calculate and indicate coolant void fraction and inventory trends.

With these measurements, the void fraction calculation is relatively easy to implement since it uses existing plant measurement data (available in the plant computer) as an input for the analytical model. In some cases, a power transducer or current transducer signal has to be installed and/or routed before all outputs can be measured at the computer. Besides these measurements, this analytical model also uses pump volumetric flow, operating head, mechanical efficiency, electrical efficiency, and motor power factor; however, in most designs these can be treated as constants for void fractions less than 30%.

Loss-of-Fluid Test (LOFT) small-break experimental data show that void fraction calculations using this system are conservatively high compared to a gamma densitometer void fraction measurement in the pipe just upstream of the pumps and the average primary system void fraction. The Electric Power Research Institute's (EPRI) analytical studies also show that a measure of void fraction at the pumps is expected to be conservatively high relative to the coolant inventory trend conditions in the primary system of a commercial PWR. Specifically, these studies show that the system provides a void fraction measurement with a 10% accuracy for void fractions less than 30%. Beyond a 30% void fraction, variations in the pump efficiency and flow parameters exceed the validity limits of the void fraction calculation algorithm.

The plant operator obtains void fraction trend data at a CRT terminal upon command with an operating procedure constraint that this information only be used for backup. Nonsafety grade RCP motor switchgear, and in some cases a nonsafety grade containment building, dictate this constraint on the ICC operating procedures.

This report concludes that the ICC trend indicator for use with pumps running is easy to implement and practical for the operator to use and meets the intent of NUREG-0737, Supplement No. 1.

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ASSESSMENT OF REACTOR COOLANT PUMP INSTRUMENTATION IN SUPPORT OF COOLANT INVENTORY TREND ANALYSIS

1. INTRODUCTION

The United States nuclear industry is currently in the process of implementing NUREG-0737, Supplement No. 1, *Requirements for Emergency Response Capability (Generic Letter No. 82-33).*"[1] The requirements in this document include instrumentation to determine inadequate core cooling (ICC) in pressurized water reactors (PWRs) while the pumps are running. These systems are required to meet the instrumentation qualification criteria in *Regulatory Guide* (RG) 1.97 Category 1.[2] These criteria are intended to be the same as the RG 1.89,[3] Class 1E instrumentation qualification requirements.[4] Since most utilities use RG 1.89, Class 1E terminology, this report will use Class 1E criteria to identify RG 1.97, Category 1 instrumentation qualification criteria.

The detection system discussed below uses reactor coolant pump (RCP) motor current or power measurements and pump inlet temperature to indicate the primary coolant system void fraction and inventory trends to meet the requirements of NUREG-0737 Section II.F.2, that states, "licensees shall provide a description of additional instrumentation or controls proposed for the plant to supplement existing instrumentation in order to provide an unambiguous, easy-to-interpret indication of inadequate core cooling." An unambiguous indication of ICC is defined in NUREG-0737 as an indication of the existence of ICC caused by high void fraction in the pumped flow as well as stagnant boil-off but, does not erroneously indicate ICC. A further measurement requirement is that the instrumentation give advanced warning of the approach of ICC. NUREG-0737 also requires that the ICC measurement system instrumentation meet the Category 1 design guidelines of RG 1.97 when used as the primary loss-of-coolant accident (LOCA) indicator.

After the TMI-2 incident, the NRC encouraged, in NUREG-0623[5], a trip of the Primary Coolant Pumps (RCPs) following reactor trip and indication of High Pressure Injection (HPI) actuation. This was a conservative decision based on various LOCA and plant specific variables. The NRC "recognized the potential desirability of running the reactor coolant pumps to provide forced circulation during small break LOCAs and. . .encouraged the continued exploration by the industry of means by which this could be accomplished."[5] Monitoring pump motor current has been recognized as a method of determining coolant system void fraction that could allow delaying pump trip until the system void fraction approaches a condition that could cause core damage if the pumps were turned off. Proof of the validity of the pump current measurement method of monitoring coolant trend was demonstrated at the Idaho National Engineering Laboratory (INEL) Loss-of-Fluid Test (LOFT) experiment. A RCP power measurement model from which void fraction can be calculated was developed and verified with small break data taken while the RCPs were running (Experiment L3-6).

It should be noted that the LOFT measurement system hardware described below was implemented to verify the analytical model and does not represent the system prototype design required by the utilities. The parts of the LOFT instrumentation system and data analyses applicable to commercial power plant designs are discussed in Section 5.3.

Rather than using the RCP current measurement, as suggested by LOFT reports[6] for pump trip criteria, many Babcock & Wilcox (B&W) plant owners have elected to use the RCP current measurement in calculating void fraction to satisfy the requirements of NUREG-0737, Supplement 1 that requests a measure of ICC inventory trends while the RCPs are running (this requirement is imposed regardless of the pump trip criteria). The B&W plant designers made a study of void trending measurement methods for their plant and recommended the RCP motor power void fraction calculation to the B&W plant owners. They also offered a computer software package that some of the plants purchased.

At least six B&W plant owners plan to implement the RCP power measurement to indicate void fraction and coolant trends during a LOCA with the pumps running. All of these have expressed concern about their ability to meet Category 1 design and qualification criteria as directed by RG 1.97. They contend that the RCP electrical power supply system is only designed to Category 3 requirements; therefore, there is no need to go to the expense of installing a Category 1 Power measurement system (see Section 3.3).

The information reported below is an assessment of the pump power measurement instrumentation and is limited to:

1. Provide background information on this relatively new measurement
2. Identify the pertinent coolant inventory measurement and trend system design requirements per NRC guidelines
3. Examine the details of the void fraction calculation analytical model
4. Consider design configurations for interfacing with existing plant instrumentation
5. Examine the system range, accuracy, and response capability to indicate local void fraction at the pumps
6. Evaluate the adequacy of local pump void fraction calculation to indicate void fraction trend in the core.

It should be noted that the signal processing technique to implement the algorithm is plant specific and is not a topic of discussion in this report. Also, it is not the intent of this report to identify pump trip criteria or methods. However, some referenced reports and monitoring techniques discussed were prepared as pump trip studies.

2. BACKGROUND INFORMATION

Following the TMI-2 accident, test data and analyses[5] indicated that for optimum reactor core protection against over heating, the RC pumps should not be left running during a LOCA. TMI-2 data and small break LOCA analyses show that during a LOCA there is a higher probability of more liquid inventory loss than with pumps off. Without RC pumps running, the liquid loss can greatly decrease as soon as the stratified primary system liquid level drops below the break elevation. Continued RC pump operation can cause a higher reactor coolant system mass loss and can, under some circumstances, result in a core uncovery if the pumps are turned off late in a LOCA. This occurred at TMI-2.

NRC responded to this information by requesting[5] that RCPs be tripped immediately following an indication that a LOCA has occurred (RC pressure dropping below the HPI setpoint) Another proposed pump trip criteria is acceptable provided it is adequately justified. As a result, most plant operating procedures call for trip of reactor coolant pumps when the HPI setpoint is reached. As a backup, when the pumps might be left running or restarted, NRC has requested, in NUREG-0737, that a capability to measure coolant inventory trend during a LOCA with pumps running be implemented by using existing plant instrumentation.

Analyses based on vendor calculations[6] supported by LOFT data[7] show that by not tripping the pumps early in a LOCA it is easier to:

1. Maintain pressure control (pressurizer spray)
2. Cool the reactor core
3. Minimize risk of pressurized thermal shock
4. Provide head coolant and minimize bubble development.

For these reasons, additional research was done to determine if an alternate pump trip criteria could be developed that would allow keeping the pumps running and at the same time prevent reaching dangerously high system void fractions. As a result, an analytical model using a RCP motor power measurement (see Section 4) from which a local pump void fraction could be calculated was developed at the Idaho National Engineering Laboratory (INEL) by the LOFT Program.[6] LOFT small break test data verified that RCP motor power or current is related to reactor coolant system density. This relationship allows the operator to use the motor power or current to monitor the RCS inventory and institute a more selective pump trip criteria. The operator display (J-plot) developed and verified using LOFT test data in support of an alternate pump trip criteria, monitored RCP motor current or power versus cold leg temperature on a CRT as shown in Figure 1.

Since pump motor power is proportional to the density of the fluid being pumped, the LOFT J-plot display shows the relationship between coolant density and temperature at any time. The plot is essentially a single value relationship for subcooled conditions and multivalued for saturated two-phase flow. The direction of display movement identifies the increase or decrease of coolant trend void fraction. This type of display is referred to as a J-plot because of the characteristic shape when the pump motor power is plotted versus cold leg temperature for single-phase and two-phase transients. The display technique was verified with LOFT transient experiment data in which the pumps were left running. The operator can determine the coolant inventory trend at any time by observing the J-plot and can trip the RCPs before the void fraction becomes enough high to damage the core.

Use of the J-plot display to delay RCP trips during a loss of coolant accident will:

1. Allow separation of overcooling transients from LOCA events, e.g., pumps will not be tripped during overcooling events

2. Provide measurement of loop voiding as a trigger for RCP and high pressure safety injection (HPSI) control

3. Allow the operator to leave the RCPs on during LOCAs when HPSI can make up the break flow

4. Minimize mass loss from the Reactor Coolant System

5. Minimize radiation release to environment

6. Minimize operator action uncertainty.

This proposed LOFT J-plot pump trip criteria is under investigation by EPRI.[7] Implementation of the pump trip criteria requires a willingness on the part of the utilities to rewrite operating procedures, to requalify reactor operators, and to submit a justification request to NRC licensing.

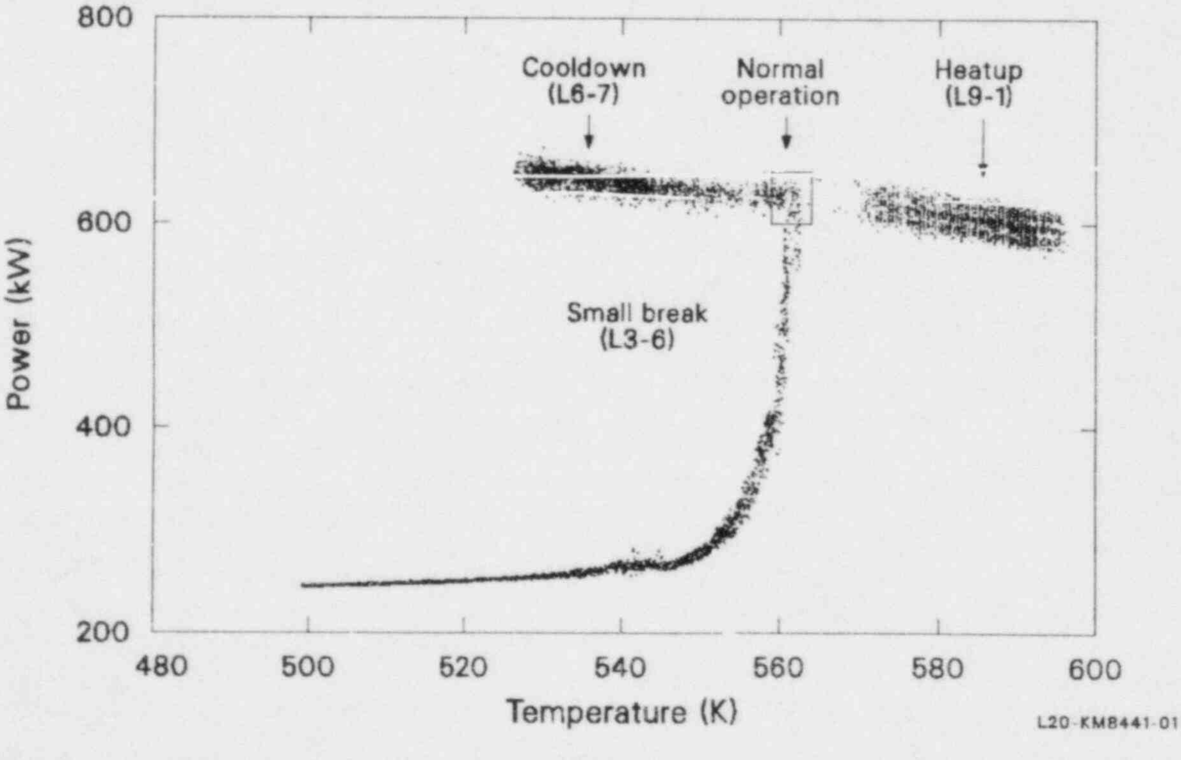

Figure 1. Operator's display (J-plot) with data from LOFT experiment.

3. SYSTEM HARDWARE REQUIREMENTS

The following section reviews the pertinent system requirements for system Class 1E design. Furthermore, the requirements for measurement, plant and operator interface, and performance qualification are reviewed and discussed.

3.1 Measurement Requirements

The pertinent functional measurement requirements for a pump power void fraction measurement system are paraphrased from NUREG-0737 and RG 1.97 with some discussion. Accuracy and range requirements are not specified. Studies[7,8] conducted by EG&G Idaho Inc. defines the void fraction range in which the pump power measurements can accurately trend void fraction (see Section 6).

The functional requirements with comments are listed below.

1. Environmental qualification of the system should be done in accordance with Regulatory Guide 1.89 and NUREG-0588.
2. A non-Class 1E display system (CRT) can be used in conjunction with computer signal processing providing that:
    a. A 99% availability of the display system exists
    b. The system has postaccident maintenance accessibility for nonredundant portions of the system
    c. There are diverse methods of monitoring the parameters which include completely qualified display systems. This allows use of a CRT display but requires an indicating device for operator backup information.
3. Class 1E qualification applies from the sensor and includes the isolation device when the instrumentation channel signal is used with a computer-based display, recording, and/or diagnostic program. All of the plants interviewed intend to measure the pump power or current at the coolant pump electrical switchgear with existing transducers and cabling or by installation of new transducers and cabling, none of which are qualified.
4. The instrumentation should be energized from station Class 1E power sources that requires a backup power source such as an auxiliary diesel power electric generator for the primary coolant pump motors.
5. To the extent practical, the sensors should directly measure the desired variables. However, in this case pump power indirectly measures void fraction at the pump that in turn indirectly indicates the void fraction in the reactor core region.
6. In order to meet seismic requirements, the building housing the pump power void fraction monitoring system instruments must be seismically qualified. However, in most of the plants the switchgear is not housed in a seismically qualified building. The Bellefonte Plant uses a seismic qualified Auxiliary Building to house the switch gear.

3.2 Plant and Operator Interface Requirements

The following plants and operator interface requirements are paraphrased from Appendix B of NUREG-0737 and from RG 1.97.

1. Continuous real time indication should be provided at all times. This may be on a dial, CRT, or strip chart recorder indicator. Most of the plants display coolant trend on a computer CRT display terminal along with various other plant parameters, but only plan on displaying the information upon request of the user. However, some plants will additionally use a continuous indication on a dial and/or strip chart recorder.
2. Recording of instrumentation readout information should be provided. Where trend or transient information is essential for operator information or action, the

recording should be performed by analog strip chart or stored and displayed continuously on demand. Intermittent displays, such as data loggers and scanning recorders, may be used if no significant transient response information is likely to be lost by such devices. It is reported that trend histories as high as 6 h will be displayed, some on CRT terminals and some on strip chart recorders.

3. The void fraction and/or trend indicator should be specifically identified so the operator can easily discern that they are intended for use under accident conditions. Using the same reasoning, it is not clear that the operators will always understand that the validity of the coolant trend is limited to 30% void fraction.

4. If the coolant system measurements supply signals to other instruments, the signals should be transmitted through isolation devices designated as part of the Class 1E monitoring instrumentation.

5. The void fraction and trend display and alarms must be designed to meet; (a) the human-factors conditions, (b) emergency procedures, (c) operator training, and (d) plant alarm criteria.

6. The monitoring instrumentation design should minimize the development of conditions that would cause meters, annunciators, recorders, alarms, etc., to give anomalous indications that could potentially confuse an operator. The software algorithm to calculate void fraction from pump power and inlet saturation temperature or pressure should place bounds on these input parameters and provide a warning if they are exceeded to prevent anomalous indication of coolant trend.

3.3 Performance Qualification

NUREG-0588-1, *Revision 1 Interim Staff Position in Environmental Qualification of Safety-Related Electrical Equipment*, endorses IEEE Std 323-1974 stating that environmental qualification can be obtained by at least three different methods that include:

1. Laboratory testing under controlled conditions

2. Operating experience or limits of extrapolation of other data, failure modes, and failure rates

3. Single-failure analysis of electrical equipment backed by test data, operating experience or physical laws of nature.

For qualification by laboratory testing it is required that the equipment be able to function in the environments and operating conditions of an accident. None of the RCP power system switchgear in the plants surveyed are qualified to Class 1E criteria. Likewise, neither are the current or power transducers qualified to Class 1E criteria.

Operating experience is of limited use as the sole means of qualification but of great use for the supplementation of testing in that it may provide an insight into the change in behavior of equipment under actual service conditions. The LOFT pump power transducer data partially satisfy this criteria. The utilities' history of past use of switchgear and current transducers could also help qualify the instrumentation system to Class 1E criteria. Also, the power and current transducers could possibly be qualified as Class 1E isolation devices by a combination of analysis and test.

Qualification by analysis must include justification of methods, theories, and assumptions used, therefore, instrumentation system analysis would be neither necessary nor sufficient. This analysis may, however, be effective in the extrapolation of test data and determination of the effects of minor design changes on equipment previously tested. For instance, the LOFT small pump data may help qualify the utility's large pump power transducers since the same power transducers used by LOFT are used in large pump switch gear circuits. However, the many years of power transducer operation in commercial PWRs is more significant as qualification data.

With all qualification methods, the end result will be the documentation that must demonstrate the equipment's adequacy to perform its required function. Studies[7,8] qualify the measurement technique, at least, to the extent possible with no two-phase flow data available on applicable commercial sized

RCPs. But additional work remains to be done to qualify the instrumentation to Class 1E criteria if it is required.

If the void fraction calculation system input channels are not environmentally qualified to Class 1E criteria, NUREG-0737, Supplement 1 clearly states that the system cannot be used "to perform a necessary safety function." In that case, the resulting calculated void fraction trend information can only be used as "back-up" to other instrumentation that the operator uses to monitor a LOCA.

3.4 Compliance Conclusions

The above review of requirements show that the pump power measurement systems being implemented are not a safety grade quality design. Some of the inherently obvious limitations of the generic design in meeting the requirements of a safety grade system are:

1. Unavailability of Class 1E switchgear and transducer hardware
2. Computer terminal data trend indications upon request do not meet the continuous display requirements
3. The system does not "directly" measure average coolant trend
4. Some buildings that house switchgear are not seismically qualified.

It is outside the scope of this report to evaluate the consequence of these variations. However, it is hoped that by stating these apparent areas of non-compliance, appropriate and/or necessary action can be taken by others to resolve the issues.

4. VOID FRACTION CALCULATION ANALYTICAL MODEL

This section defines the analytical model that relates pump motor power measurements to local density and void fraction at the pump inlet. A plant computer software program uses this analytical model to calculate void fractions for display of primary coolant system trends. The analytical model is based on simple centrifugal pump theory with assumptions stated that are necessary for extrapolation of the theory to two-phase flow.[6,7,8] The following derivation defines the relationship between pump motor power and the density of the media being pumped in terms of pump and motor characteristics. Then, by relating the pump equation to a reference power and density condition, all pump and motor characteristic parameters that are of a constant value cancel leaving the media reference average density expressed in terms of reference pump power, fluid density, and the measured pump motor power. The calculation of void fraction uses this average two-phase density calculated from pump power, fluid density, and gas density. The steam tables list the fluid and gas density information as a function of measured coolant temperature and pressure.

The shaft power required for a constant speed centrifugal pump in single-phase flow and two-phase bubbly (homogeneous distribution of small bubbles) flow can be defined as

$$P_s = \frac{Q H \rho}{\eta_p} \tag{1}$$

where

P_s = pump shaft power (W)

Q = volumetric flow rate $(M^3/5)$

H = pump head (m)

ρ = average coolant density in the pump impeller (kg/m^3)

η_p = pump efficiency.

This equation is simplified by first normalizing it to reference conditions

$$\frac{P_s}{P_{sr}} = \frac{\eta_{pr} \; Q \; H \; \rho}{\eta_p \; Q_r \; H_r \; \rho_r} \tag{2}$$

where the subscript "r" denotes a reference condition.

Generally, the pump volumetric flow rate and the pump head change very little from single-phase to small void fraction two-phase flow.[2] Therefore, assuming that

$$H_r = H$$

and

$$Q_r = Q \ .$$

Equation (2) simplifies to

$$\frac{P_s}{P_{sr}} = \frac{\eta_{pr}}{\eta_p} \frac{\rho}{\rho_r} \ . \tag{3}$$

This equation relates pump shaft power to coolant density. Pump motor power is related to shaft power by

$$P_m = \eta_e P_s \tag{4}$$

where

P_m = motor power

η_e = motor efficiency.

Combining Equations (3) and (4) produces the relationship between pump motor power and coolant density,

$$\frac{\rho}{\rho_r} = \frac{\eta_{pr}\ \eta_e\ P_m}{\eta_p\ \eta_{er}\ P_{mr}} \ . \tag{5}$$

Pump motor current is also directly proportional to coolant density. The relationship between pump motor current and power is

$$P_m = IV \ \mathrm{Cos}\Theta$$

where

I = root mean square current

V = roor mean square voltage

Θ = phase angle.

For an induction motor running at constant speed, the voltage is constant. Therefore,

$$\frac{P_m}{P_{mr}} = \frac{\mathrm{Cos}\Theta}{\mathrm{Cos}\Theta} \frac{I}{I_r} \ . \tag{6}$$

The analytical equations defining the coolant density in single-phase and two-phase bubbly flow in terms of RCP motor power and current are

$$\frac{\rho}{\rho_r} = \frac{\eta_{pr}}{\eta_p} \frac{\eta_e}{h_{er}} \frac{P_m}{P_{mr}} \tag{7}$$

and

$$\frac{P}{\rho_r} = \frac{\eta_{pr}\ \eta_e}{\eta_p\ \eta_{er}} \frac{\mathrm{Cos}\Theta}{\mathrm{Cos}\Theta_r} \frac{I_m}{I_{mr}} \ . \tag{8}$$

Equations (7) and (8) can be further simplified by assuming the pump efficiency at any time and fluid condition is the same as that of the reference condition, $\eta_p = \eta_{pr}$, by reasoning that the mechanical friction losses and hydraulic losses at the pump impeller are constant.[6]

$$\frac{\rho}{\rho_r} = \frac{\eta_e}{\eta_{er}} \frac{P_m}{P_{mr}} \tag{9}$$

and

$$\frac{\rho}{\rho_r} = \frac{\eta_e}{\eta_{er}} \frac{\mathrm{Cos}\Theta}{\mathrm{Cos}\Theta_r} \frac{I_m}{I_{mr}} \ . \tag{10}$$

The parameters that remain in Equations (9) and (10) are motor efficiency and motor power factor both of which can be obtained from pump motor manufacture's specifications. Figure 2 shows the characteristics of these parameters as a function of load for a typical utility primary coolant pump. For void fractions less than 30%, the homogeneous flow region where Equation (1) is valid, the pump load changes from 10,000 to 6,000 hp. In this range, the variations in motor efficiency and motor power factor are relatively small and can be treated as constants. Therefore, Equations (9) and (10) can further be simplified to

$$\frac{\rho}{\rho_r} = \frac{P_m}{P_{mr}} \tag{11}$$

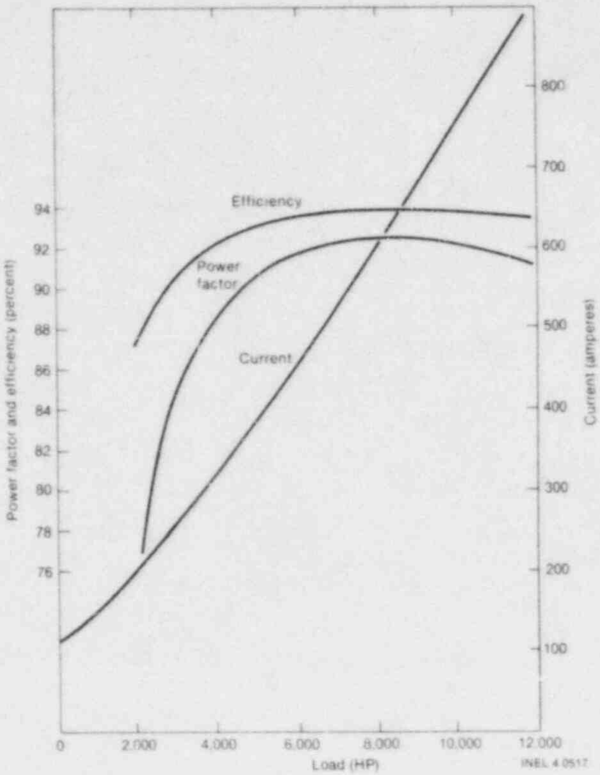

Figure 2. Motor characteristics.

and

$$\frac{\rho}{\rho_r} = \frac{I_m}{I_{mr}} \quad . \tag{12}$$

The next step relates the void fraction equation

$$\alpha = (\rho_f - \rho)/(\rho_f - \rho_g) \tag{13}$$

in terms of pump motor power and current

where

ρ_f = liquid density

ρ_g = vapor

α = homogeneous void fraction.

Substituting Equations (11) and (12) into Equation (13), the analytical model for calculation of void fraction is obtained in terms of pump motor power or current, liquid density, and vapor density.

$$\alpha = \left(\rho_f - \rho_r \frac{P_m}{P_{mr}}\right) \Bigg/ \left(\rho_f - \rho_g\right) \tag{14}$$

and

$$\alpha = \left(\rho_f - \rho_r \frac{I_m}{I_{mr}}\right) \Bigg/ \left(\rho_f - \rho_g\right) \tag{15}$$

The density of the steam is less than 4.4% of the liquid therefore it can be seen that the coolant void fraction is proportional to the pump motor power.

$$\alpha = 1 - \frac{\rho_r}{\rho_f} \frac{P_m}{P_{mr}} \quad . \tag{16}$$

As shown, the model for this measurement is relatively simple and straight forward. However, the user should carefully examine the assumptions made to determine the limits of validity of the model and not to use it for fluid conditions outside stated limits.

5. DESIGN CONFIGURATIONS

Existing design configurations for the plants surveyed are described below by first discussing design specific "trade-offs" and then describing a typical utility conceptual design. Since the qualification experimental data comes from the LOFT reactor facility, the LOFT experimental system design will also be described for clarification of the data source.

5.1 Design Trade-Off Considerations

The following paragraphs describe the design considerations for a reactor coolant trending system using coolant pumps power, coolant temperature, and system pressure measurements. This information is provided to help the reader better understand the proposed system configurations and other options to system design.

5.1.1 Power Measurements. System conceptual design configurations are based on the void fraction calculation analytical model input/output measurement requirements. The analytical model to calculate fluid density, Equations (7) and (8) in Section 4, from which void fraction can be calculated, Equations (14) and (15) in Section 4, requires a measurement of motor power or current as well as fluid temperature and system pressure. It assumes that pump mechanical efficiency, pump motor electrical efficiency, electrical load power factor, and line voltage variations with pump load are very small and can be treated as constants.

Either power or current transducers can be purchased to monitor electrical power circuits. Implementation of power transducers to directly measure pump power eliminates the small errors associated with assuming a constant motor voltage and power factor when using current transducers. However, in some cases it is more convenient to use existing pump current circuits. The use of existing current transducers over power transducers is justified since:[9]

1. Off-normal line voltages that occur due to bus transfers, pump starts or grid disturbances are rarely severe and are for short periods

2. The pump motor power factor changes very little with load. B&W research[9] indicates that for 0 to 40% void fractions, the power factor will change as little as 0.5% (see Figure 2).

The small errors that can occur with the assumption of constant line voltage and pump motor power factor have been accepted by some plant owners. The significance of accepting these errors is addressed in Section 6.

5.1.2 Temperature Sensor Selection. The temperature to be measured can be in the pump cold or hot legs. They are essentially the same temperature under LOCA conditions. An existing thermocouple or RTD can be selected depending on the safety grade desired and sensor availability. Proper electrical isolation for existing temperature channels must be provided. Most B&W plants have a Class 1E temperature measurement for the safety grade Saturation Meter temperature channel available at the computer.

5.1.3 A Pressure Measurement. A pressure measurement is required along with a temperature input to determine fluid and steam density from the steam tables. Void fraction calculations require use of these densities. At saturation conditions, either temperature or pressure can be used to find density on the steam tables. Under single-phase conditions, the fluid density is more sensitive to temperature changes than pressure, but for best accuracy in defining the single-phase density, both should be used. In either case, a safety grade measurement should be available from other instruments such as the Saturation Meter that uses both measurements.

5.1.4 Number Coolant Pumps to be Monitored. The number of primary coolant pumps running during LOCA can theoretically vary from one to four. The motor load at a particular pump will change when one or more of the other pumps is put on or taken off line due to changes in pump head. The number of pumps ON must be considered in calculating the signal processing algorithm constants so that a correction factor for the analytical model can be calculated for each possible combination. Since B&W Plants have two loops with two pumps in each loop there are five combinations of pump operation to be considered: (a) four pumps ON, (b) three pumps ON, (c) two pumps ON in one loop, (d) one pump ON in each loop, and (e) one pump ON.

Some system designs provide an average system local void fraction that compensates for the number of pumps running when the average void fraction is calculated. Other plants simply display a local void fraction for each loop or each pump. Regardless of the design a multiple pump logic needs to be considered to correct the initial power conditions used in the analytical model for pump motor load changes.

Another "number of pumps running" effect that has been considered as a potential source of error is the interpretation of the average void fraction as an indicator of reactor vessel void fraction with only one loop operational. The magnitude of this affect has been illustrated by simulating a small break for one and two loop operation with the pumps ON; both cases use a Bellefonte B&W Plant computer code. Comparison of Figures 3 and 4 shows the difference between the two average coolant system void fractions of single-loop versus two-loop pump operation. It can be seen that for void fractions less than 0 to 30% the indicated system coolant trends, regardless of one- or two-loop operation, is always less than the local pump calculated void fraction.

5.1.5 Operator Display. The operator displays can be one or more of four configurations. At least one utility displays void fraction using an analog strip chart recorder. Most use the computer CRT terminal and printer to display void fraction trend information upon request by the user. CRT displays will have digital and/or analog displays of calculated void fraction and coolant trend. Trend information will be provided by digital or analog displays with 0.5 to 6.0 h of history.

Use of the void fraction indicators by the reactor operators at the present time are limited to:

1. When at least one pump is running
2. Back up information for the safety grade LOCA monitoring instrumentation
3. Coolant trending information only.

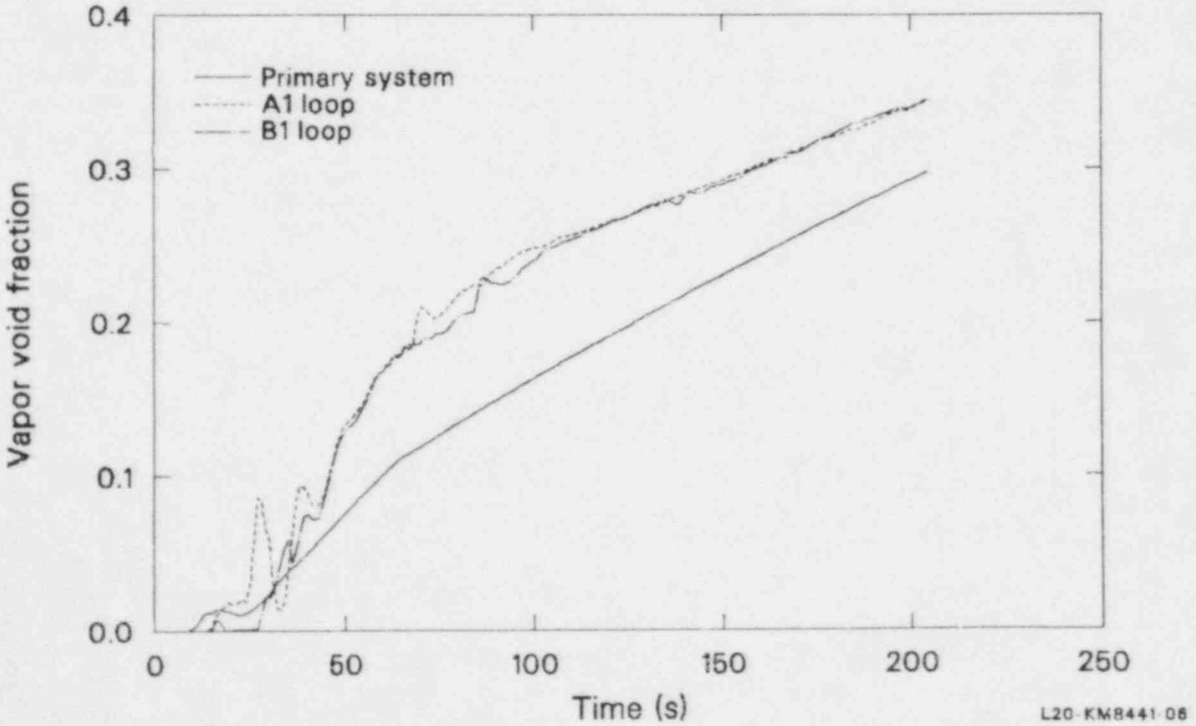

Figure 3. Bellefonte Plant local pump void fraction and primary system void fraction computer simulation of a 4-in. cold leg break LOCA with pumps running in both loops (borrowed with permission from EPRI).

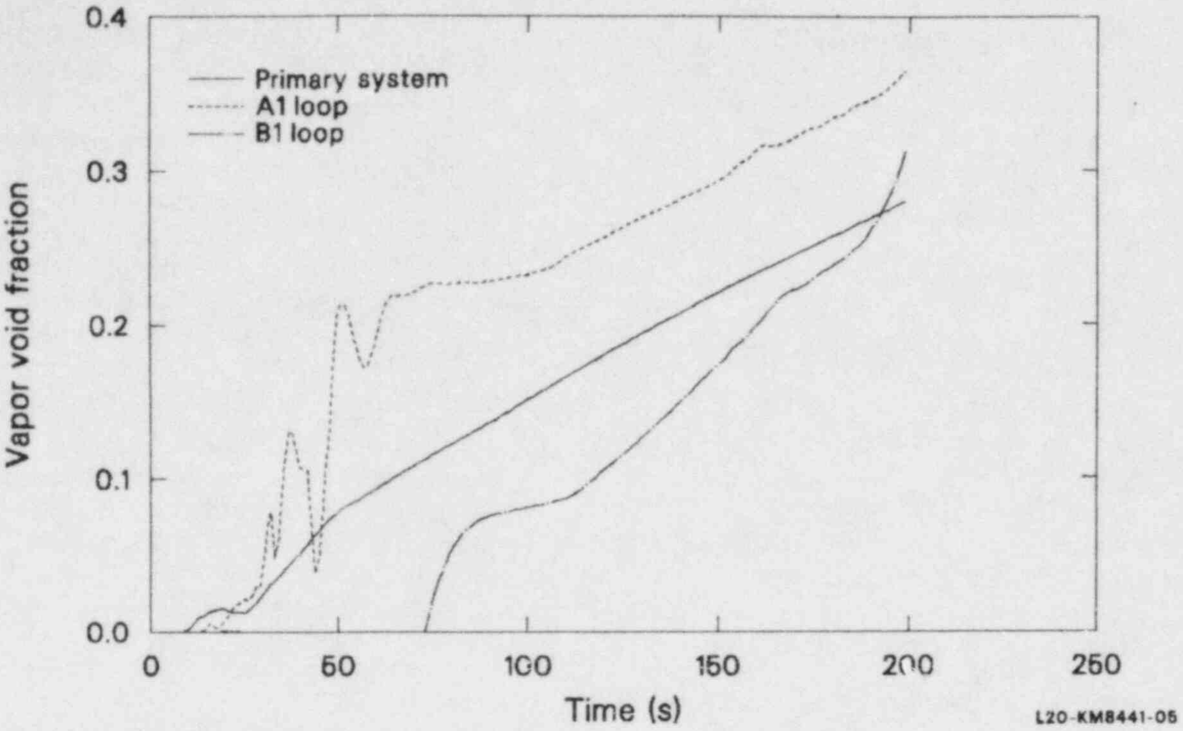

Figure 4. Bellefonte Plant local pump void fraction and primary system void fraction computer simulation of a 4-in. cold leg break LOCA with pumps running in one of two loops (borrowed with permission from EPRI).

Most existing plant LOCA operating procedures do not require a void fraction measurement while the pumps are running. The need does not exist since the pumps are tripped off early in the LOCA with initiation of the HPSI. A need only exists when the pumps are restarted to provide additional coolant to the reactor core under potential fuel damage temperature conditions.

The CRT display can be a plot of pump power or current versus coolant temperature (known at LOFT as a J-plot). At the present time, most utilities plan to display the calculated void fraction versus time. It is our belief that they do not realize the value of the additional information a CRT J-plot trend display can provide or the cost of a dedicated J-plot display does not justify the end use (see Section 2).

5.1.6 Class 1E System Qualification. NUREG-0737, Supplement 1, specifies that coolant inventory instrumentation must be qualified to Class 1E criteria per RG 1.89. This specification presents a problem for the pump motor power measurement since safety-grade reactor coolant pump power and current monitors are not required at the present to assure that plants are maintained in a safe condition. The reactor coolant pumps switchgear and sometimes the nonseismically qualified turbine building that houses the switchgear are not Class 1E qualified (however, the Bellefonte Plant houses the switchgear in the seismically qualified auxiliary building).

Utilities surveyed have justified a deviation of the pump power monitoring design from NUREG-0737 environmental qualification/Class 1E power source since:

1. Reactor coolant pumps motor and their associated electrical circuits currently are powered from non-Class 1E sources and are not environmentally qualified in accordance with IEEE 323-1974

2. The reactor coolant inventory tracking system is not a protection system, but is a monitoring system with reliable backup from the core exit thermocouples and the subcooling margin monitors

3. Upgrading cost in terms of financial expenditure, downtime, and man/rem exposure would be exorbitant.

Because of the difficulty outlined above, system designers have chosen not to provide a non-Class 1E qualified pump power measurement. Florida Power Corp. has presented the above argument to the NRC.[9] In response, the NRC issued the following statement:[10]

> "Your justification of use of nonsafety grade pump power monitoring channels is based in part on the argument that the RCP motor and their associated electrical circuits are powered from non-Class 1E sources and are not environmentally qualified. However, it is conceivable that pumps may be restarted for improved core cooling late in an ICC transient after the core has uncovered. Provide assurance that the pump monitoring channels are at least as reliable as the RCP motor and electrical circuits and can be expected to function in an environment which will permit RCP restart."

5.2 A Typical Utility Conceptual Design

As outlined in Table 1, six B&W Plant owners have submitted system design configuration proposals to the NRC for instrumentation systems to detect the trend of voids in the reactor coolant system with reactor coolant pumps running. Appendix A contains the survey sheet details. Figure 5 shows a block diagram of a typical utility conceptual design configuration. Typically, existing pump inlet or outlet temperature and pump motor power or current transducers provide inputs to an algorithm that calculates the average void fraction for each pump. A two pen strip chart recorder or a CRT display with printer indicates the average void fraction for each coolant loop.

In a typical design (see Figure 5), the computer obtains pump power measurements from the output of the existing current or power transducers located in non-Class 1E pump switchgear cabinets. A single current transducer provides a signal of the motor current in one leg of the three-phase pump motor power source. The transducer supplies the signal to indicators on the switchgear breaker panel and to the plant computer. The computer makes the void fraction calculation and presents it on the CRT display and/or sends it to a printer for hardcopy output.

Table 1. Summary of Babcock & Wilcox plants surveyed

Utility and Plant	RCP Power Measure Status	Plant Status
Florida Power Corporation Crystal River 3	Installation in 1985	Operational
Toledo Edison Company Davis-Besse 1	Operational	Operational
GPU Nuclear Corporation Three Mile Island 1	Installation 12/84	Operational
Duke Power Company Oconee 1, 2, and 3	Installation in 1985	Operational
Consumers Power Company Midland 1 and 2	1986 startup	1986 startup
Tennessee Valley Authority Bellefonte	1986 startup	1986 startup
Arkansas Power and Light Company Arkansas 1	Using heated TC	Operational
Sacramento Municipal Utility District Rancho Seco	Using heated TC	Operational

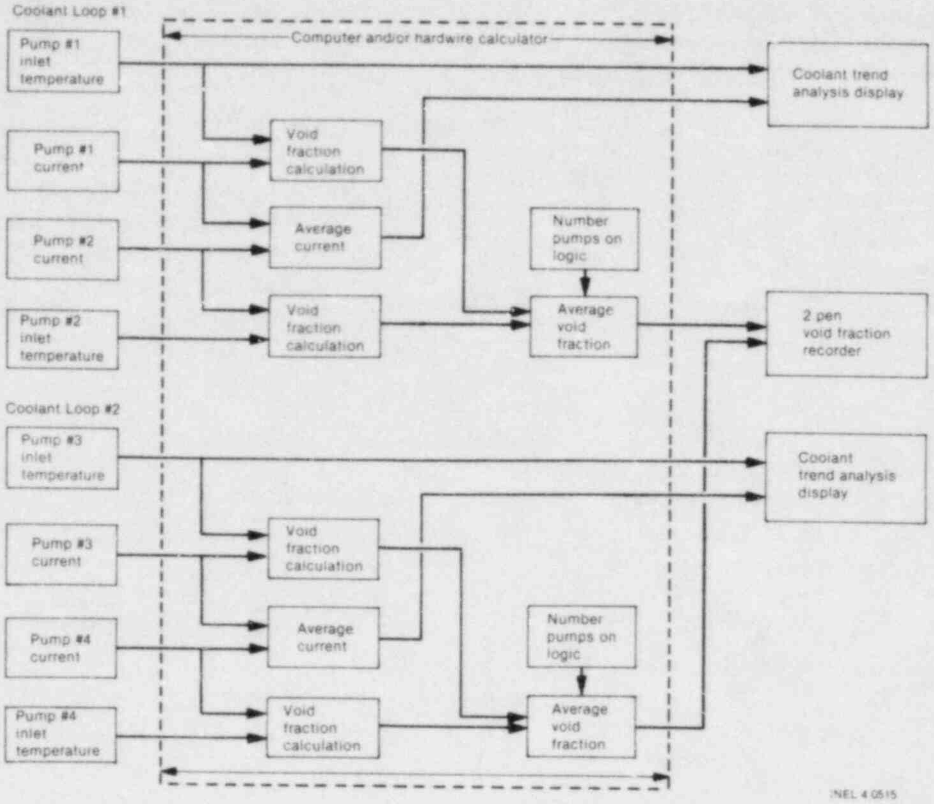

Figure 5. Typical conceptual design of a proposed coolant inventory trend analysis system.

Typical transducers have better than 0.5% full scale accuracy traceable to the National Bureau of Standards.[11] The transducers obtain an input from the power buss by an in-line current transformer. The transducer construction resembles a canned transformer. Basically, the devices use digital circuit design or utilize Hall Effect solid state chips commonly used in electrical circuits for logging, indicating, and control of power or current. Some of the units provide circuit isolation and signal processing at the same time. They are usually built rugged and are reliable, but, of the six vendors surveyed none have qualified a unit for Class 1E operation.

The void fraction calculation algorithm, Equations (14) and (15) in Section 4, requires a pump inlet or outlet temperature measurement to calculate void fraction. Typically, the same temperature sensor used for other reactor control and temperature monitors is available in the computer. In at least one of the conceptual designs, the Class 1E temperature monitoring circuit for the Saturation Meter provides the signal for the void fraction calculation.

The proposed design configurations reviewed indicate that void fraction will be calculated for each pump in the plant computer and/or with a special hardwire analog circuit design. The average void fraction for the two pumps in each loop will then be determined and/or the average void fraction for the system calculated by averaging the void fraction of the two loops. If a J-plot CRT display is used, coolant pump power or current will also be averaged to provide an input for the average system coolant trending CRT display.

Florida Power Corp. has proposed a design using both the plant computer and a separate hardwire analog circuit to provide diversity and increase the reliability of the measurement.[9]

5.3 Loft Experimental Data System Design

The LOFT experimental pump power measurement system design verifies the analytical model described in Section 4 and illustrates that the associated trend analysis display (J-plot) can help the reactor operator make correct accident management decisions[6,7,8] (see Figure 1). A display of pump motor power versus cold leg temperature allows the operator to unambiguously distinguish between a transient and a LOCA. For example, if multiple failures combine a transient with a line break, the J-plot display will change from the normal operating point in a direction that indicates both failures have taken place. Additionally, void fraction operating limits scribed on the pump power versus coolant temperature LOFT system J-plot display also provides an indirect void fraction calculation versus time (see Figure 6). The calculated void fraction has been compared with data from the gamma densitometers up stream from each RCP to validate the void fraction trend interpretation of the J-plot display. Figure 7 show a block diagram of the LOFT trend analysis instrumentation system design.

The primary coolant pump outlet temperature supplies a signal, through a buffer amplifier to the computer, that is displayed on the horizontal axis of the J-plot trend analysis display. Figure 7 includes a block diagram of the temperature measurement circuit.

Figure 8 shows the LOFT system power transducer connections to measure the total three-phase power to the pumps. The buffer amplifiers supply the power transducer signals to the computer. The computer processes these signals for use in void fraction calculations and the trend analysis algorithm.

5.4 Design Conclusions

The above sections document some system design considerations used by the utilities for coolant trending information and by LOFT for accumulation of experimental data. These considerations should be included in the design and review of a system as being generic to making a successful measurement.

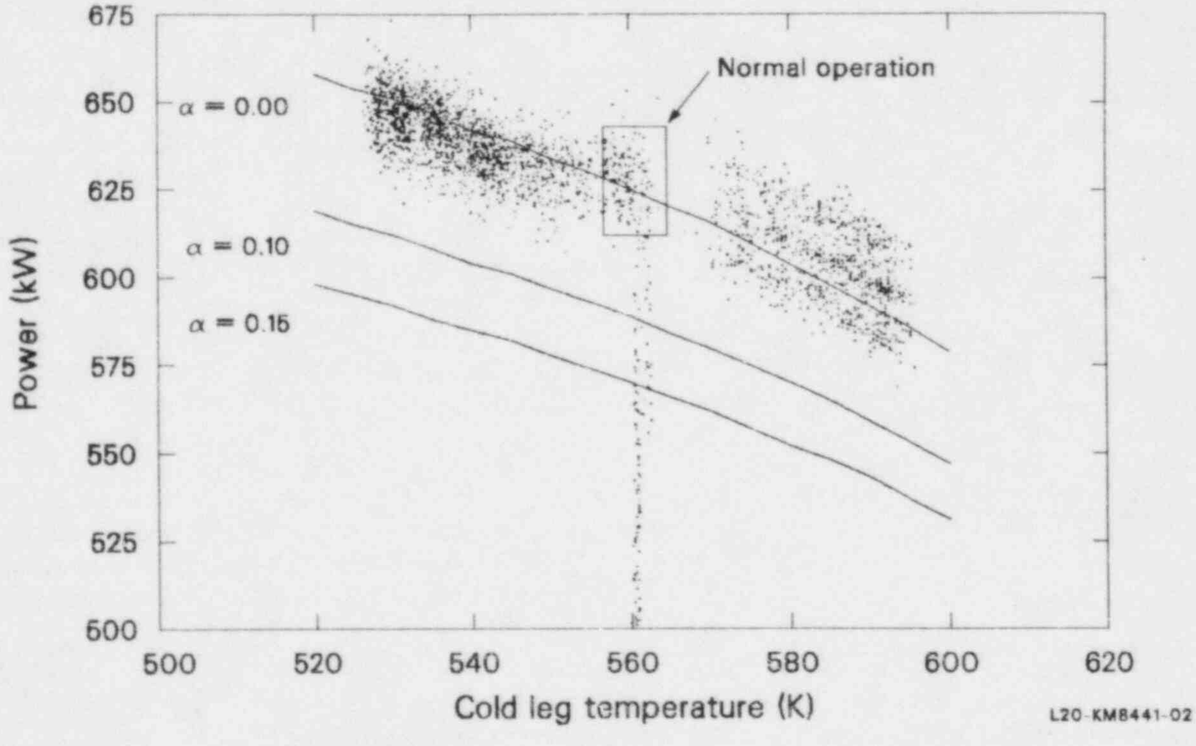

Figure 6. Operator's J-plot display with criteria void fraction lines and LOFT data.

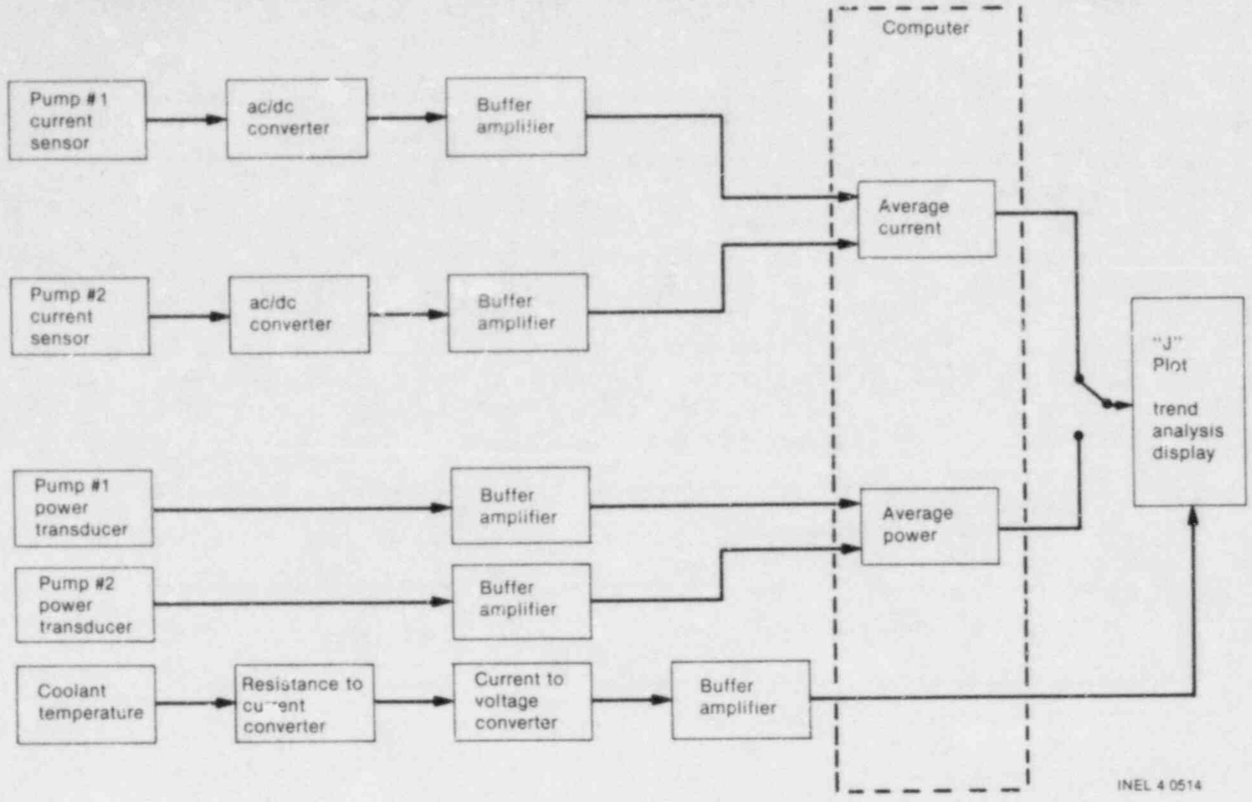

Figure 7. LOFT reactor coolant inventory trending system.

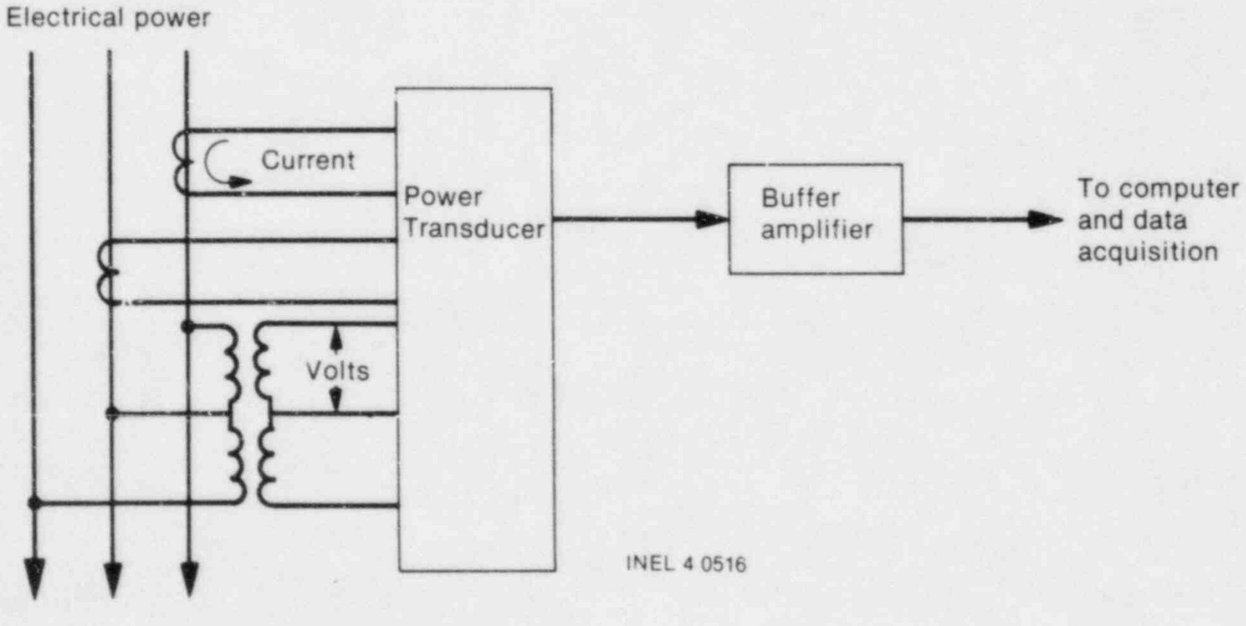

Figure 8. LOFT power transducer connections.

6. FUNCTIONAL PERFORMANCE CONSIDERATIONS

This section defines the ability of the primary coolant inventory tracking system to unambiguously indicate void fraction trend by measuring pump motor power and coolant temperature. This is done by defining the ability of the measurement system to quantify, qualify, and display the calculated void fraction where:

1. Quantification of the system considers the probable local void fraction calculation accuracy achievable at the pump as calculated from coolant temperature and RCP motor power measurements
2. Qualification of the system considers use of the pump local void fraction calculation to indirectly indicate coolant inventory void fraction trends in the reactor vessel
3. Display of the data considers the design of the void fraction indicator used by the operator for coolant trend analysis.

These three considerations define the ability of the system to perform as a coolant inventory tracking system and to meet the intent of current regulations (see Section 3). Sections 6.1, 6.2, and 6.3 contain a detailed discussion.

6.1 Data Quantification Considerations

Quantification of the local void fraction calculation at the pump is limited to homogeneous two-phase flow. The validity of the analytical model developed in Section 4 is limited by flow conditions that support the assumptions of simple one-dimensional pump theory that the model is based on. The model is limited to homogeneous two-phase flow conditions that the pump theory can treat as single-phase flow conditions.

This section quantifies the accuracy of the calculated local void fraction at the pump by examining each of the measurement system characteristic parameters. The examination is broken down into four parts as depicted in the block diagram of system sources of errors shown in Figure 9 and include:

1. Analytical pump model flow regime accuracy limitations and verification
2. Pump and motor characteristic parameter affects on the accuracy

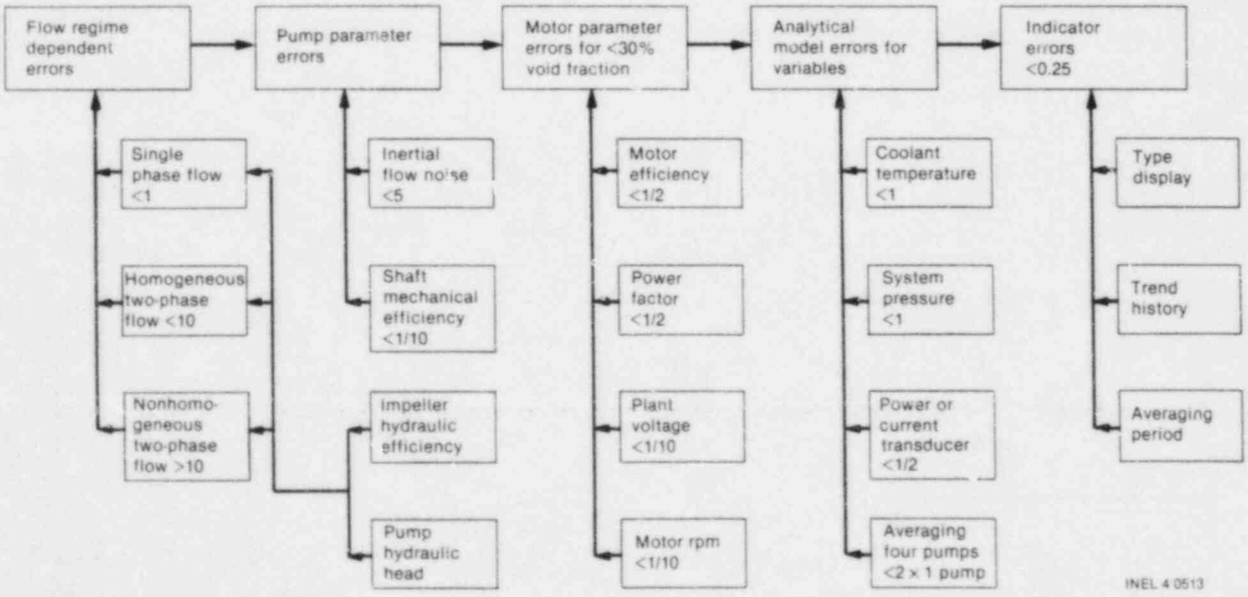

Figure 9. System sources of error.

3. Signal processing errors

4. Void fraction indicator design errors.

6.1.1 Analytical Pump Model Flow Regime Accuracy Limitations and Verification. The analytical model reported in Section 4 above is based on the premise that pump characteristics are the same for small void fractions as for single-phase flow. For void fractions greater than 30-40%, fluid separates in the pump housing and/or pump impeller invalidating the analytical model used for calculating void fraction. High void fractions allow the steam and water to flow at different velocities causing a "slip" that can cause nonhomogeneous flow regimes such as stratified flow and slug flows. Different flow regimes can require different pump power for the same void fraction.

The analytical model accuracy verification over the limits of its application to two-phase bubble flow is substantiated by the LOFT L3-6 experimental data that compares a local gamma densitometer measurement with a pump power calculated density.[6] Figure 10 show the relationship of gamma densitometer measured density to pump power calculated density using Equation (10) in Section 4.[6] The bubbly flow regime contains small bubbles homogeneously distributed and traveling at about the same velocity as the liquid. As the bubbles become larger, they coalesce causing a two-phase regime transition from bubbly to partially stratified churn turbulent flow. In churn turbulent flow, the vapor and liquid separate more distinctly and travel at different velocities. The result is a significant degradation in pump performance. At 30 s, the coolant is saturated. Then, between 30 and 100 s, the pump condenses the vapor entering the pump inlet before reaching the outlet. After 100 s, the coolant is two-phase from pump inlet to outlet. The bubbly-to-churn transition occurs at 290 s into the transient. The EPRI study[7] reports that the same pump characteristics are expected for large commercial plant pumps as shown by the LOFT data and shows that the homogeneous flow assumptions made in deriving the analytical model to calculate void fraction are correct.

In summary, the one-dimensional single-phase flow model is based upon the pump power measurement that is not valid beyond 30% void fraction. This means the user of the pump power measurement cannot use the LOFT L3-6 experimental data to determine the accuracy of the analytical model

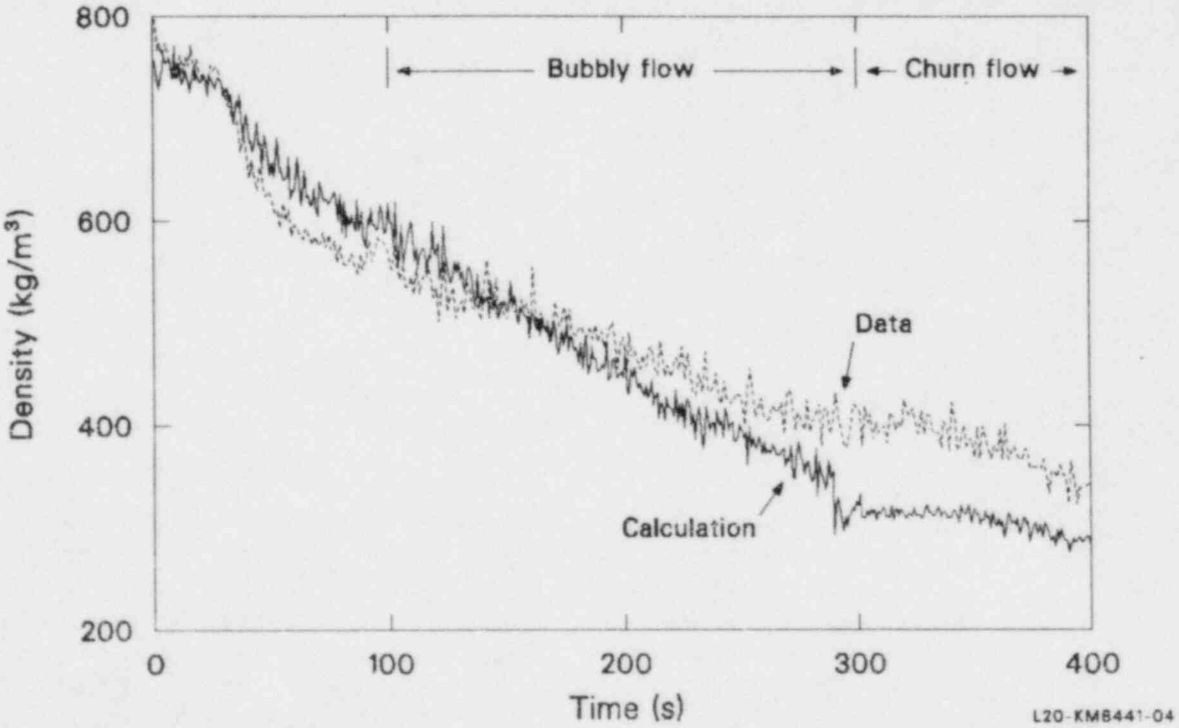

Figure 10. Measured density upstream of pump compared with calculated density using pump motor power (constant volumetric flow and pump head assumed).

described in Section 4 to calculate large scale pump void fractions greater than 30% void fraction. This is a temptation since the data in Figure 10 seems to be well behaved.

6.1.2 The Affect of Pump and Motor Characteristic Parameters on Accuracy. The most significant pump parameter void fraction calculation error for homogeneous two-phase flow is the pump inertial flow forces that show up as pump motor power fluctuations. As a result, the calculated void fraction fluctuation can be as large as ±5.0%. This fluctuation is particularly concerning at zero void fraction conditions since recorded negative fluctuations are usually clipped off and positive fluctuations must be interpreted as a zero void fraction indication. Filtering this fluctuation out is difficult since the frequency content is the same as that required for monitoring the void fraction fluctuations. The fluctuation can be seen in the LOFT data, but is not analyzed in previously referenced reports (see Section 6.3 for more information).

Since the local pump void fraction calculation is the ratio of the measured change in pump motor power to a reference condition pump power measurement, all pump and motor characteristic parameters that can be assumed to be constant cancel in derivation of the analytical model, Equation (7), Section 4. The actual variations in these parameters are examined as potentially significant errors below:

1. The pump shaft mechanical power efficiency factor varies less than 0.1% with load.

2. The pump motor electrical efficiency and power factor characteristics vary with load, but change relatively little (see Figure 2). Commercial power plant pump motor load variations associated with 0 - 40% void fraction change from 10,000 to 6,000 hp. Over this range, electrical efficiency and power factor variations are less than 1/2%. It should be noted that, below 6,000 hp, the variations become significant, but are not of concern since application of the analytical model is limited to homogeneous flows that require more than 6,000 hp.

3. The plant power supply voltage and the pump motor revolutions per minute are essentially constant except for transients. It is reported by B&W designers[12] that these variations are insignificant.

6.1.3 Analytical Model Input Errors. The analytical model requires a pump motor power measurement and a two-phase saturated water and steam density to calculated void fraction, Equation (13), Section 4. The water and steam densities are obtained from a steam table stored in computer memory and are identified by pump inlet coolant temperature or pressure measurements. As can be seen by examination of steam tables, the error in obtaining these densities from the steam table is much less than 1% void fraction for a 3°F temperature measurement error or ±15 psig (0.6% RG) pressure measurement error. The accuracy of the power or current transducer is better than 0.5% of range and affects the void fraction calculation less than 0.5%.

There are various possible methods to combine individual local pump power measurements to obtain pump average local void fraction. When four pumps are running, the average system local void fraction error will be less than two times the errors of one pump local void fraction calculation assuming independent errors for each pump. This will increase the error from less than 5% void fraction per pump to less than 10% average void fraction error when averaging four running pumps.

6.1.4 Void Fraction Indicator Design Errors. Little can be said about the accuracy of the void fraction indicator since each utility seems to have a different method of providing the indication. In general, analog indicators have accuracies better than 0.25% of range and digital indicators better than 0.1% of range. These errors are small compared to the other system errors and can be ignored. The potentially large interpretation errors are in the way the void fraction trend and history are displayed. The averaging period of local pump void fraction to obtain average system local void fraction and the length of time history is displayed are variables assumed, in this analysis, to have been properly selected in each of the plant specific designs. The plant specific LOCA operating instructions also determine the void fraction display design that is outside the bounds of the study reported here.

6.1.5 System Local Void Fraction Calculation Uncertainty. The total system local void fraction calculation uncertainty using the root mean square uncertainty model is less than 10%. This uncertainty calculation has the same (less than 30%) void fraction restriction as the analytical model. Use of the pump power measurement to calculate absolute void fraction values or trend information in the range of 30 to 100% void fraction will result in errors much greater than 10%. The magnitude of high void fraction errors is not defined in any known experiments or studies for commercial power plant systems and, therefore, the use of any model without plant specific empirical data for void fractions greater than 30% is not justifiable.

6.2 System Qualification Considerations

System qualification should show that RCP motor power data can provide the system user with unambiguous coolant inventory trend information. Data from LOFT experimental L3-6 tests (see Figure 10)[6] and computer calculations of commercial PWR LOCAs (see Figures 3 and 4)[7,8] indicate that local RCP calculated density is representative of the entire primary system density. In other words, any variations in the RCP inlet void fraction are a conservative representation of the entire primary coolant system void fraction.

A number of test programs have been carried out to determine the response of commercial PWR pumps to two-phase fluid conditions through the use of test pumps scaled to PWR pumps. These include test programs conducted by Combustion Engineering (CE),[13] Creare,[14] and Babcock and Wilcox (B&W),[15] sponsored by the EPRI. Figure 11 plots the homologous head parameter versus fluid void fraction for these three test programs where the Creare and CE steam/water test data have been combined. This figure demonstrates the large differences between the response of these pumps to steam/water and air/water two-phase fluids. Also shown on the figure are data from the LOFT pump extracted from Experiments L3-6[16] and L6-8C-3.[17] These data generally agree with the CE/Creare steam/water data (within experimental uncertainty) and support the conclusion that the LOFT pump responds to a two-phase fluid in a manner similar to commercial PWR pumps.

A series of six calculations were made of the response of a commercial PWR to a LOCA in order

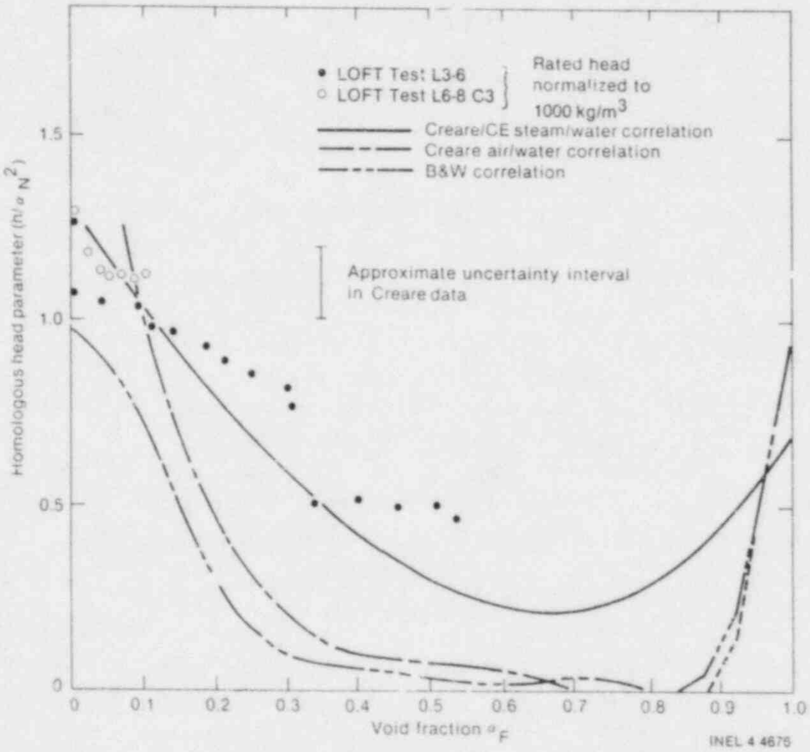

Figure 11. LOFT two-phase head compared to scaled test RCPs.

to address this question.[7] These calculations were all of the same four-inch cold leg break LOCA and were made using three different pump two-phase head degradation correlations (LOFT[16] CE/Creare[13,14] and Semiscale[17]), two independent computer codes (RELAP4[18] and RELAP5[19]), and two different PWR designs [Zion, an 1100 MW(e) Westinghouse designed PWR and Bellefonte, a 1213 MW(e) B&W designed PWR]. The key calculated parameters were the local fluid void fraction at the pump inlet and the global average primary system fluid void fraction. The Bellefonte Plant calculation with all RCPs running in both loops and only one loop is shown in Figures 3 and 4, respectively. In general, the primary system started to void earlier than the pump inlet, mainly because the pump inlet is in the cold leg. However, by time the average void fraction increased to 0.10, the void fraction at the pump inlet had equaled or exceeded the average and remained higher until long after the pumps would have been turned off (at void fraction 0.15 to 0.20).

In summary, the pump inlet void fraction is expected to provide a conservative (high) indication of the average primary system void fraction during a small break LOCA except for a short time early in the transient. This conclusion in independent of the PWR design, pump two-phase head degradation correlation, or computer code used in the analysis.

6.3 Data Display

Interpretation of the measurement data is controlled in part by how the data are displayed to the user. There are four display methods being considered for use in commercial power plants; strip chart recorder, CRT terminal digital display, CRT terminal analog display, and J plot. Human Factors Engineering should be considered in design of a safety parameter coolant trend display.[20] In design, care should be taken to emphasize the trend information and indicate coolant trend history properly. The absolute value of the void fraction should be displayed with a definition on the limits of its accuracy. Also, a warning should be provided to only consider the primary coolant system void fraction trend information to be accurate for void fractions less than 30%. It is not clear that any of the above will be considered for a nonsafety grade backup display.

The LOFT program uses another method of display useful to emphasize trend information (see Figures 1 and 6). RCP power is display versus cold leg temperature on a CRT (known as a J-plot). By this method, a clear indication of reactor coolant inventory trend can be observed with the bonus of the display uniquely defining the type of LOCA taking place.[6] For example, if the "current conditions" indicator on the plot moves along the normal, single-phase pump power/temperature (PWR/temp) curve in the direction of increasing power and decreasing temperature, the plant is cooling down and pump power is reflecting increasing water density. If "the current conditions" indicator moves along the normal, single-phase PWR/temp curve in the direction of decreasing power and increasing temperature, the plant is heating up and pump power is reflecting decreasing water density. The most interesting and valuable indication occurs when the "current conditions" indicator moves downward off the normal single-phase PWR/temp curve to show a relatively large decrease in pump power coupled with a relatively small change in temperature. This unambiguously indicates a deviation from single-phase density and the onset of voiding at the pumps. The point moving further from the single-phase PWR/temp curve indicates an increase in voiding. Operator interpretation capability is enhanced by periodically being able to observe the plot change along the single phase PWR/temp curve from reactor startup to normal operating conditions. An indication of void fraction can be included by placing an overlay scale on the CRT to show discrete calculated values of void fraction as a function of pump power versus coolant temperature.

Designing a display to discriminate against the 5% void fraction calculation noise generated by pump power fluctuations, by clipping or filtering, will cause a loss of the small void fraction trend information. Conversely, by displaying part of or all the void fraction noise the observer can have trouble interpreting zero void fraction or more importantly 5% void fraction. The best design will probably display the zero void fraction noise since it is present anyway when a void fraction is displayed. Also, the noise might have the advantage of being able to validate data since:

1. If present under normal operating conditions and of proper amplitude, the measurement system must be working properly
2. The single-phase root-mean-square value is more than likely proportional to flow and can be used to validate flow meter readings

or it can qualify the single-phase flow pump power measurement related to flow and temperature.

6.4 Functional Performance Conclusions

A quantitative evaluation of the local pump void fraction calculation model input parameter measurement errors show the uncertainty in the calculation as less than 10% void fraction. The controlling factor is shown to be the pump motor power noise that causes a 5% void fraction noise in the calculation.

An average coolant system void fraction uncertainty cannot be quantified in terms of the local pump void fraction calculation. However, simulated computer calculations of commercial PWR LOCAs indicate that local pump void fraction trend is the same as average coolant system void fraction trend and is conservative. This is emphasized as only being the case when the local pump void fraction is less than 30%.

Data display methods and interpretation are discussed, but best design conclusions are left to the reviewer of a specific plant design based on operator coolant trend indication requirements.

7. CONCLUSIONS

This report is based on information received from the utilities on coolant inventory pump power/current measurement instrumentation being installed to monitor primary coolant system inventory trends with the primary coolant pumps running. A survey has shown that six B&W plant owners have proposed to the NRC that primary coolant pump motor power/current be used for this purpose. These utilities plan to implement the system as a nonsafety grade measurement for backup information only. The nonsafety grade design justification is that current plant LOCA operating procedures require that the pumps be shut off early and only restarted under ICC conditions. When the pumps are restarted, the system coolant inventory is likely to be so low that the void fraction information will not be meaningful. In this case, it will be too late to change the system coolant inventory trend and the operator will only be concerned about enough coolant being circulated to cool the core.

The analytical model using pump motor power/current and coolant temperature to calculate local void fraction at the pump is theoretically well founded and has been shown to be valid by LOFT experimental data and EPRI analytical studies. The model only applies to void fractions less than 30% and has sufficient accuracy to measure local void fraction at the pump to better than 10%. Extrapolating the local pump void fraction calculation to indicate void fraction trend in the reactor vessel has been verified by simulated analytical studies to be indicative and conservative within the constraints of the 30% void fraction limit of the model.

Implementation of the void fraction calculation is simple and relatively inexpensive. Existing plant measurement data available at the plant computer is used as an input for the analytical model to calculate the void fraction. The exceptions are those few plants where power transducers must be added for plant specific design reasons.

Concerns exist in using the void fraction calculation for reactor vessel coolant trend analysis applications because:

1. The calculation might be misused by trying to obtain trending information for void fractions greater than 30% since use of the measurement will probably be limited to restarting the pumps after being well into ICC where large void fractions can be expected

2. Zero void fraction will not be measured as such since pump power noise will always cause a void fraction calculation noise of about ±5% that could be misinterpreted as a coolant trend

3. The utilities will want to apply the system to measuring void fraction in the coolant system for pump trip criteria as proposed in the EPRI study and they will not be able to since the system is inherently nonsafety grade and has been justified on the basis that it will only be used for backup information

4. Future pump trip criteria might require continuous display information where present operating procedures only require display of the coolant trend data for backup information upon request at the CRT terminal.

A future system qualification concern generic to all plants surveyed is that if a system were required to provide a safety parameter display, it cannot since nonsafety grade concerns exist that include:

1. Unavailability of Class 1E primary coolant pump switchgear and transducer hardware and in some cases lack of seismically qualified buildings housing the switchgear
2. Computer terminal data trend indication upon request does not meet the continuous display requirements
3. The fact that the system does not directly measure average primary coolant system inventory trend.

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APPENDIX A

UTILITIES SURVEY DATA

PUMP POWER MEASUREMENT
UTILITY QUESTIONNAIRE

Date 1/31/84

Utility Florida Power Corp (Crystal River 3)

Address Thirty Fourth St. South
P.O. Box 14042
St. Petersburg, FL 33733

Contact Name Pablo M. Rubio, C. J. Jain

Phone Number 813-866-5405

Use of Pump Power Meas. Operator Backup Information Upon Pump Restart

Status of Design Starting final design for March 1985 implementation.

Status of NRC Approval In process

Reports Available April 15, 1983 conceptual design proposal letter to NRC & July 18, 1983 response letter to NRC.

DESIGN INFORMATION:

Motor Circuit Transducer:

Type Will install additional power transducer

Model Rochester type

Interface NK

Type Signal Processing Computer and hardwired

Number Channels One per loop that averages two pumps

Type of Display Foxboro 2 pen strip chart recorder

Software Algorithm FPC design

Temp. Meas. Location Cold leg

Temp. Meas. P.C. Interface NK

Pump Trip Criteria None

Qualification Category Non-Class 1E

Schedule:

Design Completion Date Dec. 1984

Incorporation Date 1985 shutdown

Plant Startup Date Operational

PUMP POWER MEASUREMENT
UTILITY QUESTIONNAIRE

Date 3/14/84

Utility Toledo Edison Co. (Davis-Besse 1)

Address 303 Madison Ave.
Toledo, OH 43652

Contact Name Fred Miller/Frank Chen

Phone Number 419-259-5372

Use of Pump Power Meas. Backup ICC information for operator only.

Status of Design Completed.

Status of NRC Approval Completed.

Reports Available March 23, 1983 conceptual design proposal letter to NRC and Dec. 8, 1983 response letter.

DESIGN INFORMATION:

Motor Circuit Transducer:

Type Available Pump Motor Power Transducers

Model NK

Interface Those available at the computer

Type Signal Processing Computer calculation

Number Channels One per pump

Type of Display CRT terminal and printout upon request

Software Algorithm B&W design

Temp. Meas. Location Hot leg

Temp. Meas. P.C. Interface Available Hot Leg circuit at computer

Pump Trip Criteria None

Qualification Category Non-Class 1E

Schedule:

Design Completion Date Past

Incorporation Date Past

Plant Startup Date Operational

PUMP POWER MEASUREMENT
UTILITY QUESTIONNAIRE

Date 2/2/84

Utility GPU Nuclear Corp. (TMI-1)

Address New Jersey Office

Contact Name Jeff Mahn

Phone Number 201-299-2234

Use of Pump Power Meas. For operator backup information when pumps are restarted.

Status of Design Conceptual

Status of NRC Approval In process of being submitted.

Reports Available Jan. 31, 1984 conceptual design proposal letter to the NRC.

DESIGN INFORMATION:

Motor Circuit Transducer:

Type Class 1E qualified power transducers

Model NK

Interface Average output of two power transducers.

Type Signal Processing Computer

Number Channels One channel and indicator per pump

Type of Display CRT display showing six hour time history

Software Algorithm Proprietory

Temp. Meas. Location Cold leg RTD

Temp. Meas. P.C. Interface Computer buffer amplifiers

Pump Trip Criteria None

Qualification Category Non-Class 1E

Schedule:

Design Completion Date March 1984

Incorporation Date Dec. 1984

Plant Startup Date Operational

PUMP POWER MEASUREMENT
UTILITY QUESTIONNAIRE

Date 3/14/84

Utility Duke Power Co., (Oconee 1, 2, & 3)

Address P.O. Box 33189
Charlotte, NC 28242

Contact Name Bob Gillis/James E. Thomas

Phone Number 704-373-5826

Use of Pump Power Meas. For ICC backup info with pumps running.

Status of Design Conceptual design submitted to NRC

Status of NRC Approval In process

Reports Available Aug. 25, 1983 conceptual design proposal letter to the NRC.

DESIGN INFORMATION:

Motor Circuit Transducer:

Type Will be using existing current transducer

Model NK

Interface Meter output at main control boards.

Type Signal Processing Computer

Number Channels One per pump

Type of Display Computer CRT terminal & printout

Software Algorithm Own design

Temp. Meas. Location Cold leg

Temp. Meas. P.C. Interface At computer

Pump Trip Criteria None

Qualification Category Non-Safety Grade

Schedule:

Design Completion Date 1984

Incorporation Date Fuel loading in 1985

Plant Startup Date Operational

PUMP POWER MEASUREMENT
UTILITY QUESTIONNAIRE

Date 3/8/84

Utility Consumer Power Co., (Midland 1 & 2)

Address 1945 West Parnall
Jackson, Michigan

Contact Name Robert Hamm/Lou Gibsome

Phone Number 517-788-7159/517-788-0501

Use of Pump Power Meas. Coolant trend analysis with pumps running

Status of Design Will use B&W design

Status of NRC Approval Proposal not submitted yet

Reports Available

DESIGN INFORMATION:

Motor Circuit Transducer:

Type Will use current transducer signal available at the computer

Model NK

Interface NK

Type Signal Processing Computer

Number Channels One per pump

Type of Display Computer CRT terminal display & printout

Software Algorithm B&W design

Temp. Meas. Location Cold leg safety grade

Temp. Meas. P.C. Interface Class 1E available at computer

Pump Trip Criteria None

Qualification Category Non-Class 1E

Schedule:

Design Completion Date NK

Incorporation Date 1986 Fuel Load

Plant Startup Date 1986

PUMP POWER MEASUREMENT
UTILITY QUESTIONNAIRE

Date 3/14/84

Utility Sacramento Municipal Utility District

Address (Rancho Seco)

Contact Name NRC Program Manager, Sidney Minor

Phone Number 8-492-8352

Use of Pump Power Meas. No. 1 will use heated TC or ΔP.

Status of Design If they go with ΔP inventory measurement then will use RCP power meas.

Status of NRC Approval Will submit proposal June 1984, and complete ICC system installation in 1986.

Reports Available None

PUMP POWER MEASUREMENT
UTILITY QUESTIONNAIRE

Date 3/8/84

Utility Tennessee Valley Authorities (Bellefonte Plant)

Address 400 West Summit Hill Drive
Knoxsville, TN 37902

Contact Name Jim Young, Harry O'Brien

Phone Number 8-856-7121/8-856-4491

Use of Pump Power Meas. Not clear - still working on LOCA Proc.

Status of Design In a state of flux.

Status of NRC Approval No conceptual design proposal submitted to NRC yet.

Reports Available None

DESIGN INFORMATION:

Motor Circuit Transducer:

Type Have the option of using the current transducer used to monitor pump performance.

Model NK

Interface NK

Type Signal Processing All signals processed in the computer.

Number Channels One for each of four loops.

Type of Display CRT display, might use "J" plot type

Software Algorithm A TVA design

Temp. Meas. Location RTD Class 1E or Non-Class 1E

Temp. Meas. P.C. Interface In computer

Pump Trip Criteria None

Qualification Category Non-Class 1E

Schedule:

Design Completion Date May 1984

Incorporation Date 1985

Plant Startup Date 1986

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3201, 3202

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In Support of Coolant Inventory Trend Analysis

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13. ABSTRACT (200 words or less)

Reactor coolant pump motor power and temperature measurements are used by Babcock & Wilcox (B&W) plant owners to calculate void fraction for trending ICC conditions while the pumps are running. This new measurement technology satisfies NUREG-0737, Item II. F.2, "... licensees shall provide . . . additional instrumentation . . . to supplement existing instrumentation in order to provide an unambiguous, easy-to-interpret indication of inadequate core cooling." In this report, the Nuclear Power Plant Instrument Evaluation (NPPIE) project compares system accuracy, capability, and limitations to measurement requirements using small-break test data and full-scale plant analytical studies. Small-break experimental data show that ICC void fraction calculations are conservative compared to gamma densitometer void fraction measurements in the pipe just upstream of the pumps and liquid level conductivity probes in the reactor vessel. Analytical studies verify that a measure of void fraction at the pumps is conservative relative to the desired coolant inventory trend conditions in the reactor vessel.

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