EVALUATION OF INSTRUMENTATION

TO DETECT

INADEQUATE CORE COOLING

PREPARED FOR

177 OWNERS GROUP

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1.0 BACKGROUND

The major concerns raised in the aftermath of the TMI-2 accident were identified in the "TMI-2 LESSONS LEARNED TASK FORCE STATUS REPORT, NUREG-0578". Section 2.1.3.b of that report addressed additional instrumentation which could assist in the detection of inadequate core cooling. The NRC position on additional instrumentation was that

> "licensees shall provide a description of any additional instrumentation or controls (primary or backup) proposed for the plant .... giving an unambiguous, easy-to-interpret indication of inadequate core cooling."....

Subsequently, the NRC's position was clarified and amplified in Enclosure 1 to H. R. Denton's letter of October 30, 1979 to all operating nuclear power plants entitled "Discussion of Lessons Learned Short Term Requirements". This letter addressed the following requirements for any additional instrumentation proposed. (The complete clarification is reproduced in Appendix A.)

a. Design of new instrumentation should provide an unambiguous indication of inadequate core cooling.

b. The indication should have the following properties:

   (1) It must indicate the existence of inadequate core cooling caused by various phenomena.

   (2) It must not erroneously indicate core cooling because of the presence of an unrelated phenomena.

c. The indication must give advanced warning of the approach of inadequate core cooling.

d. The indication must cover the full range from normal operation to complete core uncovering.

H. R. Denton's letter of October 30, 1979, clarified the requirements that any investigation of additional instrumentation include an evaluation of reactor water level indication.

In response to NUREG-0578 B&W has developed operator guidelines for action to recover from a condition of inadequate core cooling using existing instrumentation (References 1-5). The evaluation provided in the following sections reviews the adequacy of existing and proposed instrumentation to indicate inadequate core cooling (ICC). To perform this review, it is important to understand when ICC actually occurs, what operator actions occur prior to ICC, and the guidelines followed once ICC has occured. The next two sections describe ICC and the actions taken before and after ICC is indicated. These sections are then followed by a comparison of existing and proposed equipment for indicating ICC which conclude with a section describing why the existing installed instrumentation provides the best indication.

2.0 DEFINITION OF INADEQUATE CORE COOLING

In a depressurization event, the reactor coolant system (RCS) must first reach saturation conditions before there is any danger of inadequate core cooling. Subsequently if the RCS inventory is reduced and uncovery of the core begins, temperatures in the uncovered region will increase causing superheating. It is important to note in this discussion that inadequate core cooling does not begin until reactor vessel (RV) water inventory falls below the top of the core thus resulting in an increasing fuel clad temperature.

3.0 OPERATING PHILOSOPHY AND GUIDELINES FOR INADEQUATE CORE COOLING

The goals of the operator prior to ICC are different than those once ICC has occured. Prior to an indication that ICC has occured, the operator is taking actions which will stabilize pressure and refill the RCS. The goal is to re-establish the subcooling margin at the high pressure condition or cooldown and depressurize to low pressure injection plant conditions. Indication that ICC has occured changes the operator's guidance because the goal of refilling at the high pressure cannot be attained. The operator at this point is instructed to partially depressurize using the PORV to increase RCS inventory addition rate. Note: If this fails the operator is instructed to further depressurize and establish low pressure injection (LPI). These last two steps are based on conscious decisions that recovery at the higher pressure is not possible and that depressurization will cause more immediate core voiding, but in the longer term will result in improved core cooling by increased RCS inventory.

Based on this logic it is important that the indication not be ambiguous and not occur prematurely. It is important to provide as much time as possible for recovery at the higher pressure which leads to the preferred mode of operation.

Symptoms of an overcooling transient are similar to the small break loss of coolant transient up to the point of inadequate core cooling. At this point, if the operator has taken actions for inadequate core cooling when in fact overcooling exists, an unnecessary serious transient would result. Thus, the operator must not proceed with the inadequate core cooling actions until inadequate core cooling is confirmed.

The following sections describe the actual operator actions taken prior to ICC and those once ICC is indicated.

3.1 Operator Actions During Approach to ICC

Operator actions during the approach to an inadequate core cooling condition are summarized as follows:

1. Initiate HPI
2. Maintain OTSG level
3. Trip RC pumps if ESFAS initiated by low RC pressure
4. Monitor incore thermocouple temperatures to determine if inadequate core cooling exists.

These actions are verified when saturation conditions exist. No further actions are taken until thermocouple temperatures reach a predetermined temperature from Small Break Operating Guidelines (see Figure 3.1-1, Curve 1). This indicates that superheating is ocurring, that fuel clad temperature has increased above saturaction and that inadequate core cooling exists.

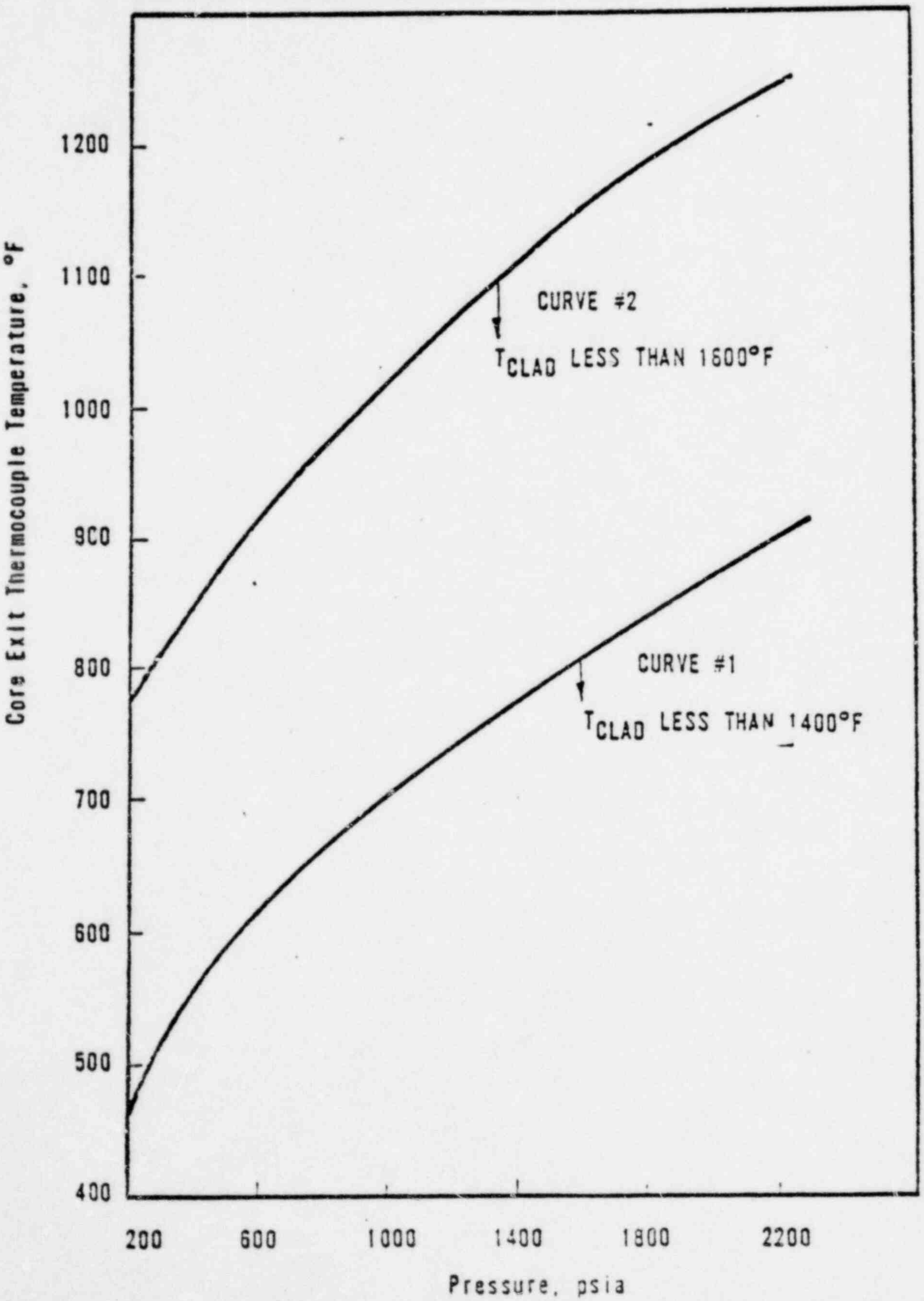
3.2 Operator Actions Once ICC is Indicated

Once inadequate core cooling is indicated the operator is instructed to take the following actions:

1. Start one RCP per loop
2. Depressurize operative OTSG(s) to 400 psig as rapidly as possible
3. Open the PORV to maintain RCS pressure within 50 psi of OTSG pressure
4. Continue cooldown by maintaining 100°F/hr decrease in secondary saturation temperature to achieve 150 psig RCS pressure

FIGURE 3.1-1

CORE EXIT THERMOCOUPLE TEMPERATURE FOR INADEQUATE CORE COOLING



These actions are taken to reduce RC pressure thus increasing HPI flow and RCS inventory addition rate. If thermocouple temperature continues to rise above a higher predetermined temperature which indicates a significant increase in fuel clad temperature (see Figure 3.1-1, Curve 2) the operator should:

1. Start all RCPs
2. Depressurize OTSG(s) to atmospheric pressure
3. Open the PORV to depressurize the RCS and allow LPI to restore core cooling

4.0 DISCUSSION OF METHODS TO DETECT INADEQUATE CORE COOLING

The following methods of indicating core cooling were examined in this evaluation:

1. Existing core thermocouples
2. Additional axial core thermocouples
3. Ultrasonic RV level indication
4. Neutron or gamma beam RV level indication
5. Differential pressure (dp) transmitters for RV level indication

The capabilities and evaluations associated with each type of indication are discussed below. Table 4.0-1 provides a summary of the methods and their capabilities.

4.1 Core Outlet Thermocouples

The existing core thermocouple instruments indicate inadequate core cooling when interpreted using the operator guidelines of References 1, 2 and 3. The location of these thermocouples provides indication of sharply increased temperatures at the top of the core when the top of the core reaches conditions of inadequate cooling. The locations of the thermocouples in the core and fuel assembly are shown on figures 4.1-1 and 4.1-2.

Figure 4.1-1 Layout of Core Thermocouples

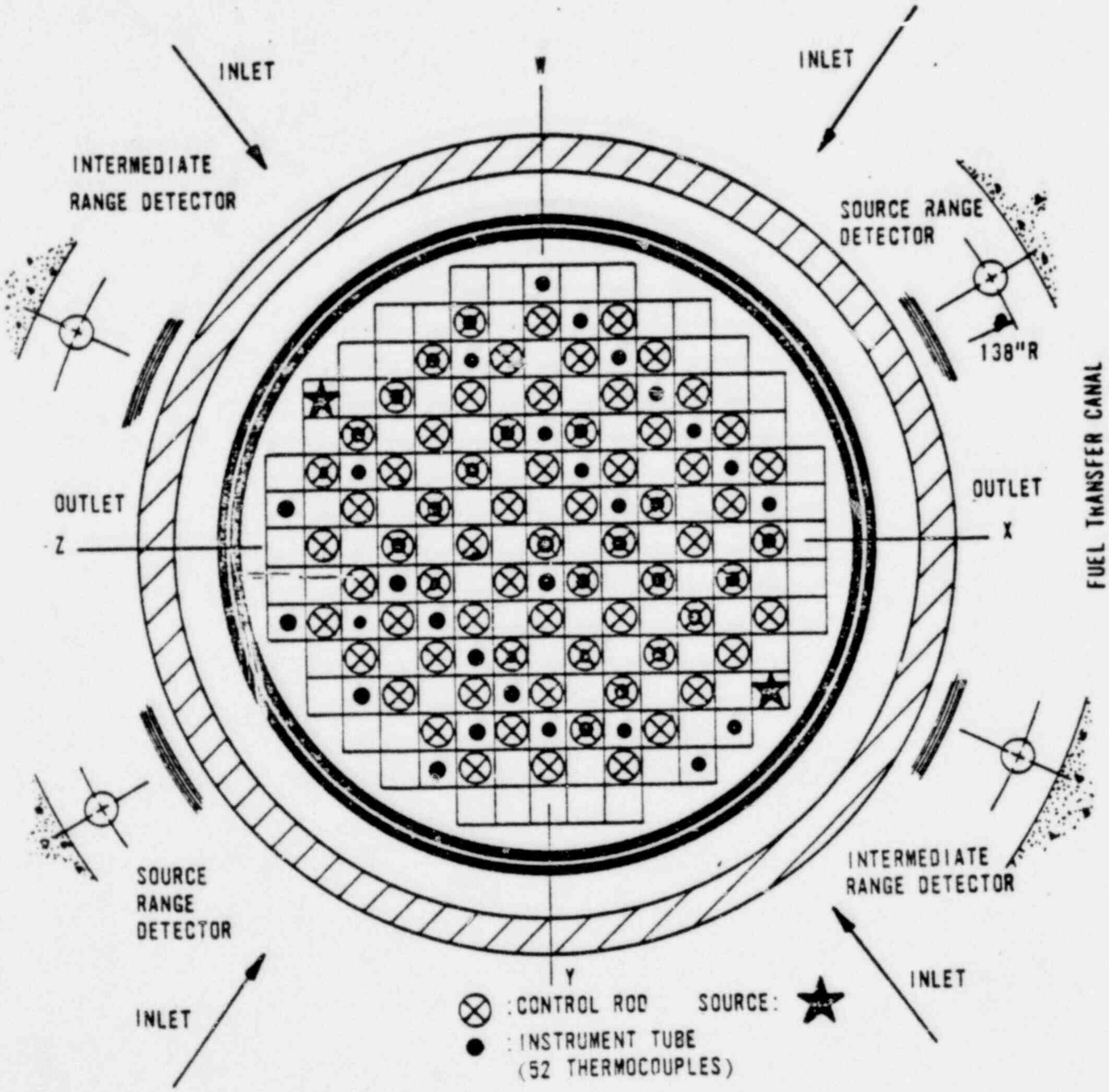
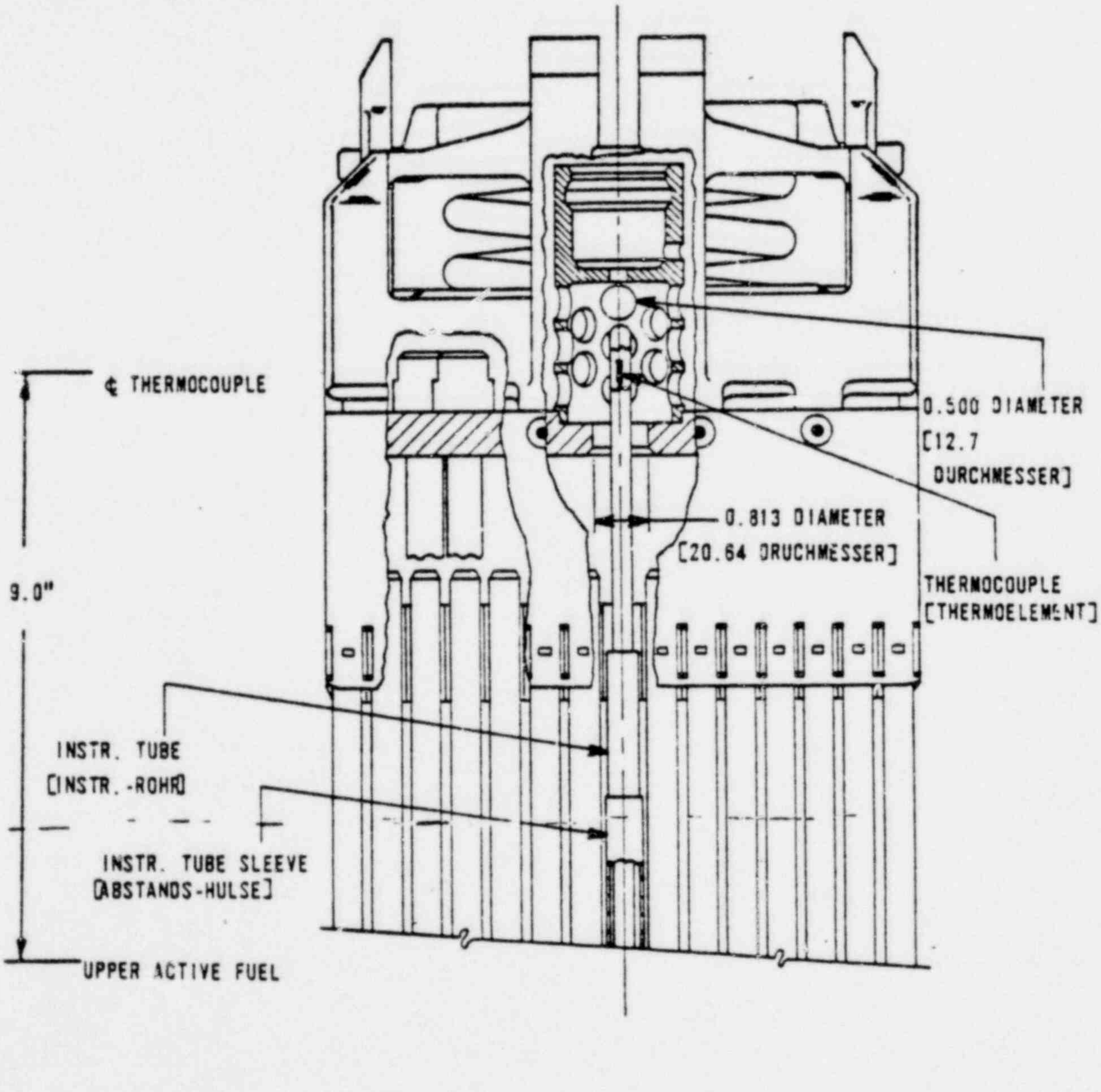


Figure 4.1-2 Location of Thermocouple



4.2 Axial Incore Thermocouples

Additional thermocouples installed axially in the incore instrument guide tube will provide an indication of the extent of inadequate core cooling; but, an indication that the middle of the core is inadequately cooled will not elicit any further operator action over and above the actions taken when the top of the core indicates inadequate core cooling. There would be no change in operator guidance even if this thermocouple information were available.

4.3 Ultrasonic Techniques

Several methods of ultrasonic techniques were considered. These included using existing internal structures as wave guides, installing an externally excited ultrasonic vibrating rod and installing a head mounted transducer. In simple applications, all of these methods have been proven. However, in the reactor vessel the core provides a heat source which changes the density of the fluid. The fluid changes state from a single phase liquid to a two phase fluid, and finally to a single phase vapor. Ultrasonic level measurement techniques are frequently used where there is a sharp density change at the fluid interface. The level created in a reactor vessel as a result of a LOCA will be a frothy, two-phase mixture height rather than a fixed phase interface. The variable density change will not provide an easy-to-interpret indication, and could provide an ambiguous output signal.

The ambiguous signal could lead the operator to believe that the core was inadequately cooled when in fact sufficient heat transfer was causing the frothy condition and adequate cooling was in progress. As a consequence of the incorrect belief, the operator would take the incorrect actions of depressurizing the RCS.

4.4 Neutron and Gamma Beams

Neutron and gamma beams have been used successfully to determine the level of fluid in a vessel. The application of this method to a RV level would be the use of the core as a source and use the existing out of core detectors to monitor the water level through changes in count rate. Normally, the detector count rate decreases at rates characteristic of the various mechanisms of neutron production that exist following a reactor trip.

One concept of water level measurement uses the installed source range detectors which respond to a decrease in water density. As water level decreases, the detector output increases. However, if the water level decreases to below the top of the core, the detector output decreases. The intensity of the neutron beam and thus detector output would be very dependent on previous power history, thus requiring calibration prior to each use of the instrument. This is not reasonable during accident conditions. For this reason, further investigation of this method was terminated. A more detailed discussion of the application of this nuclear radiation method is included in Reference 6.

Another concept of RV water level measurement system has been tested at three reactor sites. The system employs BF_3 neutron detectors above and below the reactor vessel. Data was collected and extrapolated to determine neutron count rate between one and six days after shutdown as a function of water level above the core. The data showed a relatively slow increase in count rate as the water level decreased from a full condition, with a marked increase in count rate when the water level reached five feet above the top of the core. At this level water was still above the hot leg nozzles. This indication system is capable of providing a discrete data point indicating that reactor vessel level is five feet above the core. Evaluation of the remaining data requires interpretation by the operator to determine the correct reactor vessel water level. The capability of this instrument must be evaluated immediately after a shutdown to show its effectiveness in a high background level which would be the case following a LOCA.

4.5 Differential Pressure Transmitters

The use of differential pressure transmitters to measure reactor vessel level was considered. Three level measurement ranges, one across the reactor vessel, a second across the hot leg, and one combining these ranges, were evaluated.

The first, a reactor vessel differential pressure (dp) measurement, would require new penetrations in an incore nozzle at the bottom of the reactor vessel and at the top in a control rod drive mechanism (CRDM) closure. An instrument could be installed to provide a differential pressure between the bottom of the core and the top of the reactor vessel, but the differential pressure (dp) would be affected by not only the water level head, but also by shock loss, friction loss, and flow acceleration loss. During forced flow conditions, the shock loss, friction loss, and flow acceleration loss terms dominate the signal.

Additionally, the magnitude of these terms varies depending on the density, and thus flowrate, of the pumped fluid. Due to the changing magnitude of these terms, it is not possible to compensate the dp signal to achieve a water level from head only. During stagnant boiloff, the decay heat in the core will cause the level of coolant in the core region to swell to a level greater than that in the downcomer region of the reactor vessel. A dp level measurement would measure the collapsed level in the downcomer region. A swelled level of 12 feet might be indicated by a collapsed level of between 7.4 and 8.625 feet, depending on system pressure. The unpredictable peak power distribution and decay heat level preclude compensating the dp signal for this error. Although the parameter of interest in this case is the mixture height, the dp cell would measure a collapsed level which means that under some conditions this signal would be ambiguous, and could lead to premature depressurization of the plant by the operator's misinterpretation of the indication.

The second method, a hot leg differential pressure measurement would require new penetrations at the bottom of the hot leg and the vent line at the top of the hot leg. This instrument would provide a dp signal and not an actual water level. In this instance, measuring any water level would be a valid indication that the core was covered. During flow conditions, the output signal would be affected by the same effects as the reactor vessel dp signal discussed above. However, the hot leg dp signal could be temperature compensated. The fact that the hot leg contains coolant would indicate that the core was covered and thus no new operator actions for inadequate core cooling would be required. However, if the operator takes actions for inadequate core cooling based on only a level in the hot leg then he would be taking incorrect actions for some casualties which could also be indicated by a level in the hot leg; i.e., overcooling, partial steam voiding in the hot leg caused by transients.

The third method, a differential pressure measurement from the bottom of the reactor vessel to the top of the hot leg, would require new penetrations in an incore nozzle at the bottom of the reactor vessel and at the vent line at the top of the hot leg. This range is a combination of the two previous instrument ranges. It provides an advantage over the hot leg level measurement in that it can measure the entire RV level span, but it would still exhibit the same ambiguity as the reactor vessel dp described earlier. In addition, due to the greatly expanded range, the inaccuracy of the instrument would be greater, perhaps as large as ± 4.0 feet. This measurement would be inaccurate in the hot leg range and would be ambiguous in the reactor vessel range as discussed above.

All three methods of dp level measurement require additional structural penetrations or modifications. Additionally, the operator would not be directed to take action until he confirmed the existence of inadequate core cooling with the core exit thermocouple, thus these additions would not change any operator guidance.

5.0 CONCLUSIONS

As has been discussed, no proposed method of indication of inadequate core cooling would meet all the established criteria. The introduction of ambiguous information provided by some proposed systems of inadequate core cooling indication would cause operator confusion. This confusion could lead to incorrect and unsafe actions in some situations; i.e., premature depressurization during LOCAs, or incorrect actions during overcooling events.

Reliance on existing core exit thermocouples and previously published operator guidelines for interpreting the available information is the best and most direct method of determining that the inadequate core cooling condition has ocurred. The existing instrumentation in the B&W designed nuclear steam supply system is able to detect inadequate core cooling. The incore thermocouples provide an unambiguous indication of the existence of inadequate core cooling, and will not erroneously indicate inadequate core cooling. The thermocouples provide the most discriminating capability of defining the existence of inadequate core cooling

The basis for this conclusion is further supported by the following:

- The recently installed T_{sat} meter provides a long term indication of the approach to inadequate core cooling since saturation conditions must be achieved prior to the onset of inadequate core cooling. Saturation conditions would be reached a significant time before inadequate core cooling, thus the operator would be alerted to the condition.
- The existing core thermocouples will indicate the immediate approach, the existence of and termination of the inadequate core cooling condition.
- The instruments will ensure direct, appropriate interpretation of plant conditions by the operator when used in conjunction with previously published operator guidelines.
- Each proposed reactor vessel level measurement system concept fails to provide any additional aid to the operator for detection of inadequate core cooling. Core cooling is directly indicated by temperature measurement, not level measurement. Secondly, each of the level measurement concepts fails to meet all of the established criteria as outlined in Table 4.0-1.
- The potentially ambiguous information provided by the proposed RV level indication instrument systems could lead to unsafe and incorrect actions if the operator acted on the level indication.
- No new or additional detectors are required to cover the full range of plant conditions. Adequate core cooling is determined by core heat removal capabilities. It is directly indicated by the reactor coolant system temperature/pressure relationship. The approach to inadequate core cooling is indicated in sufficient time by the T_{sat} meter to allow the operator to take mitigating action. If

his actions are unsuccessful and inadequate core heat removal conditions exists, sufficient indication for the operator is available by means of the core thermocouples. As superheated conditions are reached the thermocouple temperature will increase. If additional operator actions of partial depressurization of the RCS are successful and he can regain control of the core heat removal, the thermocouple indication will provide the necessary feedback to tell him that his actions were effective.

It is B&W's technical judgement that the existing plant sensors provide a reliable and accurate method of detecting the approach to and existence of inadequate core cooling for all modes of plant operation.

TABLE 4.0-1

LEVEL MEASUREMENT METHOD WHICH MEET EXISTING CRITERIA

CRITERIA Ranked in Order of B&W Assigned Priority	LEVEL MEASUREMENT METHODS							
	Subcooling Monitor	Existing Incore T/C	Additional Incore T/C	Ultra-Sonics	Neutron or Gamma Beam*	SPND	Hot Leg Level	RV ΔP
1. Must be direct indication of ICC		X	X					
2. Unambiguous - not erroneously indicate ICC		X	X					
3. Cover full range from normal operation to core uncovery				X	X			X
4. Provide advanced warning of ICC	X				X		X	X
5. Unambiguous - indicate ICC during pumped high void fraction and stagnant boiloff		X	X					
6. No major structural changes to plant	X	X			X	X		
7. Unambiguous - meeets safety grade criteria**								

*Develop work is still required to prove capability of this method immediately after shutdown.

**State-of-the-art hardware to meet safety grade criteria is not available to comply with the schedule installation date.

APPENDIX A

NUREG-0578 POSITION ON INSTRUMENTATION FOR DETECTION OF INADEQUATE CORE COOLING AND CLARIFICATION FROM H. R. DENTON'S LETTER OF OCTOBER 30, 1979

POSITION

Licensees shall provide a description of any additional instrumentation or controls (primary or backup) proposed for the plant to supplement those devices cited in the preceding section giving an unambiguous, easy-to-interpret indication of inadequate core cooling. A description of the functional design requirements for the system shall also be included. A description of the procedures to be used with the proposed equipment, the analysis used in developing these procedures, and a schedule for installing the equipment shall be provided.

CLARIFICATION

1. Design of new instrumentation should provide an unambiguous indication of inadequate core cooling. This may require new measurements to or a synthesis of existing measurements which meet safety-grade criteria.
2. The evaluation is to include reactor water level indication.
3. A commitment to provide the necessary analysis and to study advantages of various instruments to monitor water level and core coolng is required in the response to the September 13, 1979 letter.
4. The indication of inadequate core cooling must be unambiguous, in that, it should have the following properties:
   a) it must indicate the existence of inadequate core cooling caused by various phenomena (i.e., high void fraction pumped flow as well as stagnant boil off).
   b) It must not erroneously indicate inadequate core cooling because of the presence of an unrelated phenomenon.

5. The indication must give advanced warning of the approach of inadequate core cooling.
6. The indication must cover the full range from normal operation to complete core uncovering. For example, if water level is chosen as the unambiguous indication, then the range of the instrument (or instruments) must cover the full range from normal water level to the bottom of the core.

REFERENCES

1. Small Break Operating Guidelines, B&W Document 69-1106001-00, November 1979

2. Small Break Operating Guidelines, B&W Document 69-1106003-00, November 1979

3. Small Break Operating Guidelines, B&W Document 69-1106002-00, November 1979

4. Inadequate Core Cooling Decay Heat Removal System Mode of Operation, B&W Document 69-1106921-00, December 1979

5. Inadequate Core Cooling - DNB at Power, Site Instruction 3/4/9/187, 5/355, 7/364, 8/172, 11/191, 14/402 dated December 21, 1979

6. Analysis Summary in Support of Inadequate Core Cooling Guidelines, B&W Document 86-1105508-01, December 5, 1979