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Nuclear Power Plant Anticipatory Measurement Recommendations

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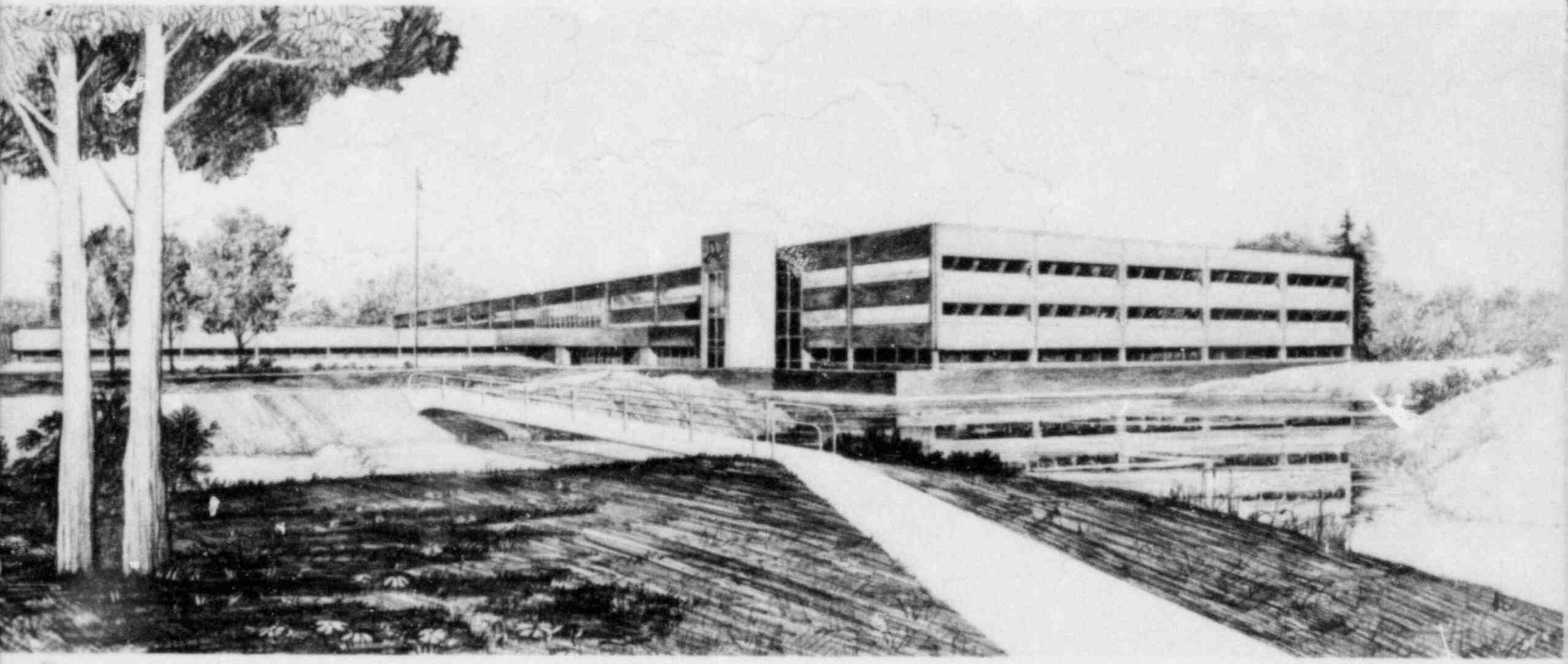

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INTERIM REPORT

ABSTRACT

Measurements that might be useful in preventing accidents in nuclear reactor power plants are identified and evaluated according to a qualitative cost-benefit ratio. Recommendations are given for future anticipatory measurement implementation and development.

SUMMARY

An analysis of nuclear reactor power plant accident event trees was used to identify potential accident causes and measurements that might enable early prediction of the accident condition. Such anticipatory measurements are beneficial (or important) if they reduce the expected costs or consequences of accidents. In this work, the importance of each potential anticipatory measurement is qualitatively estimated according to the expected frequency of the accidents that the measurement might prevent or mitigate. The cost of developing and implementing each anticipatory measurement is also estimated qualitatively, and the implementation cost and the benefit of each anticipatory measurement are combined to obtain a qualitative estimate of the cost-benefit ratio for each measurement. Primarily on the basis of this cost-benefit ratio, several types of measurement are recommended for implementation or further investigation. The three major recommended development projects deal with acoustic techniques, instrument performance diagnostics, and general signature analysis.

FOREWORD

This report discusses work done for the U.S. Nuclear Regulatory Commission under the project Diagnostic Instrumentation Evaluation, FIN No. A6380, since October 1981. Some of this work was also reported earlier[1], and this report repeats the essential information in that earlier report. This report is felt to cover the required work listed in Section 2 of the Statement of Work for this project, although the final decision on this matter must be made only after NRC review and with NRC concurrence.

ACKNOWLEDGMENTS

Part of this report is based on earlier work done by James R. Fincke. Darrell I. Monnie and other individuals in EG&G Idaho's Reliabitity and Statistics Branch--including Stanley J. Bruske and Donald E. Baxter--supplied essential information about nuclear power plants. The support and guidance of Nuclear Regulatory Commission personnel, most notably Nenad N. Kondic, are greatly appreciated.

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1. INTRODUCTION

The objectives of the work reported herein are (1) to determine what types of measurements are necessary or useful in early detection of abnormal conditions which may lead to radioactivity release accidents in nuclear power plants, (2) to evaluate the present capabilities for making such measurements, and (3) to recommend research that would be useful in the development of such measurements where the measurement capability does not already exist.

The term "anticipatory" is used here to describe measurements and instrumentation with accident prediction capability. Anticipatory measurements can be considered a subset of the broader class of diagnostic measurements, which includes instrumentation for indicating that an accident has occurred and for monitoring conditions after the accident has started. There is not always a clear separation between anticipatory measurements and accident-tracking measurements, for two reasons. First, there is often no precise definition of when an accident has started, so a given condition may be described as "post-accident" by some observers and as an accident precursor or an abnormal condition by others. Second, the same measurement may be useful for both anticipatory and accident-tracking purposes. The philosophy used here is that an accident condition exists whenever there is cause to scram the reactor or take similar emergency action to avoid a release of radioactivity as a result of a malfunction or an abnormal condition in the nuclear power plant. Any measurement that can give some warning of an accident condition before that condition occurs is regarded as an anticipatory measurement. It is recognized, and is even desirable, that a single measurement might serve an anticipatory function as well as some other function such as accident tracking or normal plant operation and control.

2. METHODOLOGY

The primary method used in this work to identify anticipatory measurements is analysis of accident event trees. These trees were examined to see what measurements might be useful for detection or prediction of events that might eventually lead to accident conditions. As a backup to these event tree analyses, several other documents describing accident sequences and diagnostic instrumentation were examined in an effort to assure that no important anticipatory measurement possibilities had been overlooked. These analyses and the resulting list of potential anticipatory measurements are described in Section 3.

Some of the potential anticipatory measurements would not be useful, because they would not give warning early enough to allow avoiding or even reducing the consequences of an accident. Of the useful anticipatory measurements, some may be relatively unimportant, either because the expected consequence (probability of occurrence of the accident multiplied by the consequence or cost if the accident occurs) is extremely low, or because there are other warnings of the impending accident which make the anticipatory measurement unnecessary or redundant. The only interesting anticipatory measurements are those which reduce the expected consequences of accidents, and the amount of this reduction is a good measure of the value or the benefit of the anticipatory measurement.

A complete and detailed analysis of the benefit of each potential anticipatory measurement would be a very large task, far beyond the scope of the present task. As an alternative, the importance of each type of potential anticipatory measurement is qualitatively assessed on the basis of the expected frequency of occurrence of the accident condition that might be avoided by the anticipatory measurement. This assessment of importance is discussed in Section 4.

The importance or the benefit of an anticipatory measurement is not the only factor that must be weighed in deciding whether to implement the measurement. The cost of implementation must be balanced against the benefit to be derived from the measurement. Some anticipatory measurements may already exist as standard plant instrumentation, in which case the cost of implementation would be trivial. In the other extreme, some anticipatory measurements may require years of development work at very high cost. The "costs" of the potential anticipatory measurements are estimated qualitatively on the basis of the current state of development of the measurement, in Section 7. This cost is combined with the importance estimate to obtain a rough indicator of cost-benefit ratio for each type of anticipatory measurement.

Primarily on the basis of the estimated cost-benefit ratio, some types of anticipatory measurement were selected for implementation or further investigation. These recommendations for future actions are discussed in Section 8.

3. POTENTIAL ANTICIPATORY MEASUREMENTS

This section describes the procedures used to identify potential anticipatory measurements, including the analyses of accident event trees and various other documents. It also lists the potential anticipatory measurements and describes the less obvious ones.

3.1 Event Tree Analysis

The first method used for identifying potential anticipatory measurements was analysis of event trees. The event trees published by Chamany et al.,[2] seem particularly suitable for this task, in that they contain the appropriate amount of detail. They are simple enough to be useful, and detailed enough that they are expected to yield a reasonably complete set of anticipatory measurements. Figures 1 and 2 show the Chamany event trees, slightly modified, for breach of cladding and breach of pressure boundary. These event trees were done primarily for pressurized water reactors (PWRs), so not every event listed can occur in a boiling water reactor (BWR). Although there are some questions about the logic of some sequences represented in these Chamany trees, it is generally agreed that the initiating events described are a valid and probably reasonably complete set. This is the only important requirement in this work. The breach of containment event trees of Figures 3 and 4 were constructed by EG&G personnel for this study.

The event trees of Figures 1-4 show individual abnormal events that may contribute to or be a necessary part of a radioactivity release accident. The trees do not show all the various combinations of events that may be required for an accident to occur. For example, the breach of containment event trees indicate various modes of containment failure which may contribute to an accident; but, they do not indicate the presence of free radioactive material inside of the containment, which is a necessary event (in combination with breach of containment) for a radioactivity release accident. This incompleteness of the event trees would be important in a detailed risk assessment or an accident probability analysis, but it is not important here where the goal is to identify measurements that might serve a useful anticipatory function.

Table 1 lists the events from Figures 1-4 along with comments on the possibility of anticipatory measurements associated with each event. This table contains some repetition, because several different types of event may have similar measurement possibilities and because a single type of event (loss of a pump, for example) may occur in different parts of the plant and in different accident sequences.

3.2 Other Analyses

The major backup to the event tree analysis was a review of two final safety analyses reports.[3, 4] These reports contains information which, although not actually arranged as event trees, is essentially the same type of information as that in the event trees of Figures 1-4; it is lists of events which might cause or contribute to radioactivity release accidents in the plant. Although these event lists were constructed for specific plants, they are expected to be quite representative of plants in general.

Several other documents, including References 5-15 related to nuclear power plant safety were reviewed for suggestions of other potential anticipatory measurements, in an effort to see that no possibilities were overlooked. It is felt that the event tree analyses, the FSAR analyses, and the reviews of the other reports should be adequate to ensure that no significant accident-initating events have been overlooked.

There are several types of system failure which are not specific to any one event of Table 1, but which might be a cause or a contributing factor to a number of different events. These are failures in measurement systems, control systems, and pneumatic or hydraulic power supplies. These system failures are not listed in Table 1 or included in the event trees of Figures 1-4 because such inclusion would make the lists needlessly long and repetitive. However, each of these types of system failure does suggest a possible anticipatory measurement. These will be referred to as instrument system status, control system status, and fluid power system status.

3.3 Potential Anticipatory Measurement Descriptions

The possible anticipatory measurements identified in this study are listed in the first column of Table 2. This list includes all the possible types of anticipatory measurement obtained from Table 1 as well as those suggested by References 3-15. In view of the numerous and varied sources of information that were examined, it is expected that this list of types of anticipatory measurement should be quite complete.

The Table 2 list does not specify particular measurements, such as a particular valve sticking, but only the type of measurement directed toward some general problem. This is because the major thrust of this work is to evaluate existing technology and suggest research for new technology development, rather than to construct a detailed set of instructions for installing instruments in a power plant.

Some of the measurements in this list are commonplace and well known, but others are at this point very vague and poorly defined. The following paragraphs give explanations of these vague measurements.

3.3.1 Rotating Machinery Status

Motors, generators, turbines, pumps, fans, and other systems that normally rotate continuously for long periods have some common failure mechanisms and some common potential anticipatory measurements. Such systems will be referred to in this report as rotating machinery. Rotating systems which operate intermittently or rarely, such as motors that operate valves, are not included in this class of rotating machinery and are usually not amenable to rotating machinery anticipatory measurements.

Possible failure mechanisms for rotating machinery include rotor imbalance; misalignment; thermal stress and warping during heatup; bearing wear or failure; lubricant deterioration or lubricant flow failure; and fracture of the shaft.[16, 17] Pumps and turbines may have additional problems of vane or impeller fracture; fluid dynamic forces associated with vane or impeller irregularities; abnormal fluid conditions, such as cavitation or two-phase flow; and leakage or failure of the shaft seals.

The leading anticipatory measurement candidate for rotating machinery is vibration analysis,[18-20] which can be useful in detecting all of the problems listed in the previous paragraph except gradual crack growth (leading to fracture), seal leakage, and perhaps, lubricant deterioration. In some situations, vibration analysis cannot be regarded as an anticipatory measurement because it does not give significant advance warning of a dangerous condition. If a pump impeller or a turbine blade breaks suddenly, for example, immediate action is required and the vibration monitor must be regarded as an indication of an existing accident condition rather than as a warning of a possible future accident condition. However, these sudden events are often the result of some conditions such as cavitation that can be detected by vibration analysis significantly before the accident condition occurs.

Acoustic emission[21, 22] (or, more properly, detection of stress relief waves) is useful in detecting crack propagation that may eventually lead to fracture. This technique may allow the detection of crack propagation in a rotor through sensors mounted on a stationary part of the system.[23] An array of several sensors and data interpretation using techniques similar to triangulation sometimes allows quite accurate location of the crack.

Acoustic emission may also be useful in detecting seal leaks, but there are usually more direct and reliable techniques such as a direct measurement of the fluid flow rate through the seal.

Fluid flow noise is useful in detecting cavitation and abnormal two-phase flow conditions.

The three acoustic techniques--flow noise, acoustic emission, and vibration monitoring--are not always clearly distinguished, and there may sometimes be questions about which is being observed in a given situation, but this ambiguity is not normally important. The significant disadvantages of the acoustic techniques are that noise from other sources may interfere with the desired measurement and that it may be difficult to correctly interpret the observed signals in terms of a specific accident precursor.

A set of proximity sensors, using eddy current or capacitance techniques, can give quite detailed information on lateral motion of a rotating shaft. This should give quite direct and unambiguous information about bearing wear, misalignment, and shaft warping. This technique is more complicated but gives more specific information than vibration monitoring.

Excessive bearing friction can be detected by bearing temperature or, if there is a circulating lubricant, by the temperature rise of the oil as it flows through the bearing. Bearing wear may also be indicated by the pressure drop of the lubricant flowing through the bearing. Any of these may serve as a warning of future bearing failure.

3.3.2 Pump Status

The phrase "pump status" includes all aspects of the pump and its driving motor that might sooner or later affect pump performance. The earlier discussion of rotating machinery is applicable to pumps, and the potential anticipatory measurements mentioned there are included in the pump status measurements.

An additional type of measurement that should be included in the pump status class is the relationship between the electrical power into the pump motor and the fluid flow parameters such as flow rate, pressure rise, and density. In its simplest form, the measurement might consist of a comparison of pump current with fluid flow rate. More complicated and hopefully more informative measurements would include consideration of current, voltage, and power into the pump motor as well as a more detailed description of the fluid.

3.3.3 Motor and Generator Status

Motors are used in a variety of applications in a power plant, and many motors operate for extended periods and are therefore included in the category of rotating machinery in this report. This category also includes generators, both those which supply the power to be sold for external use and those which supply power for use inside the power plant (such as in a motor-generator set that supplies controlled power to recirculation pumps). The measurements listed for rotating machinery--except for fluid seal measurements--are generally applicable to these motors and generators. In addition, the general technique of comparing the mechanical power output (or input, for a generator) with the electrical power input (or output) may be a very useful anticipatory measurement for motors and generators. Another technique, monitoring the output voltage for spikes or high frequency noise, has been suggested as a method for early detection of certain electrical problems in generators;[24] a similar technique might be applicable to motors.

3.3.4 Valve Status

The valve status category encompasses all valve malfunctions, including leakage through a seal; leakage past a seat; failure to open or close properly; abnormal fluid flow through the valve; bent valve stems; and cracked or broken bellows, diaphragms, gaskets, or valve bodies.

Leakage past a seat may be detected in a variety of ways, depending on the particular application. In some cases, the mere presence of fluid in the wrong place can serve as an indicator of a valve seat leak. In others, a fluid with the wrong temperature, pressure, flow rate, or chemisty indicates leakage. One other method of leak detection is acoustic emission,[25-28] already mentioned in connection with leaking seals on rotating machinery.

Acoustic techniques may also be useful in detecting abnormal fluid flow conditions (cavitation or undesirable two-phase conditions) and in detecting leakage through a valve stem seal or past a gasket. These external leaks may also be detectable by much simpler techniques, such as visual observation of the leaking fluid or, in some cases, of boron deposits around the leak.

Failure of a valve to open or close completely, or total failure to operate at all, may be detected by valve position monitors. In some cases, the pressure drop across a valve can also indicate incomplete opening or closing. Acoustic techniques may or may not be helpful in this type of measurement.

Monitoring the power necessary to drive the valve may give an indication of future failure from such gradually-developing causes as dirt accumulation or gradual bending of the valve stem.

Valves driven by electric motors may suffer damage, primarily bent valve stems, from excessive application of torque. This may happen during motor stall conditions[29] or as a result of motor inertia after the electric power has been shut off at the end of the valve's travel.[30] Damage such as a bent stem may render the valve completely inoperable. A bent valve stem would not normally be noticed until an unsuccessful attempt to operate the valve. The bent stem condition--even minor bending not severe enough to impair valve operation--could be detected by several techniques including strain gauges on the valve stem, position sensors to detect lateral movement of the stem, and possibly monitoring of the electrical power input to the motor during valve operation. However, it seems more reasonable to simply use a well-designed motor-valve combination so that the excessive torque condition does not occur.

Flow noise or acoustic emission can be useful in detecting cavitation which can harm a valve.[23] Noise monitoring could also be useful in detecting excessive flow-induced vibration or chatter of relatively fragile valve parts such as diaphragms and bellows.[31]

3.3.5 Control Rod Status

The control rod positions are obviously very important factors in determining the status of an operating nuclear reactor, and they may sometimes be useful as anticipatory measurements. The operability of a control rod system is also very important, and the future operability may be to some degree predictable by anticipatory measurements.

The speed with which a control rod assembly moves during a major change in rod position may serve as an indicator of problems in the drive mechanism or of excessive friction in the movement. For electrically driven rods, the power required to move the rods may also be a useful indicator of such problems. These parameters cannot be measured during normal, steady-state operation of the plant, because rod positions are changed infrequently. However, it would be possible to exercise the rods occassionally to determine these parameters.

3.3.6 Instrument System Status

If the instruments that monitor the plant status malfunction, the result could be a serious error in the operation and control of a plant which is otherwise functioning normally. Thus, diagnosis of instrument malfunctions is as important to plant safety as diagnosis of defects in the plant itself.

Instrument integrity diagnostic techniques can be divided into two categories, which will be called "active" and "passive". In passive techniques, the instrument output signals are studied with the instruments in their normal modes of operation. Various types of tests can be performed with these signals, including checks on the noise characteristics (the signature) of the signals, checks on whether the signal is within the normal instrument operating range, and checks for consistency between redundant signals. This sort of passive verification of instrument performance has been the subject of a separate program conducted at EG&G Idaho, Inc.,[32, 33] and related work has been done by others.[34-37]

Active techniques for checking instrument performance involve doing something abnormal with either the instrument or the plant. For example, a thermocouple response time might be checked by driving a current pulse through the thermocouple (an abnormal operation for a thermocouple) and observing the time history of the thermocouple output immediately after the current pulse. Pressure transducers might be checked by introducing a pressure pulse into the system, perhaps by opening a pressure relief valve momentarily. Such active techniques for instrument diagnostics are not now common, but there may be a great potential in this area.

3.3.7 Control System Status

Control system failures can result in erroneous operation of such components as pumps, valves, control rods, etc., and can lead to accident conditions the same as if the component itself had failed. Thus, it is desirable to be able to anticipate control system failures.

Which anticipatory measurement techniques might be applicable to control systems depends strongly on the type of control system in question. One fairly general technique is to monitor both the input and the output signals and check the transfer function (or some similar descriptor) based on small fluctuations in the signals. In some cases, it may be possible to obtain useful information by signature analysis of the output signal alone. However, in most cases, it is simpler to replicate the control system and use majority logic for the final control decision than to implement an anticipatory measurement system. Therefore, although the concept of anticipatory measurements for control systems is not entirely dismissed, it is given a low priority in this report.

4. IMPORTANCE

Ideally, the importance or benefit of each anticipatory measurement would be based (at least in part) on how much that measurement would reduce the expected consequences of nuclear power plant accidents. Thus, a measurement that prevents frequent and costly accidents is more important than a measurement that prevents only infrequent or inconsequential accidents. However, a reasonable estimation of the costs and occurrence probabilities of all the possible accidents would be a very large task, far beyond the scope of the present task. Therefore, a simpler, approximate indication of measurement importance is used in this work.

In this task, the indicator of measurement importance is taken to be the qualitative estimate of the frequency of accidents that might be prevented by the measurement. These estimates of accident frequencies were obtained from FSARs for two specific nuclear power plants,[3, 4] but the results are expected to be quite generally applicable. The accident frequency classes are moderate frequency (designated by M in Table 2), infrequent (I), and limiting fault or very infrequent (LF).

In Table 2, an "0" is entered for those measurements that are apparently not connected with any accidents of significant frequency, and "X" is entered for those measurements associated with events that are not initiating events but are the results of other events. This accident frequency is used not only as the importance, but also as the qualitative indicator of the benefit in the cost-benefit ratio evaluation of the measurements.

5. RG 1.97 REQUIREMENTS

Regulatory Guide 1.97 requires that certain measurement systems be installed in nuclear power plants to allow for detecting accident conditions and monitoring the plant status after the accident condition starts.

If any of those required measurements coincide with anticipatory measurements, the anticipatory measurement is available at no cost (or nearly no cost) because the measurement system already exists to satisfy RG 1.97. A potential anticipatory measurement that is free obviously merits special consideration, since it has a very low cost-benefit ratio if it provides any benefit at all. Therefore, the third column of Table 2 indicates whether a type of measurement is required by RG 1.97.

In many cases, the RG 1.97 requirement is for one or a few specific applications of a type of measurement, whereas there are many potential applications for that type of measurement in an anticipatory function. Thus, not all applications of a measurement type required by RG 1.97 are totally free, but at least the technology presumably exists so these measurements are not extremely expensive and they still merit some extra consideration.

6. TECHNIQUES AND INSTRUMENTS

The fourth column in Table 2 lists measurement techniques or instruments that might be useful in accomplishing the desired measurements. Identification and evaluation of these instruments and techniques is a major goal of this task.

In some cases, there are several types of instruments that can directly measure the parameter of interest. At the other extreme, there are some important measurements for which no direct measurement techniques are known. This accounts for the apparent lack of a direct relationship between the desired measurement and the measurement technique in some Table 2 entries. An example is the first entry. We have no direct measurement technique for detecting breach of cladding (clad failure). Instead, we try to detect the fission products that might escape through the breach. This technique may not be very sensitive or prompt, but it is hopefully better than no measurement at all. A similar situation occurs in a number of other measurements, most notably those using acoustic techniques. It is usually quite easy to record the acoustic signals, but there is often a large uncertainty in the relationship between the observed acoustic signals and the desired measurement parameter (such as bearing wear or seal leakage).

The measurement techniques listed in Table 2 are limited to those that are applicable during normal, steady-state operation of the power plant. There are of course a wide variety of inspections and tests that can be done while the plant is not operating, and others that can be performed by exercising certain components while the plant is operating, and these are usually more informative than the on-line measurements considered here. However, the interest of this task is in anticipatory measurements that can be performed during normal reactor operation.

7. INSTRUMENT EVALUATION

There are several criteria to be considered in evaluating instruments or techniques for making anticipatory measurements. One important consideration is the cost-benefit ratio for implementing the technique. In this discussion, the cost includes the cost of hardware, software, design, licensing and regulatory approvals, development and all other costs arising from installing an instrument or measurement system. The costs are estimated qualitatively, mainly on the basis of expected development costs. The benefit of a measurement system is, as has been mentioned before, qualitatively estimated in terms of the frequency of occurrence of accident conditions that could be prevented by the measurement system. These two parameters are combined to give a qualitative estimate of the cost-benefit ratio of the various instruments or measurement techniques, except for those that already exist in the nuclear power plant. For existing measurements, the cost is essentially zero and the cost-benefit ratio is very low if the measurement is at all useful. The pertinent cost related parameters are listed in the "development status", "cost", and "cost-benefit ratio" columns of Table 2.

An estimate of cost-benefit ratio is meaningless without the assumption that the measurement technique will actually work and give the expected information. The estimate of the probability of success of the measurement technique is, in many cases, the most difficult and most critical part of the evaluation of a measurement technique. Even when some development work has been done with a technique, it is often difficult to predict how it will perform in different applications. The "comments" column in Table 2 includes some judgments about the prospects for success of various not-yet-available measurement techniques.

In Table 2, there are some question marks in the cost-benefit ratio column. These indicate that the measurement is essentially free (because it already exists or is required by RG 1.97) but has little or no value as an anticipatory measurement. This low anticipatory values is, in most cases, the result of the event not occurring or the measurement not functioning properly until after an accident condition exists. These measurements should certainly be monitored, but their role is more accident detection than anticipatory.

The other Table 2 measurements that are marked "existing" are measurements that already exist in nuclear power plants and are expected to have some anticipatory value. In all cases (except perhaps for signature analysis, to be mentioned later), these existing measurements are adequate in range, accuracy, etc., to perform the anticipatory function, and their use as anticipatory measurements is recommended.

The development statuses of the other Table 2 measurements range from "speculative" to "available". The "available" notation means that the measurement system can be obtained through commercial suppliers and can be implemented with no more than simple routine applications engineering. The "speculative" notation means that there is some reason to expect that the measurement technique might work, but that this particular application has not been demonstrated and there is no assurance that the application would be successful. The "partly developed" and "mostly developed" notations mean that at least some development work has been done, and the technique may have been proven in other applications, but this particular application still requires some development effort and its success is not completely assured. The evaluations and recommendations on these various measurements are in the last column of Table 2.

Acoustic techniques are listed as speculative or partly developed for a variety of the measurements of Table 2, most of which have a high cost-benefit ratio and rather uncertain propects for success. It would be difficult to justify funding a high-cost, high-risk development program for any one of these applications. However, it seems that a single development effort might be applicable to a variety of measurements, so that the development cost per measurement using acoustic techniques might be quite low. Therefore, despite the apparent high cost-benefit ratio and the uncertainty of success of the several individual measurement applications using acoustic techniques, a development program for investigating acoustic techniques in general seems advisable. The Table 2 measurements that would be affected by such a general development program are indicated by a reference to Note 2 in the evaluation column.

8. RECOMMENDATIONS

The analyses and considerations of the preceding sections lead to the following recommendations for future work. These suggestions include implementation of existing or available measurements for anticipatory purposes, several minor investigations, and three larger research and development projects: investigation of acoustic techniques, instrument diagnostics development, and a comprehensive evaluation of general signature analysis techniques.

8.1 Investigation of Acoustic Techniques

In this discussion, acoustic techniques include vibration analysis, flow noise analysis, and acoustic emission analysis. These three areas are not always clearly distinguished, and no attempt is made to separate them here. Acoustic techniques have a potential application in a variety of anticipatory functions, including detecting crack propagation in a metal part; detecting leakage of pressurized fluid; detecting abnormal flow conditions such as cavitation, two-phase flow, excessive turbulence, flow oscillations, and resonance conditions; detecting imbalance, misalignment, and bearing wear in rotating machinery; and detecting flow-induced vibration of structures and parts such as bellows and diaphragms in valves.

There is a considerable body of reported work with acoustic techniques for various applications. However, many of the reports are vague or uncertain in their conclusions; most of the projects focus on one specific technique for a certain application, and other acoustic processes are carefully excluded or are assumed to be absent; and much of the work is done in a relatively pure laboratory environment with no allowance for the multitudes of background noises that may exist in a real nuclear power plant.

Three questions should be addressed in evaluating the potentials of acoustic techniques:

1. How well can interesting acoustic signals be separated from uninteresting background noise?

2. How reliably can the cause of the signals be determined? That is, is the source a bad bearing, a fluid leak, a crack growing, etc.?

3. How accurately can the location of the source be determined? That is, where is the fluid leak, or which bearing is noisy?

A major element in all three of these questions is the ability to detect common signal components in several detectors and reliably measure the relative delay times of the signals in the several detectors. Some work has been done in optimal delay time estimation, but this work is limited in that it assumes optimization criteria that may not always be appropriate and it usually assumes large data records which may not be available in real applications. Past work does not adequately address the problems of separating the signals from background noise and sorting out the effects of multiple transmission paths from the acoustic source to the detector. Thus, a major part of the effort in investigating acoustic techniques should be devoted to theoretical analyses and experimental verification of how to distinguish interesting signals from noise; how to know whether such a separation is actually accomplished, or what confidence one can have that he is really working with interesting signals instead of noise; how to optimally estimate the acoustic source location when working with limited data and multiple transmission paths; and, how much confidence one may have in a given estimate of a source location, and the degree of uncertainty in the estimate. Reliable location of the source of an acoustic signal is important not only because it can indicate where to look for a crack or a leak; it can also indicate the general nature of a problem (if the noise comes from a location where there is a bearing, one might suspect bearing wear problems) and whether the signal is interesting (it is not interesting if its source is located far from the region of interest). Thus, this first goal--reliable and accurate identification of the acoustic source location--is of great importance.

Determining the location of the acoustic source is not the only method of identifying the cause of the signals. The cause may in many cases be identifiable by examining various characteristics of the signal without any knowledge of the source location. The frequency content of the signal is a simple criterion for distinguishing between some types of acoustic sources. There may be a wide variety of other signal characteristics that would be useful in source type identification. The second goal of the investigation of acoustic techniques would be to determine signal characteristics that can uniquely identify the type of acoustic source.

The third goal in the investigation of acoustic techniques should be to measure typical background levels in a power plant and make some judgments about which acoustic signals should be detectable in the presence of such a background. This goal should be of low priority, because the background noise levels may be very different for different plants and the measurements made at one plant may be useless elsewhere.

8.2 Instrument Diagnostics Development

Proper instrument functioning is clearly important to safety in nuclear power plants. An instrument malfunction might cause dangerous, erroneous plant control actions. Some instrument systems include redundancy in an effort to detect and eliminate instrument errors, but some systems do not have any redundancy and very few systems are totally redundant. Even highly redundant systems may sometimes benefit from instrument diagnostics.

One trivial diagnostic test is to check whether the instrument reading is within the proper operating range of the instrument. This range check is recommended for implementation wherever it is applicable to an instrument that is important to plant safety. The range check test can be very useful and it has a good cost-benefit ratio, but it is by no means a complete instrument diagnostic system. The major interest in the work recommended here is in more complicated instrument diagnostic techniques. Two of these techniques are quite well known: redundancy checks and signature analysis. There may also be a variety of other useful diagnostic techniques. Many of these others may be applicable to only one type of insturment. Radiation measurement instruments, for example, should exhibit a predictable ratio of root-mean-square signal fluctuation to mean signal level.

Three main goals should be addressed in the investigation of instrument diagnostics:

1. The common, existing techniques--redundancy checks and signature analysis--should be formalized. These techniques are generally recognized as useful, but the details of implementation and the meanings of results are usually quite vague.

2. New possibilities for instrument diagnostics should be identified and evaluated.

3. Specific applications for the various techniques should be identified. There are many potential applications for the known techniques, but the practical feasibility and prospects for success depend strongly on the details of the particular application.

These investigations should include both passive and active diognostic techniques.

8.3 General Signature Analysis Evaluation

In some cases, signature analysis of one type of signal--neutron flux, for example--can give informaton about plant conditions that are apparently far removed from the signal--such as mechanical vibrations. This type of plant monitoring is referred to here as general signature analysis. This was not mentioned earlier in this report because it is not specifically associated with any particular accident related event. There are some indications that such techniques can be very powerful, although comprehensive and objective reports seem rather scarce.

The suggested activity in this area of general signature analysis is to do a comprehensive, objective survey of useful techniques, their capabilities, and their cost-benefit ratios. Such a survey should of course include a thorough literature search, and it should also involve personal contact with the designers, sellers, and users of existing systems.

8.4 Recommendations for Minor Investigations

The flow rate-pressure drop combination is recommended as an anticipatory measurement for pumps. By itself, this combination should be able to detect gross pump malfunctions. In combination with a measurement of the electrical power into the pump, it may be a quite sensitive anticipatory measurement. Further consideration of this possibility is recommended, if a low-cost experiment opportunity can be found. Such an opportunity might exist in the form of data recorded during the lifetime of a pump that eventually failed.

The use of signature analysis techniques to determine heat transfer coefficients seems to have a rather small chance for success, and the low importance of the associated reactor accident conditions does not justify the investigation of such techniques for anticipatory measurements. However, these techniques may warrant some consideration for other purposes, not included in this task.

The available information on detecting lateral shaft motion in rotating machinery is rather sketchy. This technique is expected to be a quite powerful anticipatory measurement. Further investigation is recommended.

Radiation monitoring of the secondary coolant to detect steam generator tube leaks is recommended for further study, to determine its sensitivity. Analysis of existing relevant data, if any can be found, is recommended.

8.5 Recommendations for Implementation of Available Techniques

Those Table 2 instruments and measurement techniques that are marked "existing" and "adequate" are recommended for implementation as anticipatory measurements.

Those existing measurements with a question mark in the "cost-benefit ratio" column of Table 2 should be monitored primarily as accident detection indicators. They may possibly serve some anticipatory function, but their anticipatory value is expected to be so small that no extra effort is justified for using these as anticipatory measurements.

Differential pressure measurements are recommended as the best technique for measuring liquid level, as long as there is no significant interference from pressure drop associated with fluid flow. Heated thermocouple techniques are the recommended alternative.

For monitoring valve position (how far open or shut the valve is), simple techniques using mechanical linkages to the valve stem are preferred. When this type of measurement is not possible, a quite good indication of valve position may be obtained from a combination of flow rate and pressure drop measurements. Acoustic techniques are not well-developed enough to allow their recommendation as a quantitative indicator of valve position.

Flow rate and pressure drop measurements are also recommended as a technique to detect flow path blockage. However, this technique is not applicable to the important case of local flow blockage in the core. No reasonable technique is known for this very desirable measurement.

Monitoring for voltage spikes to detect generator arcing has been reported,[24] and a similar technique should be applicable to motors. Implementation is recommended.

Pressure and temperature measurements are, for the most part, routine and almost trivial. Implementation of these measurements is recommended wherever an anticipatory function might be served. The one notable exception is that in-core temperature measurements might be very useful but very difficult.

9. DESIGN AND QUALITY REQUIREMENTS

One objective of this task is to determine design requirements (range, response time, accuracy, etc.) and qualification criteria (reliability, environmental tolerances, emergency power requirements, etc.) for anticipatory instrumentation, as is done in RG 1.97 through the definition of three categories for design and qualification criteria. In RG 1.97, these categories "provide a graded approach to requirements depending on the importance to safety of the measurement of a specific variable".

A superficial application of this importance criterion is obvious and trivial. The second column of Table 2 lists importance ratings for the various measurements. One could simply assign measurements with importance rating M (the most important) to RG 1.97 Category 1; those with rating I to Category 2, and those with rating LF to Category 3. However, such a casual approach is not very realistic.

A cost-benefit analysis would be a reasonable approach for deciding into which RG 1.97 category each measurement should be included. If a particular category's extra accuracy, reliability, etc., provide safety benefits that justify the extra cost of those attributes, then the measurement should be included in that category. Unfortunately, a detailed assessment of the benefits of particular instrument attributes would be an extremely difficult task, far beyond the scope of the present project. What is needed is a much simpler but still realistic approach.

Some insight into this categorization problem can be obtained from examination of RG 1.97 statements of the general intent for each category. Category 1 is intended for key variables, which "most directly indicate the accomplishment of a safety function." Anticipatory measurements are clearly not in this category since their use is in predicting an accident before it starts and the accomplishment of a safety function is not of interest until after an accident is detected. Anticipatory measurements might be included in Category 2, which is for measurements that indicate system operating status. However, it seems more likely that anticipatory measurements should be in Category 3, included as part of the diagnostic instrumentation in Category 3. This assignment to Category 3 is supported by the observation that most anticipatory measurements are not essential to nuclear power plant operation; many of the measurements mentioned in this report do not exist in plants that have been operating for years, and the anticipatory functions of many existing measurements are not required for plant operation. (Note that, even though the anticipatory measurements may not be essential, they may be important and cost-effective in improving nuclear power plant safety.)

It is our judgment that all anticipatory functions should be included in RG 1.97 Category 3. Of course, if one measurement system serves both an anticipatory function and another function that falls into a different RG 1.97 category, then the measurement system must meet the more stringent category requirements.

It is not possible to specify detailed performance requirements without considering specific instruments in specific applications, which is not done here. However, a few general observations can be made.

Anticipatory measurements are made while the nuclear power plant is operating normally or very nearly normally. This implies that the range and environmental tolerance requirements for anticipatory instrumentation are the same as those for normal plant instrumentation in the same application. In particular, both existing plant instrumentation and instrumentation required by RG 1.97 automatically satisfy the range and environmental tolerance requirements of anticipatory measurements for which those instruments might be used.

Consideration of the measurements marked [illegible]xisting" in Table 2 indicate that they all have accuracy, sensitivity, and response speed adequate for whatever anticipatory functions are suggested for those existing measurements.

For all the anticipatory measurements that do not now exist but are suggested for implementation or further investigation, it is believed that commercially available instruments can easily meet the requirements of accuracy, sensitivity, and response speed, with one general exception: measurements involving signature analysis may require faster response--and possibly also greater sensitivity--than is commonly available in reactor power plant instrumentation. Apart from signature analysis applications, the anticipated difficulties are not associated with instrument performance limitations, but with interference from extraneous phenomena or background noise. Pressure drop associated with fluid flow may interfere with a differential pressure measurement of liquid level, for example, or background radiation may interfere with attempts to detect radioactive fission products in the coolant.

In short, it is suggested that anticipatory measurement systems be included in RG 1.97 Category 3. Although no specific performance parameters are recommended here, it is expected that there will be no difficulty in achieving the performance appropriate for individual applications, with the possible exception of measurements using signature analysis.

10. CONCLUSIONS

A list of potential anticipatory measurements has been constructed. The justification for inclusion of these measurements is their ability to predict or give an early indication of accident-related events, with a low cost benefit ratio. Specific performance requirements are not listed, but standard nuclear power plant instrumentation will satisy the performance requirements for all anticipatory measurements except perhaps those that will use signature analysis (not yet developed). RG 1.97 design and qualification Category 3 is recommended for all anticipatory measurements, unless concurrent use of the measurement systems for other purposes requires a more stringent category. Overlaps between potential anticipatory measurements and RG 1.97 requirements are noted in Table 2. A qualitative assessment of the importance of the potential anticipatory measurements is also included in Table 2.

There seems to be no need for more than the three RG 1.97 categories for design and qualification requirments for anticipatory instrumentation. Category 3 is judged applicable to all anticipatory instrumentation.

Existing nuclear power plant measurements that might be useful for anticipatory functions are indicated in Table 2. These existing measurements are believed to meet all performance requirements for their anticipatory functions.

No new types of commercially available instrumentation have been identified for use in anticipatory measurements. There may be some anticipatory measurement applications that require commercial instrumentation of the same types as those already used in other nuclear power plant applications.

Several recommendations are made for development of new measurement techniques that might be useful in anticipatory functions. No potential for self-testing or self-calibration capabilities have been identified, but development work in the closely related area of instrument status diagnostics is recommended.

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TABLE 1. ACCIDENT-RELATED EVENTS FROM TREES, AND POTENTIAL ANTICIPATORY MEASUREMENTS

EVENT	MEASUREMENT COMMENTS
0: clad failure	no direct, on-line measurement. This may be detectable by fission product monitoring.
1: high clad temperature	no direct, practical measurement in a power plant. This may be indicated by the presence of voids in a PWR.
2: corrosion by reactor coolant or fission gas	possibly detectable by presence of corrosion products in coolant.
3: clad defect	no on-line measurement. Clad defects should be detected by pre-service inspection.
4: clad fatigue and creep	no on-line measurement.
5: high reactor power	no direct measurement. Power is measured indirectly by several methods.
6: inadequate fuel heat removal by coolant	no direct measurement.
7: reactor inlet primary coolant temperature high	directly measurable (temperature).
8: high neutron power	directly measurable (global neutron flux).
9: positive reactivity insertion	no direct measurement.
10: reactivity insertion due to control rod error or boron dilution	Both control rod position and boron concentration are measurable, but interpretation is required to verify correctness. Control rod position errors may also be detectable by local neutron flux measurements.
11: reactivity insertion due to fueling error	This may be detectable by local neutron flux measurements or local coolant temperature measurements, with interpretation.

TABLE 1. (continued)

EVENT	MEASUREMENT COMMENTS
12: reactivity insertion by feedback	There is no direct measurement of reactivity insertion, but an effect (increased neutron flux) is directly measurable and some causes (cold primary coolant inlet, for example) are directly measurable.
13: crud deposition on fuel	no direct, on-line measurement.
14: loss of primary coolant	directly measurable. Saturation measurements may indicate severe loss of PWR coolant.
15: change in heat transfer coefficient	may be detectable by measuring the relationship between local neutron flux and local coolant temperature fluctuations.
16: low flow or loss of primary flow	directly measurable (volumetric flow rate).
17: primary coolant pipe break	may be predictable and detectable by acoustic techniques. There may be indirect indications through measurements of coolant pressure, primary coolant inventory (pressurizer level), containment liquid inventory, or containment radiation level.
18: spurious opening of safety/relief or bypass valve	directly measurable (valve position)
19: stuck open relief or bypass valve	directly measurable (valve position)
21: flow path blockage	Major flow blockage is measurable (flow rate & differential pressure); limited blockage in the core may be difficult to detect.
22: loss of primary coolant pump	directly measurable (pump speed).
23: secondary coolant temperature high	directly measurable (fluid temperature).

TABLE 1. (continued)

24: inadequate heat transfer from primary to secondary coolant	may be detectable by measuring the relationship between primary and secondary coolant temperature fluctuations.
25: loss of secondary coolant	directly measurable (liquid level)
26: steam generator isolation from turbine	directly measurable (valve position).
27: turbine trip	directly measurable (electrical signal).
28: generator load rejection	directly measurable (electrical current).
29: steam generator tube fouling	no direct measurement.
30: flow instability in secondary coolant	no direct measurement. This may be detected by monitoring liquid level fluctuations.
31: loss of feed pumps	directly measurable (pump speed).
32: stuck closed feed water valve	directly measurable (valve position).
33: rupture of feed water line	may be detectable and predictable by acoustic techniques. There may be indirect indications from liquid inventory and pressure and flow measurements.
34: spurious opening of steam generator relief or turbine bypass valve	directly measurable (valve position).
35: stuck open relief valve	directly measurable (valve position).
36: steam line rupture	see event 33.
37: steam out flow more than feed flow, feed water control malfunction	indirectly measurable, calculated from volumetric flow rates, temperatures, pressures, & qualities.
38: breach of primary coolant boundary	see event 17.

TABLE 1. (continued)

39: material welding defect	no direct, on-line measurement. Welds should be inspected before plant start-up. Defect growth may be detectable by acoustic techniques.
40: fatigue, creep, or corrosion	no direct, on-line measurement. Corrosion may be detectable by measuring corrosion products in the coolant.
41: external events	detectable after occurrence. Certain events may be predictable; seismic monitoring may predict earthquakes, for example.
42: vibration	Vibration is directly detectable, but interpretation is required to determine whether the vibration is harmful.
43: pu[illegible]ive seal failure	Detectability depends on severity. Gradually-developing seal failures may be detectable.
44: primary coolant pressure high	directly measurable (pressure).
45: increase in primary coolant energy	indirectly measurable (temperature with interpretation).
48: PRV, PORV, or LPIS check valve failure	may be measurable, depending on failure mechanism; valve position is measurable; seat leakage may be measurable.
100: breach of containment	Detectability depends on mechanism and severity.
101: breach of LPIS system	Detectability depends on mechanism (valve leakage, pipe break, etc.).
102: external event	see event 41.
103: containment pressure high	directly measurable (pressure).
104: material defect	see event 39.
105: feedthrough seal failure	may be detectable by acoustic techniques.

TABLE 1. (continued)

106: failure of LPIS isolation valves	see event 48.
107: inadequate heat removal from containment	no direct measurement. A correctly interpreted temperature measurement may serve this function.
108: hydrogen burn or explosion	predictable through hydrogen concentration measurements.
120: containment spray failure	may be directly measurable, depending on failure mechanism.
121: containment heat exchange system malfunction	may be directly measurable, depending on failure mechanism.
122: flow blockage	see event 21.
123: loss of CSR system pump	directly measurable (pump speed).
124: inadequate containment sump water level	dirctly measurable (liquid level).

TABLE 1. (continued)

125: inadequate ECC injection	flow rate is measurable.
126: flow blockage	see event 21.
127: loss of HPIS or LPIS pumps	directly measurable (pump speed).
128: inadequate water level in RWST	directly measurable (liquid level).
129: inadequate primary flow (LPIS)	flow rate is measurable.
130: inadequate secondary flow	flow rate is measurable.
131: fouling of heat exchanger	see event 29.
132: loss of pumps	directly measurable (pump speed).
133: flow blockage	see event 21.
134: flow blockage	see event 21.
135: loss of pumps	directly measurable (pump speed).
136: inadequate coolant supply	directly measurable (liquid level).
201: breach of containment	see event 100.
202: material defect	see event 39
203: containment pressure high	directly measurable (pressure).
204: containment isolation failure	detectability depends on mechanism and severity.
205: external forces	see event 41.
210: breach of high energy piping in containment	see event 17.
220: atmosphere dilution system failure	detectability depends on specific failure mode.
221: hydrogen explosion	see event 108.
222: ventilation system failure	detectability depends on specific failure mode.

TABLE 1. (continued)

223: inadequate heat removal from containment	see event 107
224: residual heat removal system	detectable by temperature measurement with interpretation.
225: vacuum breaker system failure	directly measurable (pressure).
230: isolation valve failure	see event 48.
231: seal failure	see event 43.
240: earthquakes, tornadoes, etc.	see event 41.
241: airplanes, projectiles, etc.	see event 41.
250: loss of containment spray	see event 120.
251: improper water level	directly measurable (liquid level).

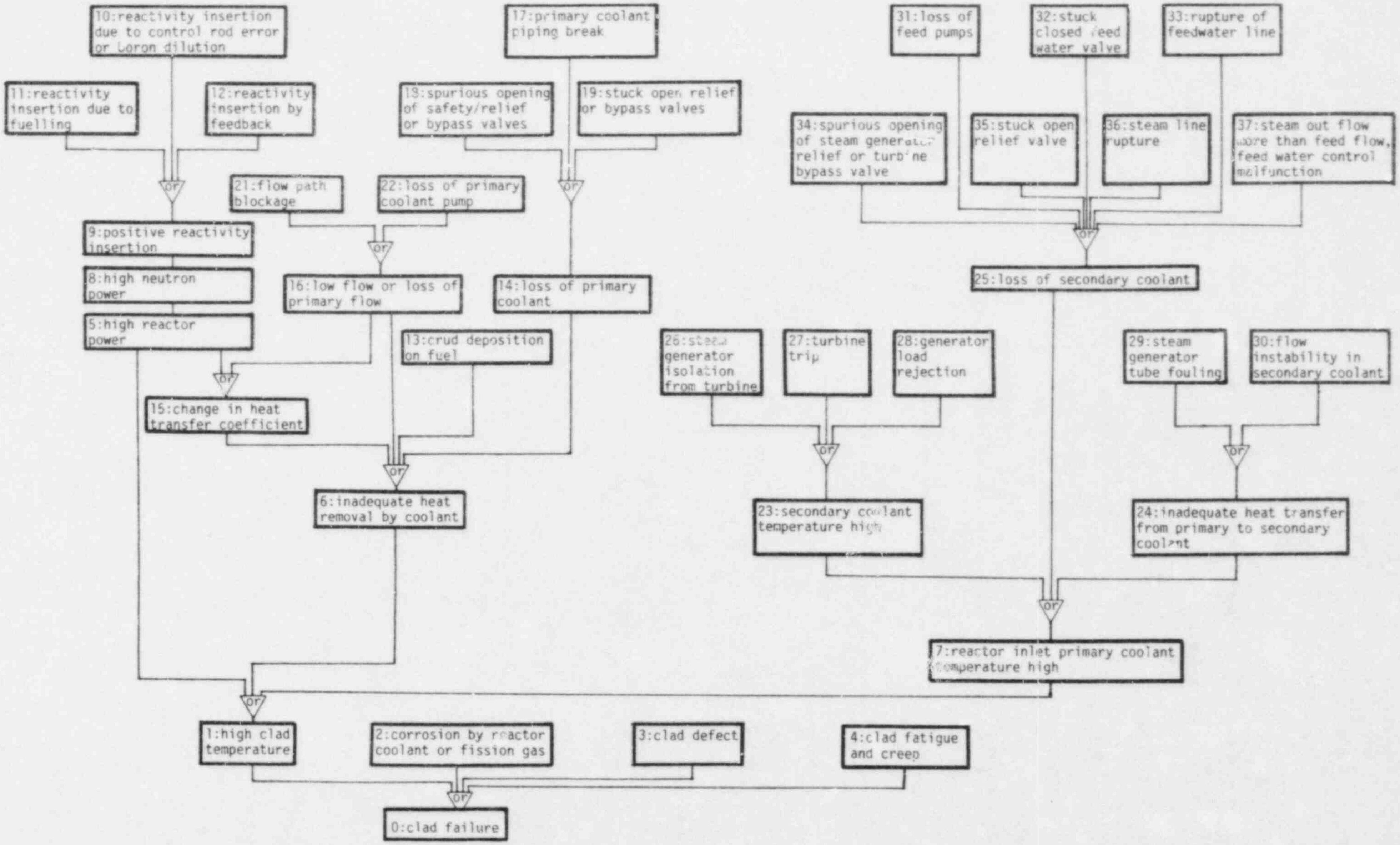

Figure 1. Breach of cladding event tree.

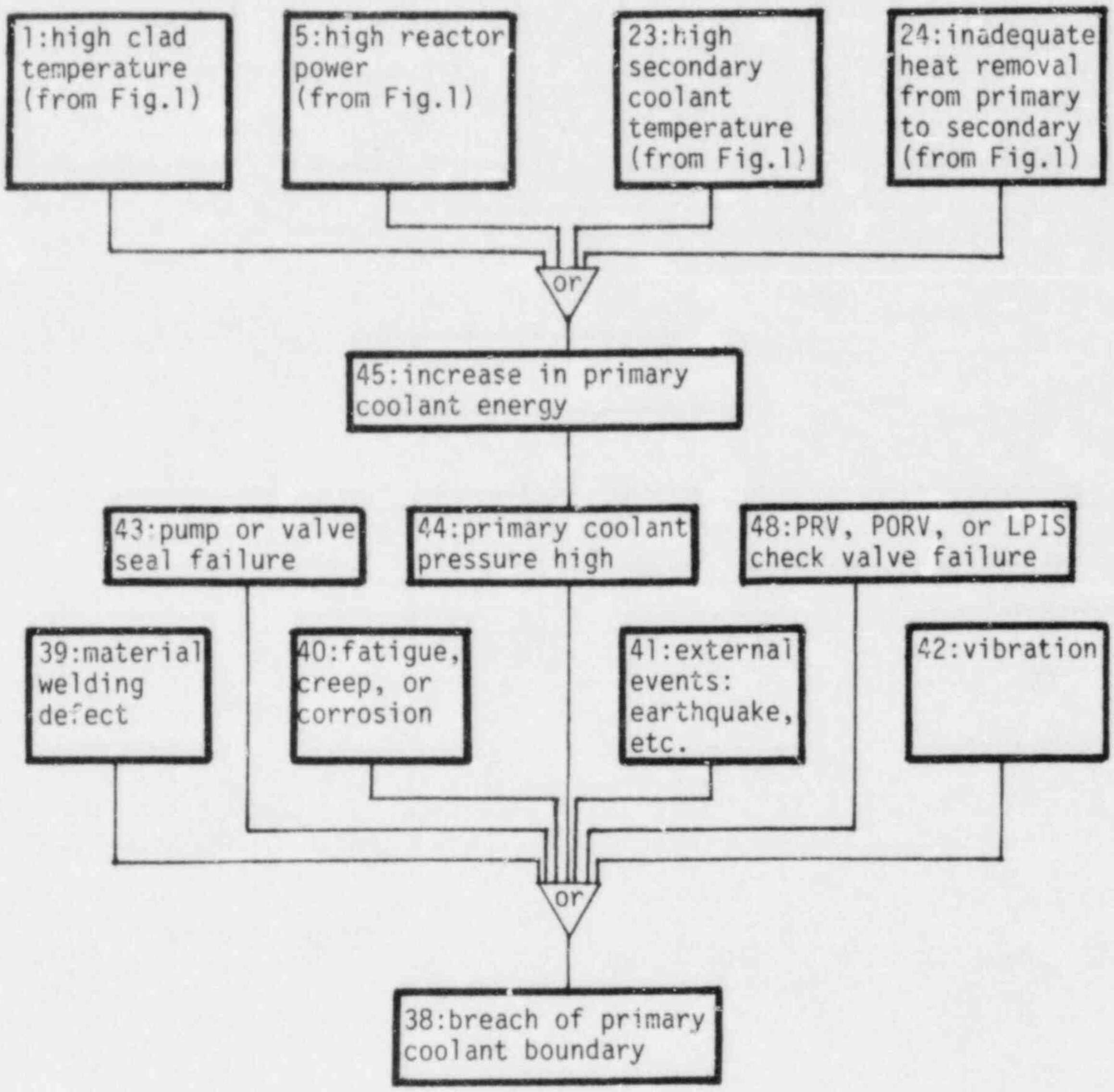

Figure 2. Breach of primary coolant boundary event tree.

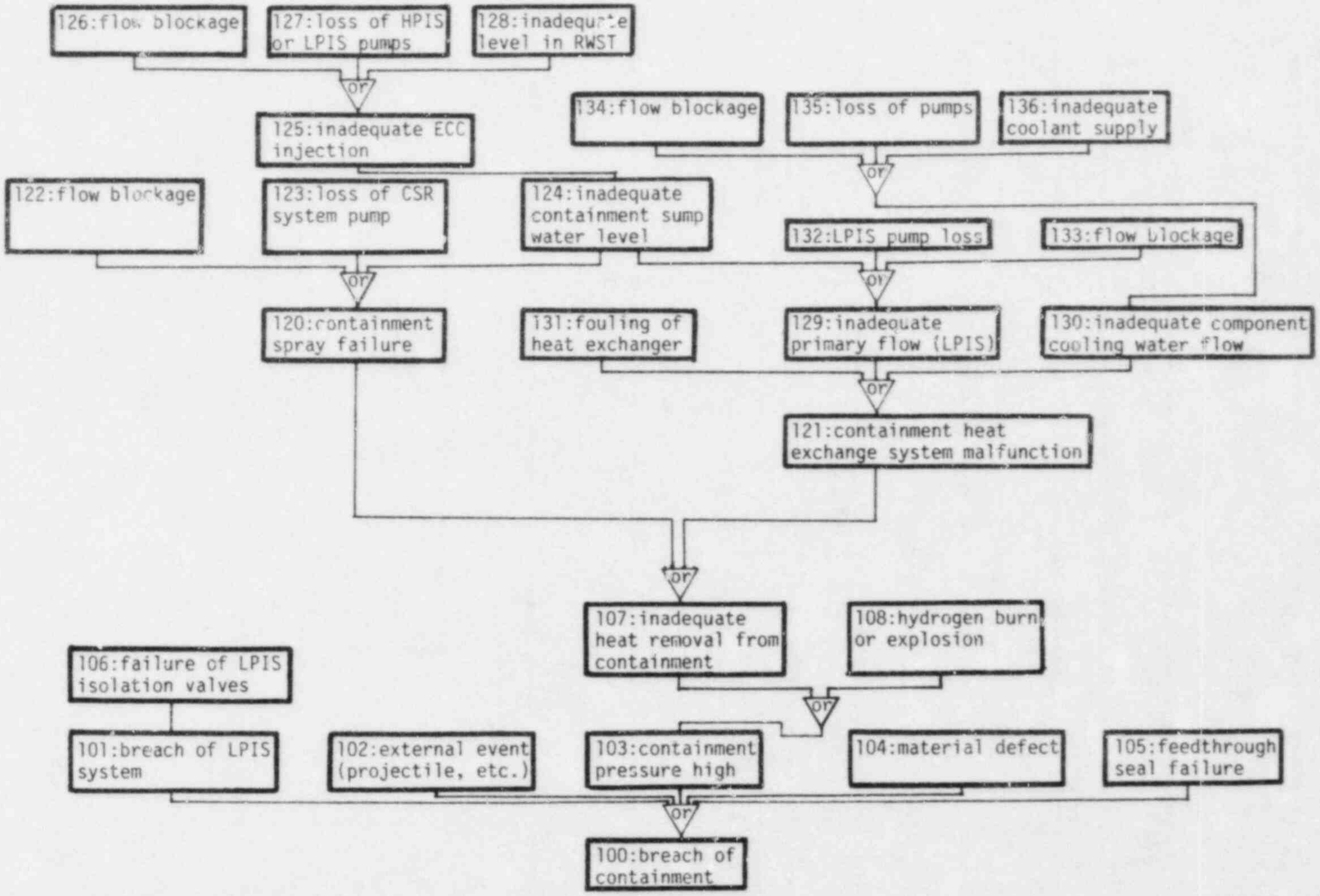

Figure 3. Breach of containment event tree for PWRs.

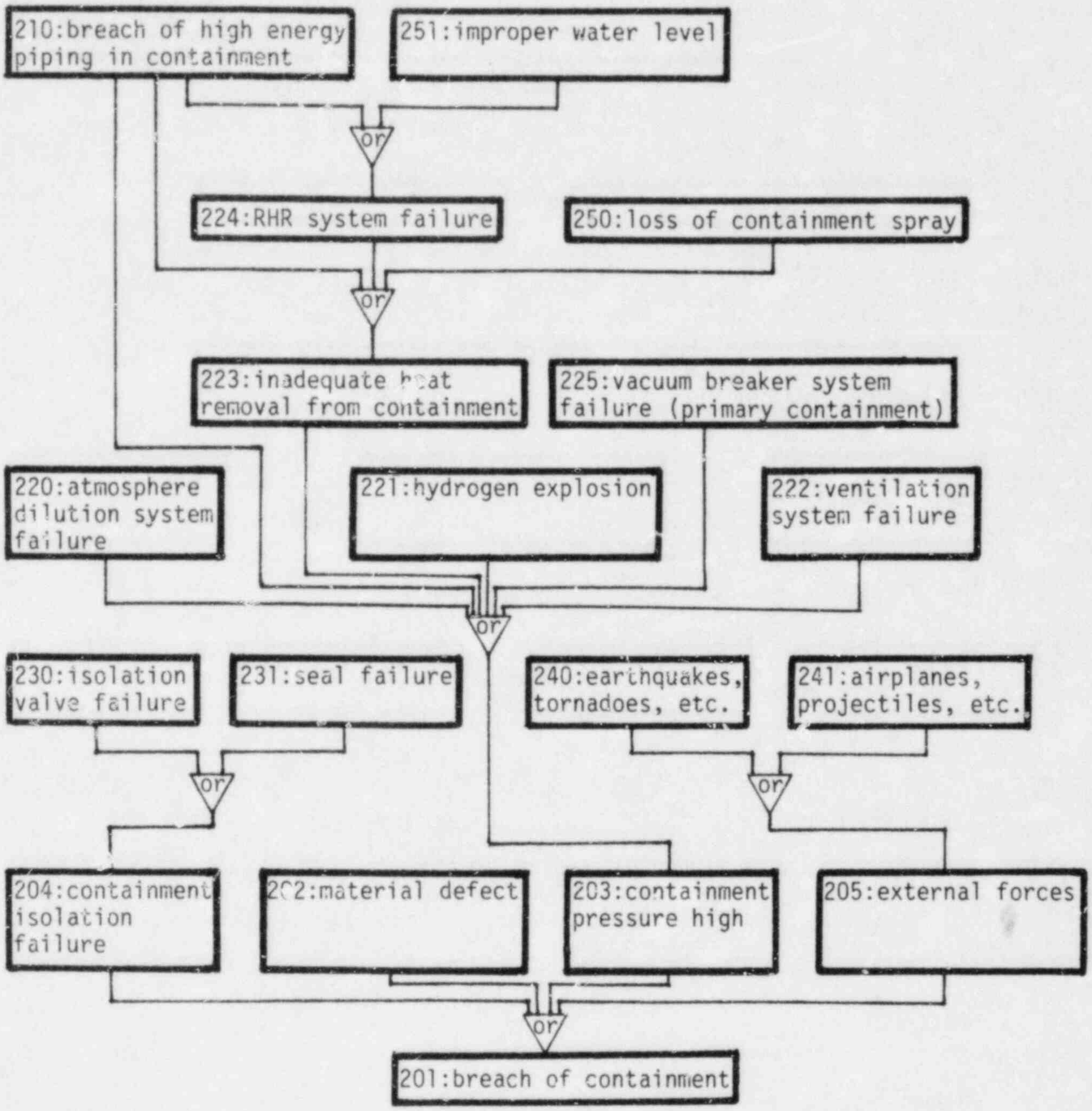

Figure 4. Breach of containment event tree for BWRs.

TABLE 2. ANTICIPATORY MEASUREMENTS

MEASUREMENT	IMPORTANCE (ACCIDENT FREQUENCY)[a]	RG 1.97 REQUIREMENT	TECHNIQUE OR INSTRUMENT	DEVELOPMENT STATUS	COST	COST BENEFIT RATIO	EVALUATION AND COMMENTS
Clad failure (breach)	X	Yes	radiation monitoring for fission products in coolant	developed[38]	zero	?	This measurement is "free" because of the RG 1.97 requirement. However, its anticipatory value is questionalbe because it does not give an early enough warning of clad breach.
High clad temperature	X		acoustic monitoring for core boiling in a PWR	speculative	high	high	Success is questionable. Technique applicable only in water-covered core, when clad overheat is unlikely. Further work not recommended.
Clad corrosion	O		chemical monitoring for corrosion products in coolant	speculative	high	high	Success is questionable. Further work not recommended
Reactor power	I		neutron flux mesurements	existing	zero	zero	Adequate
			caliometric measurements	existing	zero	zero	Adequate
Fluid temperature	LF	Yes	thermocouple or RTD	existing	zero	zero	Adequate
Global neutron power	I	Yes	direct measurement	existing	zero	zero	Adequate
Control rod position	M	Yes	direct measurement	existing	zero	zero	Adequate
Boron concentration	I	Yes	direct measurement	existing	zero	zero	Adequate
Local neutron flux	I		direct measurement	existing	zero	zero	Adequate

TABLE 2. ANTICIPATORY MEASUREMENTS (continued)

MEASUREMENT	IMPORTANCE (ACCIDENT FREQUENCY)[a]	RG 1.97 REQUIREMENT	TECHNIQUE OR INSTRUMENT	DEVELOPMENT STATUS	COST	COST BENEFIT RATIO	EVALUATION AND COMMENTS
Liquid Level	M	Yes	Differential pressure	existing or available	zero or low	zero or low	This is the recommended technique as long as flow-induced pressure drop is insignificant.
			Electrical conductivity	Partly developed	moderate or high	high	Success in commercial plant applications is questionable. Further work not recommended.
			Heated Thermocouples	Available	Moderate	Moderate	Best alternative to differential pressure.
			Ultrasonic	Partly developed	Moderate or high	High	Success is questionable. Further work not recommended, because alternatives exist.
			Neutron flux and energy analysis (for core liquid level only)	speculative or partly developed	Moderate or high	High	Some success is expected, but accuracy is questionable. Further work not recommended.
Saturation, sub-cooling, superheating	X	Yes	Temperature and pressure comparison	existing	Zero	?	Anticipatory values is expected to be very limited.
Fuel-to-coolant heat Transfer coefficient	0		Signature analysis of neutron flux and temperature fluctuations	speculative	High	Very high	Success is very questionable. Further work not recommended.
Volumetric flow rate	M	Yes	Normally, differential pressure across a flow restriction	existing or available	Zero or low	Zero or low	Acceptable.
Pipe break with pressurized fluid fluid leakage	M	Yes	Acoustic emission for prediction and detection	partly developed	moderate or high	moderate	Success is questionable. A comprehensive system would require a lot of hardware. Note 2
			Radiation monitoring	Partly developed	moderate	moderate	Anticipatory value is limited. Further development not recommended.

TABLE 2. ANTICIPATORY MEASUREMENTS (continued)

MEASUREMENT	IMPORTANCE (ACCIDENT FREQUENCY)[a]	RG 1.97 REQUIREMENT	TECHNIQUE OR INSTRUMENT	DEVELOPMENT STATUS	COST	COST BENEFIT RATIO	EVALUATION AND COMMENTS
Valve position	M	Yes	Mechanical position indicator	existing or available	zero or moderate	low	This is the perferred technique.
			Flow noise monitoring	mostly developed	low or moderate	low or moderate	This has some potential for detecting incomplete closing, otherwise probably not a quantitative measurement.
			Flow rate and pressure drop	existing or available	low or moderate	low or moderate	Acceptable but indirect and not perferred.
Stuck valve	M		(See valve position)				
Valve status	M		Acoustic emission for leak checks	partly developed	moderate or high	moderate or high	Success is questionable. Note 2.
			Acoustic emission for crack propagation	partly developed	moderate or high	moderate or high	Success is questionable. Note 2.
			monitoring for vibration of diaphragus, bellows, etc.	partly developed	moderate or high	moderate or high	Success is questionable. Note 2.
			Flownoise monitoring for cavitation or abnormal flow	partly developed	moderate or high	moderate or high	Success is questionable. Note 2.
			Monitor power needed to drive valve	speculative	moderate or high	moderate or high	Success is quite questionable. Further work not recommended.
			Strain quages on valve stem (for stem bending)	mostly developed	moderate	moderate	Success is expected, but the problem would be better handled through good engineering.
			Seal leakage flow rate measurement	existing or available	zero or low	low	Acceptable when applicable.
Flow path blockage	M		Flow rate differential pressure	existing or available	zero to moderate	zero to moderate	Very effective when applicable, but not always applicable, especially to local blockage in the core. Implementation recommended where applicable.
			Flow noise monitoring	speculative	high	high	Probably of limited applicability, questionable success. Note 2

TABLE 2. ANTICIPATORY MEASUREMENTS (continued)

MEASUREMENT	IMPORTANCE (ACCIDENT FREQUENCY)[a]	RG 1.97 REQUIREMENT	TECHNIQUE OR INSTRUMENT	DEVELOPMENT STATUS	COST	COST BENEFIT RATIO	EVALUATION AND COMMENTS
Pump failure	M		Pump speed	existing	zero		
			flow rate and pressure rise	existing or available	zero or moderate	low or moderate	Installing new flow measurements could be expensive, otherwise cost is low. Implementation recommended where not already existing.
Pump status	M	Yes (pump motor current)	Compare electrical power input with mechanical power output to fluid	speculative	moderate or high	moderate or high	Success is questionable. Investigation is recommended if a low-cost opporunity is available.
			Seal leakage flow rate measurement	existing or available	low	low	Implementation recommended where applicable.
Heat transfer coefficient primary to secondary	0		Signature analysis of temperature fluctuations	speculative	high	very high	Success is very questionable. Further investigation not recommended.
Turbine-steam generator	M		(see valve position)				
Turbine trip	I		electrical signal indication	existing	zero	?	Anticipatory value of this signal is limited.
Generator load loss	I		electrical signal indication	existing	zero	?	Anticipatory value of this signal is limited.
Flow instability in secondary coolant	0		monitor void fraction, liquid level, or equivalent collapsed liquid level fluctuations	speculative	moderate or high	high	Success is questionable because of uncertainty about the individual measurements. Not recommended for further investigation.
Mass flow balance in steam generator secondary side	0		calculate from measurements of volumetric flow, temperature, pressure, and quality	speculative	moderate or high	high	Success is questionable because of uncertainty about the individual measurements. Not recommended for further investigation.
Vibration	0		(see specific vibration monitoring applications)				

TABLE 2. ANTICIPATORY MEASUREMENTS (continued)

MEASUREMENT	IMPORTANCE (ACCIDENT FREQUENCY)[a]	RG 1.97 REQUIREMENT	TECHNIQUE OR INSTRUMENT	DEVELOPMENT STATUS	COST	COST BENEFIT RATIO	EVALUATION AND COMMENTS
Seal failure in a pump or valve	M		(see pump status or valve status)				
Fluid pressure	I	Yes	direct measurement	existing or available	zero or low	low or moderate	Implementation recommended where appropriate and not already existing.
Containment feed-through seal failure	O		acoustic emission	partly developed	moderate or high	high	Success is questionable. Note 2.
			leakage flow rate measurement	existing or available	low or moderate	low or moderate	Sensitivity is questionable.
Hydrogen concentration	X	Yes	direct measurement	existing	zero	?	Value as an anticipatory measurement is probably low.
Excessive steam generator tube leak	I		acoustic measurements	speculative	high	high	Sucess is very questionable. Note 2.
			secondary coolant monitoring	existing or available	moderate or low	moderate	Effectiveness is uncertain.
Loss of offsite power	I		(not predictable)				
Loss of internal power	I	Yes (status of standby power)	(certain generator failures may be predictable; see motor-generator status)				
Iodine concentration	LF		primary coolant radio-activity monitoring	developed[38]	moderate	high	Anticipatory value is probably low.
Control rod status	LF		(no known anticipatory measurement)				
Motor-generator status	M		monitor for voltage spikes	partly developed	moderate	moderate	Recommended for development and application.
			compare input & output power (see rotating machinery status)	speculative	moderate or high	moderate or high	Success is uncertain. Further consideration is recommended.

TABLE 2. ANTICIPATORY MEASUREMENTS (continued)

MEASUREMENT	IMPORTANCE (ACCIDENT FREQUENCY)[a]	RG 1.97 REQUIREMENT	TECHNIQUE OR INSTRUMENT	DEVELOPMENT STATUS	COST	COST BENEFIT RATIO	EVALUATION AND COMMENTS
Rotating machinery status	M		vibration analysis, for various failure modes	partly developed	moderate or high	moderate or high	Success is uncertain for some failure modes. Note 2.
			acoustic emission for crack propagation	partly developed	moderate or high	moderate or high	Success is uncertain. Note 2.
			fluid flow noise monitoring for cavitation & abnormal two-phase flow	partly developed	moderate or high	moderate or high	Success is uncertain. Note 2.
			lateral shaft motion	existing or available	moderate	moderate	Available information is vague. Further investigation is recommended.
			bearing temperature	existing or available	zero or low	zero or low	Adequate.
			flow lubricant temperature	existing or available	zero or low	zero or low	Adequate.
			lubricant flow rate & pressure drop	existing or available	zero or low	zero or low	Adequate.
			seal leakage flow rate	existing or avilable	zero or low	zero or low	Adequate.
Fluid power system status	M	Yes	monitor pressure and flow from pump or compressor	existing or available	zero to moderate	zero to moderate	Adequate
Instrument system status	M		signature analysis	partly developed	moderate or high	moderate or high	Success probability depends on specific application. Application recommended where no alternatives are available.
			range check	existing or available	zero or low	zero or low	Data-within-range checks are easy and valuable, but not a complete instrument status indicator. Application recommended where not already existing.

TABLE 2. ANTICIPATORY MEASUREMENTS (continued)

MEASUREMENT	IMPORTANCE (ACCIDENT FREQUENCY)[a]	RG 1.97 REQUIREMENT	TECHNIQUE OR INSTRUMENT	DEVELOPMENT STATUS	COST	COST BENEFIT RATIO	EVALUATION AND COMMENTS
			redundancy check	partly developed	zero to moderate	zero to moderate	Not universally applicable, but very powerful. Application recommended where applicable and not already existing.
Control system status	M						The potential success and the value of anticipatory measurements applied to control system depend on this specific application and are quite limited is most cases.

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1. Accident Frequency Codes:

M = moderate frequency
I = infrequent
LF = limiting fault (very infrequent)
O = negligible or zero frequency
X = not on initiating event, but a result other events.

2. This measurement would be affected by the recommended investigation of acoustic techniques.