INTERIM REPORT

Accession No. ______________
LO-87-80-130

Contract Program or Project Title: LOFT PROGRAM

Subject of this Document: (Title) "Special LOFT Features for Improved Monitoring and Survival of LOCA Transients"

Type of Document: Technical R & D

Author(s): L. D. Goodrick, L. P. Leach

Date of Document: January 1980

Responsible NRC Individual and NRC Office or Division: G. D. McPherson

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Prepared for
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

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NRC Research and Technical
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LO-87-80- 30

Report No.

Date: January 7, 1980

RELEASED BY LOFT CDCS

USNRC-P-394

INTERNAL TECHNICAL REPORT

Title: SPECIAL LOFT FEATURES FOR IMPROVED MONITORING AND SURVIVAL OF LOCA TRANSIENTS

Organization: LOFT EXPERIMENTAL PROGRAMS DIVISION

Author: L. D. Goodrich, L. P. Leach, et al

NRC Research and Technical Assistance Report

Checked By: D. J. Hanson

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EG&G Idaho, Inc.

LOFT TECHNICAL REPORT
LOFT PROGRAM

FORM EG&G-229
(Rev 12-78)

TITLE SPECIAL LOFT FEATURES FOR IMPROVED MONITORING AND SURVIVAL OF LOCA TRANSIENTS	REPORT NO. LO-87-80-130
AUTHOR L. D. Goodrich, L. P. Leach, et. al.	GWA NO. 53AMP0104
PERFORMING ORGANIZATION LOFT Experimental Programs Division	DATE RELEASED BY LOFT CDCS January 17, 1980
LOFT APPROVAL R. E. Ford (PSE) D. J. Hanson (LEMB Mgr.) L. P. Leach (LEPD Mgr.)	

ABSTRACT

LOFT is designed to monitor and survive Loss-Of-Coolant-Accidents (LOCAs). This report presents the primary design difference from LPWRs that were required to accomplish this. These design differences may be of interest to the nuclear power generatior industry. This report should be revised semi-annually or as developments in the LOFT Program require.

DISPOSITION OF RECOMMENDATIONS

This report will be revised semi-annually or as developments in the LOFT Program require it.

NRC Research and Technical Assistance Report

LTR LO-87-80-130

SPECIAL LOFT FEATURES FOR IMPROVED MONITORING AND SURVIVAL OF LOCA TRANSIENTS

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SUMMARY

LOFT is designed to monitor and survive Loss-Of-Coolant-Accidents, (LOCAs). The design has many features that are not typical of a Large Pressurized Water Reactor (LPWR). This report briefly presents and discusses some of these features. Some of these features are more easily retrofitted on existing LPWRs than others. Some of the easily retrofitted changes were TV cameras in the containment, subcooled meter, expanded range instrumentation, and Joint Experiment Group (JEG). Some of the major retrofit changes were: 1) unpressurzied fuel rods, 2) reactor vessel liquid level, 3) primary coolant loop seal and high capacity charging/HPIS pumps. This report should be revised semi-annually or as developments in the LOFT Program require.

1.0 INTRODUCTION

The purpose of this report is to make available for NRC consideration information developed during the design and operation of LOFT which may be of value to improving the safety of operating reactors. This report was prepared at the request of NRC.

The objectives of the Loss-Of-Fluid-Test (LOFT) Experimental Program are:

(1) To provide data required to evaluate the adequacy and improve the analytical methods currently used to predict the Loss-Of-Coolant Accident (LOCA) and anomalous transients response of Large Pressurized Water Reactors (LPWRs). The performance of engineered safety features (ESF) with particular emphasis on emergency core cooling system (ECCS) and the quantitative margins of safety inherent in the performance of the ESF are of primary interest.

(2) To identify and investigate any unexpected event(s) or threshold(s) in the response of either the plant or the ESF and develop analytical techniques that adequately describe and account for such unexpected behavior.

Several series of experiments have been planned to meet the LOFT program objectives. The first series was a nonnuclear series in which a core hydraulic simulator was installed to simulate the pressure drop to LOFT 1.68-m (5.5-ft.) nuclear core. The last experiment in the series (L1-5) was conducted with a nuclear core installed, but not producing power. The subsequent several nuclear experiment series have been conducted at various power levels with several sizes and types of breaks.

To accomplish the above objectives, special features were designed into LOFT. These features were designed for the Loss-Of-Coolant-Experiment (LOCE) phases, i.e. subcooled and saturated blowdowns. In addition to the special designs, special changes have been made based on the LOCE experience. These special features were based on the fact that losses of coolant would occur in LOFT. The changes make the understanding, control, and plant capability more amenable to undergoing such events. This information may be of special interest to the nuclear power generation industry in order to improve the capability of commercial power plants to detect and recover from unexpected loss of coolant events.

2.0 SPECIAL LOFT FEATURES FOR IMPROVED LOCE RESISTANCE

During a large break LOCE, the LOFT system depressurizes from 15.5 MPa to saturation pressure in approximately 70 ms (subcooled blowdown) and then from 10 MPa down to approximately containment pressure in 70 seconds (saturated blowdown). Superheated steam may be present in parts of the system. Fuel rod temperature may be high (>1000K) and fuel failures may occur. The special features in LOFT are designed for these conditions. The following is a presentation and discussion of these features. A brief description is given of all the special features and the most important features are discussed in some detail.

The brief descriptions are presented in tabular form which include: (1) the LOFT feature, (2) the comparable LPWR design, (3) any comments, and (4) a priority/recommendation. The priority is given as high, moderate, or low. The high priority features are discussed in further detail in the applicable section.

2.1 Fuel

The 1.68-m (5.5-ft.) core used in LOFT is designed to have the same physical, chemical, and metallurgical properties as those in LPWRs. It is also designed to provide thermal-hydraulic relationships, mechanical response, and fission product release behavior during the LOCEs and ECC recovery which are representative of LPWRs during a LOCA. The present 1.68-m (5.5-ft.) core and the reload cores are rated at 50 mW(t) with 2000 effective full power hour (EFPH) design life. Figure 1 shows a cross-sectional layout of the LOFT core.

Two basic fuel assembly configurations are used in LOFT. Five assemblies have a square cross-section with fuel pins and (guide) tubes in locations typical of those in LPWR fuel assembly structures. Four assemblies have a triangular cross-section using a portion of the square cross-section structure.

The square fuel bundles contain 225 pin locations (15 pins along each side). Twenty-one of these locations are occupied by guide tubes, except in the center bundle where the center guide tube is not installed to allow for instrumentation. The triangular assemblies contain 78 pin locations (12 pins along each side). Eight of these locations are occupied by guide tubes.

Table I lists the features of the LOFT core which were designed to improve LOCE resistance. The possible value of each feature to an LPWR is also noted. Of the features listed, the most important ones are unpressurized fuel rods and fuel cladding thermocouples (discussed under Instrumentation).

2.1.1 Unpressurized Fuel Rods

The large pressurized water reactor (LPWR) fuel rod prepressurization feature which may enhance fuel rod durability during normal power ramping operations creates the potential for severe cladding ballooning and failure

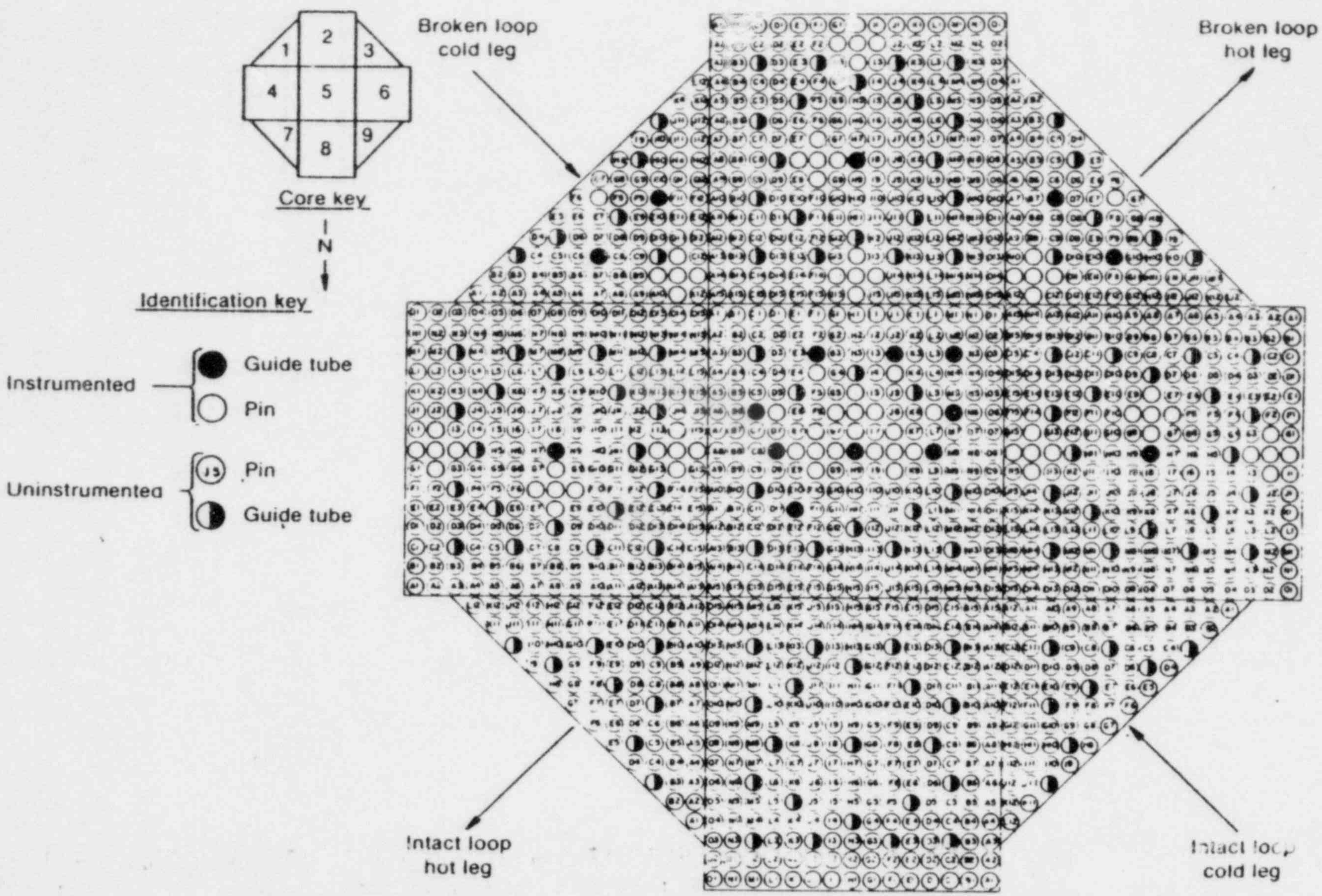

Fig. 1 LOFT core map showing position designations.

TABLE I

SPECIAL LOFT FUEL FEATURES FOR IMPROVED LOCE RESISTANCE

LOFT FEATURE	TYPICAL LPWR DESIGN	COMMENT	PRIORITY/ RECOMMENDATION
1. Un-pressurized Fuel Rods	Pressurized Fuel Rods	Power operation at 53 kW/m & 3 LOCES have not damaged the LOFT fuel rods - nondensifying fuel pellets and careful power ramping are potentially effective preventatives to premature PCI fuel failures - During the slow heat-up of a small break LOCE, the risk of extensive clad ballooning, (hence channel blockage), is high with the pressurized fuel rods in LPWRs.	High/ Potential requirements depending on analysis of performance of current generation un-pressurized and pressurized fuel and TMI autopsy.
2. Stainless Steel Guide Tubes	Zircaloy guide tubes	Cold-worked 304 stainless steel used instead of zircaloy for resistance to subcooled decompression loads and subsequent high guide tube temperatures during the LOCE core heat up. LOFT data indicates decompression loads and large break guide tube temperatures are less than expected.	Low/ Low parasite Zr will maintain "coolable" geometry in the large break LOCE
3. Close Span Spacer Grids	Spacer grids are 20 inches apart	The 16 inch axial spacing compares to the 20 + inch axial spacing of LPWRs and provides improved resistance to subcooled decompression loads and loss-of-material strength during the core heat up. Also, the test data indicates that the spacer grids help retain liquid in the core during the saturated decompression.	Low/ Increased PWR flux depression, fabrication costs and core flow resistance.
4. Heavy Construction Spacer Grids	Spacer grids are not as heavy as LOFT	Relatively thick-webbed, Inconel 718, welded intersection spacer grids improve resistance to LOCE decompression/heat up loads and seismic loads.	Low/ Increased parasitic capture of neutrons. LPWR experience with low-parasite design is satisfactory.
5. Solid Block Control Rod Spider Construction	Brazed arm-to-hub joints	Control rod spiders are machined from solid block (forging) material compared to LPWR designs using brazed arm-to-hub joints which have failed during power operation.	Low/ No problem seen in long term use of LPWR control rods.
6. Uniform Diameter Guide Tubes	Guide Tubes are necked down	LOFT guide tubes are not necked down for control rod deceleration because the snubber is in the CRDM. The uniform diameter guide tubes improve resistance to LOCE decompression/heat up loads. Analysis indicates the LPWR guide tubes will retain enough fluid long enough to decelerate the control rods if the scram is not delayed.	Low/ Changes would require modification of the basic CRDM design & increased column strength appears unnecessary.

during a 'small break' LOCA in which partial core uncovering could result. By comparison, use of unpressurized rods under the same LOCA conditions (core uncovery) would cause cladding collapse which resulted in little or no fuel cladding deformation failure.

Unpressurized fuel rods were selected for LOFT fuel rods in the hope repeated Loss-Of-Coolant-Experiments could be performed with the same core. One LOFT center bundle, however, is being fabricated with prepressurized fuel rods to evaluate prepressurization effects during Loss-Of-Coolant-Accidents. The standard design unpressurized LOFT fuel rods also feature densifying, high length-to-diameter, non-chamferred fuel pellets. Careful quality control during fuel rod fabrication and power ramping during operation have allowed the 1300 LOFT fuel rods to function without cladding failure for approximately 1000 MWD/MTU peak during which time the fuel was exposed to 53 kW/m peak linear heat generation rate (12 hours) and three Loss-Of-Coolant-Experiments with measured cladding surface temperatures as high as 920K.

Since prepressurization became popular, first as a preventative for fuel rod cladding flattening into pellet stack discontinuities (gaps) caused by densifying fuel pellets and then, for minimizing pellet-cladding-interaction, a number of other remedial features for the above problems have also been adopted. The other remedial features include:

a. Stable (non-densifying) fuel pellets. The increased number of large pores in the pellet enhances gaseous fission product retention by the pellet (small pores disappear during the densification process),
b. Chamferred fuel pellet ends
c. Shorter fuel pellets

d. Careful controlled power ramp rates during startups and power increase maneuvers.

e. Controlled fuel pellet temperature to minimize gaseous fission product release from the fuel pellets.

The Three Mile Island (TMI) event created conditions that could cause the prepressurized fuel rod cladding to (1) swell and constrict the coolant passages sufficiently so that forced or natural convection cooling was ineffective and (2) perforate releasing fission products. The fission product escape to the containment may have created radioactive contamination that causes plant recovery to be impractical. It is conceivable that unpressurized (or lower pressure) fuel rods in TMI would have precluded ballooning and allowed effective natural convective cooling to occur without cladding deformation failures and thus significantly reduced fission product release. The TMI fuel autopsy that could confirm the above conjecture is probably two to three years away.

A set of analytical studies is suggested to provide additional information for assessing the effects of internal fuel and prepressurization in light of current fuel technology and the fuel rod failure hypothesized for TMI. These include:

a. A best-estimate analytical prediction of fuel rod internal pressure for pressurized and unpressurized fuel rods from beginning to end-of life in a representative LPWR.

b. A best-estimate analytical prediction of fuel rod behavior during the TMI-event assuming prepressurized and unpressurized fuel rods and early, intermediate, and end-of-life fuel rod conditions.

c. A best-estimate analytical prediction of power ramp restrictions at 0, 1000, 5000, 10,000, 20,000, 30,000, 40,000, and 50,000 MWD/MTU fuel burnup assuming prepressurized and unpressurized fuel rods.

With the recognized potential for additional small break LOCA events, and desire to reduce the amount of fission product release in such events, a re-evaluation of the use of prepressurized fuel should be made.

2.2 Instrumentation

The instrumentation in LOFT is comprised of two different systems: the process and experimental. Process instrumentation is designed to NRC requirements and is used for plant control. The primary function of the test assembly experimental measurements system is to provide the measurements necessary for verification of codes and plant performance. Table II briefly lists the instrumentation that are special features of LOFT, potentially applicable to LPWRs. Of these features, the upper plenum fluid temperature measurement, pump parameter, vessel liquid level, subcooled meter, and nuclear hardened gamma densitometer and expanded range instruments are believed to be the most important.

2.2.1 Core Exit Thermocouples

Core exit coolant temperatures are measured in LOFT using thermocouples. The coolant thermocouples on the tie plate closely measure the radial power factor (in ΔT) of the core coolant channel over which they are located at both high and low flow conditions. Coolant thermocouples about five inches above the fuel bundle top measure the fuel bundle radial power factor in core ΔT. The tie plate thermocouples measure superheated steam within about three seconds of the commencement of CHF in the core.

TABLE II

SPECIAL LOFT INSTRUMENTATION FOR IMPROVED LOCE RESISTANCE

LOFT FEATURE	TYPICAL LPWR DESIGN	COMMENT	PRIORITY/ RECOMMENDATION
1. Core Exit Coolant T/C's	No Core Exit Thermocouples at some plants, limited range at others.	Core exit coolant temperatures are measured in LOFT using thermocouples. The thermocouples are located on the tie plate above the fuel bundle.	High/Core exit T/C's will indicate (1) Film boiling or post CHF condition in the core, (2) rod-to-rod power or flow maldistributions, and (3) fuel bundle to fuel bundle power or flow maldistributions. Thermocouples would be part of upper support structure.
2. Instrument Penetration Cartridge	Not Determined	The LOFT instrument penetration can accommodate about 175 1/16 in. in diameter instrument cables through a 5 inch diameter hole and provide double sealed (braze) instrument cable penetration, submersible double K-sealed features. The LOFT design has been reproducible and durable surviving several core heat-up/cooldown cycles and three LOCEs.	High/Potential use with instrumented upper core support structure and one dedicated reactor vessel head nozzle. It is available for LPWR use; but need is not clear as adequate penetration methods appear to be in use.
3. Expanded Range Instrumentation	Most instruments read only in a narrow range of plant operation	Most plant protective pressure and temperature measurements have lower limits at 1500 psi and 500°F respectively.	High
4. Pump Parameters	Pump power, Voltage and current are measured.	LOFT LOCE experience indicates pump power may be correlated to loop density. Pump speed is also measured on LOFT which provides an independent check of pump operation.	High/Provides an independent check of pump operation and may be used to determine loop fluid density.

TABLE II (Cont.)

SPECIAL LOFT INSTRUMENTATION FOR IMPROVED LOCE RESISTANCE

LOFT FEATURE	TYPICAL LPWR DESIGN	COMMENTS	PRIORITY/ RECOMMENDATION
5. Liquid Level a) Vessel	No liquid level measurement	LOFT has conductivity liquid level detectors in the core, downcomer, and lower and upper plenums.	High/Would allow the operator to know liquid level in vessel. The hot leg ΔP used during LOFT test L3-1 does indicate vessel liquid level and could easily be retrofitted on existing plants.
b) Pressurizer	Differential Pressure	LOFT has the standard Δp measurement for liquid level in the pressurizer. This measurement is only correct if the reference leg remains filled and if the level is compensated for temperature. An alternative filling system for the reference leg should be used.	Moderate/Allows accurate determination of liquid level in pressurizer.
6. Subcooled Meter	Some new installations	A subcooled meter will be installed for scheduled small break tests. It will basically display whether the reactor vessel upper plenum is in a subcooled or in a superheat condition.	High/Useful to determine condition of fluid in RV upper plenum.
7. Nuclear Hardened Gamma Densitometer	None	Nuclear hardened densitometers are used to determine the density of the hot and cold legs.	High/Would allow density in loops to be determined.
8. Natural Circulation	None	A transit time flowmeter will be installed for scheduled small break tests. LPWR operating procedures call for "determination if natural circulation exists". It is not clear that present methods of doing so are adequate.	Moderate/Useful, if it proves out, for assuring natural circulation.
9. Full Range Steam Generator Level Instruments (Tube sheet to top of Generator)	Level is limited to operating range	In case of main stream line/turbine bypass valve, etc. leak, following 100% scram, some generators (CE) lose level indication. This leaves the operators ignorant of the status of their most important heat sink - the only means of rejecting decay heat, in fact. Lack of information also leads to improper decision.	Moderate/Some generators lack full level range instrumentation.

TABLE II (Cont.)

SPECIAL LOFT INSTRUMENTATION FOR IMPROVED LOCE RESISTANCE

LOFT FEATURE	TYPICAL LPWR DESIGN	COMMENT	PRIORITY/ RECOMMENDATION
10. Fuel Clad TC	Not in Common Use	Allows measurement of cladding temperature, hence allowing evaluation of radial and axial temperature profiles.	Moderate/Would allow cladding temperature to be measured. Long life qualification and instrument lead out problems must be weighed against information gain in operating reactor relative to core exit T/C's.
11. Flow Measurements	Hot to Cold Leg Δp and Elbow Taps	Mass flow rate is measured independently using venturis, turbines, drag discs, and densitometers. These individual flow measuring devices will give an accurate indication of the mass flow rate regardless of the condition of the core.	Moderate/LPWR's typically use cold to hot leg differential pressure or elbow taps as an indication of flow. These methods are affected by changes in flow resistance and have a range limitation. These methods are also inaccurate. The measurement techniques used in LOFT are not subject to changes in flow resistance Present LOFT instruments have lifetime limitations.
12 Data Integrity Check	Procedures similar to LOFT are not in common use.	Evaluates value of preselected parameters and compares to predicted values. Prints out parameters outside bound of predicted limits.	Moderate/Problems in de-calibration not clear.
13 Strain Gage Pressure Transducer	Force Balance Transducer	Strain gage transducers have a faster response than the force balance transducer currently in use. They also have an advantage that they can be remotely calibrated using shunt calibration.	Moderate/Would allow easy remote calibration of transducers and would quickly identify degradation/failure of transducers. Commercially available, but LOFT has had leakage problems.

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TABLE II (Cont.)

SPECIAL LOFT INSTRUMENTATION FOR IMPROVED LOCE RESISTANCE

LOFT FEATURE	TYPICAL LPWR DESIGN	COMMENT	PRIORITY/ RECOMMENDATION
14 Nuclear Instrument to determine reactor fluid density	Ion Chamber and SPND's	LOFT large break data shows external core ion chamber detectors are useful to determine downcomer voiding and in-core SPNDs to determine local core voiding. Similar information was available at TMI and misinterpreted as a power increase.	Moderate/Quantitative unambiguous evaluation needs to be determined.

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2.2.2 Instrument Penetration Cartridge

The system provided to allow passage of instrumentation cables through the reactor pressure vessel boundary is unique to the LOFT reactor. The system provides passage for several hundred instrumentation cables into the vessel. The pressure boundary consists of one or more brazed penetration buttons on each fuel assembly. The number of buttons and the number of swaged cables brazed into each button varies with the instrumentation demand of each fuel module. The buttons provided for the thermocouple circuits are brazed with material specially prepared for the titanium sheath to stainless steel button braze requirements. The fuel module assembly was designed so the complete individual fuel modules could be assembled in the fabrication facility and plugged into the reactor vessel as part of the modular core assembly.

The reactor vessel brazed penetrations have operated for several hundred hours at test conditions without problems.

2.2.3 Expanded Range Instrumentation

Normal instrumentation design requirements for nuclear power systems provide instrumentation to monitor key system parameters through startup and normal operational ranges. Due to the types of experiments LOFT has been designed to perform, expanded range capability has been provided for selected key parameters. From experience gained in tests to date, consideration is being given to extending this capability to additional instrumentation channels.

Most expanded range capability in LOFT is in the experimental measurements systems. The operational instrumentation has generally been designed to cover the normal operating range. Should a LOCE happen without expanded range capability, operators and analysts are in the dark as to maximum levels attained, possible extent of damage, or proper corrective action to be taken.

2.2.4 Pump Parameters

Pump performance is monitored on LOFT using standard voltage, current and power measurements and an eddy current pump speed measurement. The pump speed measurement allows a pump performance check to be made that is independent of voltage and current. An interesting use of pump power is in evaluating the primary coolant system fluid density. The pump power should be a direct function of fluid density. This technique is being evaluated at LOFT using large and small break test data.
To date, this evaluation has indicated some correlation with density. The correlation is empirically derived from a given test, therefore, the exact method of applying this technique to an LPWR has not been determined. A report will be prepared to document the results of this evaluation.

2.2.5 Vessel Liquid Level

The need for a vessel liquid level measurement was clearly illustrated at TMI. LOFT uses discrete conductivity probes to evaluate the liquid level in the core, upper and lower plenums, and the downcomer. These measurements have been extremely valuable in evaluating LOFT tests. The LOFT conductivity liquid level transducer probably is not directly applicable to LPWRs due to reliability and data interpretation problems. The original LOFT liquid level transducer design was for measuring exactly that, liquid level. Experience since then indicates that a liquid level transducer would be more valuable if it could also measure void fraction. Future designs for liquid level measurements should seriously consider this.

A separate report (LTR-LO-87-79-128) was written that evaluated the ability of instrumentation, other than the conductivity liquid level transducers, to measure liquid level in the reactor vessel. Transducers evaluated were: cladding and fluid thermocouples, self powered neutron detectors, differential pressure transducers, and power and intermediate range ion chambers. Data from two large and one small break test were used for the evaluation. The results indicated that qualitative liquid level information could be obtained from all the above measurements. However, there are limitations such as; response time, reliability, and ease of obtaining and presenting quantitative information on a real time basis. Also, voiding and refilling of the reactor vessel occurred in 50 seconds for the large break tests analyzed, therefore, it is not clear that the conclusions drawn are applicable beyond that time.

Of the transducers currently installed in LOFT, excluding the liquid level transducer, the SPND and nuclear channels show the most promise for the time frame investigated. Also the reactor head to hot leg differential pressure measurement gave good results during the first nuclear small break test. A heated thermocouple, used in PBF, was also considered. This technique is the most adaptable to LPWRs, both from a retrofit and new construction viewpoint. If taps are available at the bottom of the reactor vessel a differential pressure measurement could easily be used for reactor vessel liquid level information.

2.2.6 Subcooled Meter

Approach to saturation conditions is a simple and accurate technique of identifying possible voiding. To accomplish this, the absolute pressure is measured in the upper plenum and then the corresponding saturation temperature is obtained from standard saturation tables. The temperature in the upper plenum is also measured and the difference between this temperature and the saturation temperature indicates the degree of subcooling. This difference can then be displayed and an automatic alarm point established. This will aid operators who are not as familiar with saturation tables as we who work with them on a daily basis. The subcooled meter worked well for L3-1, but it should be noted that there are uncertainty limits and it is not a measure of reactor vessel liquid level when saturation conditions are indicated. This technique is viable for a real time display and is recommended for retrofit and new construction.

2.2.7 Nuclear Hardened Gamma Densitometer

During a LOCA, the density in the loops becomes vital to allow determination of the mass flow rate. Gamma densitometry with a nuclear background has been successfully used on LOFT. Densitometers also allow an evaluation of the spatial distribution of the fluid within the pipes to be made (flow regime).

A densitometer on an LPWR could be installed, but not operational during normal operation. It would be used only if an accident occurred.

2.3 Primary Coolant System

The LOFT primary coolant system consists of:

(1) The intact (operating) loop containing:

- (a) steam generator
- (b) primary coolant pumps
- (c) pressurizer
- (d) flow measuring element (venturi meter)
- (e) interconnecting piping
- (f) reactor vessel

The primary coolant piping consists of that piping which connects components in the intact loop and represents the unbroken loop(s) in a LPWR. Pipe lengths and routings were selected, so that fluid volume would be typical of LPWRs while thermal stresses were not excessive. The reactor vessel is a vertical cylinder with a semi-elliptical bottom head and a flanged and bolted two piece top head. It is a stainless steel clad, low alloy steel vessel which conforms to the ASME Boiler and Pressure Vessel Code, Section III. The two primary coolant inlet and outlet nozzles are diametrically opposed and provide the interface between the primary coolant piping and the reactor system. The reactor vessel also has two ECC injection nozzles (lower plenum and downcomer). An upper plenum ECC injection nozzle is located on the reactor vessel top head. A simplified system schematic is shown in Figure 2. Table III lists the primary coolant system features that have been integrated into LOFT for improved LOCE resistance. Of the features listed, the most important are the primary coolant pump injection, the high capacity charging pump, and the primary coolant loop seal.

2.3.1 System Volume Distribution and Pump Loop Seal Design

In LOFT, the elevation of the primary pump loop seal (lowest primary pipe elevation) is above the core. About 18% of total system volume is below the elevation at the top of the core. This resulted from a series of separate design choices relating to core design and piping geometry rather than a specific design criteria. Designs vary; in many, however, the elevation of the primary pump loop seal is below the top of the core. The relative volume required to cover the core is generally somewhat larger than in LOFT; about 23%. Some plants (B & W) incorporate vent valves connecting the reactor upper plenum to the reactor inlet annulus.

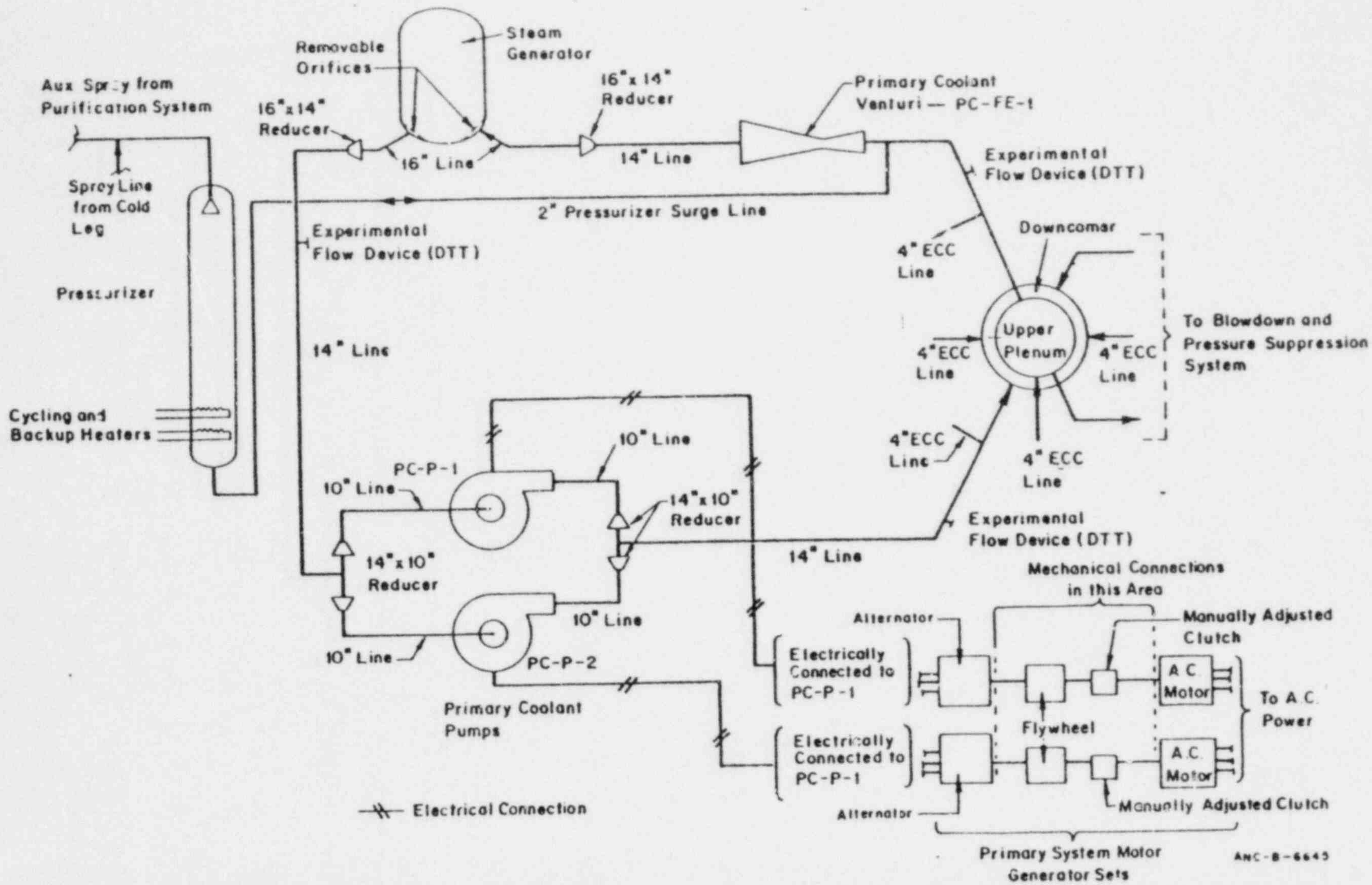


Fig. 2 Primary coolant system simplified schematic.

TABLE III

SPECIAL LOFT PRIMARY COOLANT SYSTEM FEATURES FOR IMPROVED LOCE RESISTANCE

LOFT FEATURE	TYPICAL LPWR DESIGN	COMMENT	PRIORITY/ RECOMMENDATION
1. Primary Coolant Pump Injection (PCPI)	None	The PCPI is utilized to provide pump bearing lubrication and auxiliary cooling when the pump volutes contain steam or two phase mixtures which could damage the pumps if the volute media entered the bearing cavity. The water is injected in the top of the pumps and is allowed to flow through the pumps into the volutes. LOCE testing and requalification testing have shown that the PCPI functions as designed and that pump damage is prevented under severe thermal/depressurization transients experienced by the pumps during a LOCE provided the PCPI is operating.	High/A PCPI system could be activated during an abnormal plant transient to provide pump lubrication. Such a system would very likely reduce the probability of pump damage and consequently eliminate the need for LPWR management to address the question of pump operability during an accident situation.
2. High Capacity Charging Pumps or Higher Head Higher Capacity HPIS (to Safety Setpoint)	Charging Pump capacity is approx. a factor of four less than LOFT.	LOFT has high capacity pumps, by a factor of approximately 4, which gives LOFT a great margin of safety. While some LPWRs have full pressure range capability on HPIS, it is at a reduced flow rate.	High/The loss of one train would not reduce HPIS to $\leq$ decay heat removal requirements.
3. Loop Seal PCP	Varies-In most plants loop seal exists, but is lower than LOFT's	In small break LOCE's, core generally uncovers to bottom of PCP loop seal. If this is above the core, uncovery does not occur.	High/Unnecessary increase in vulnerability during small break.
4. Automated Ultrasonic Testing (AUT)	None	The LOFT AUT System currently contains ultrasonic heads and skates to remotely ultrasonic inspect pipe welds for pipes ranging from 10" through 18". The computer controlled system contains software permitting data acquisition, storage, and processing as permanent, removable data. The information provides flaw identification and propagation throughout the plant lifetime and early identification of sources of potential pipe leakage or pipe ruptures. The system is currently being expanded to permit inspection of double curvature surfaces such as valve bodies and pipe elbows.	Moderate/An AUT system could provide very accurate, retrievable pipe weld inspection data. This data could be used to plan plant repairs during normal downtime before plant leaks or pipe ruptures occur. This could potentially prevent costly & undesirable (potentially embarrassing) plant downtime.

TABLE III (Cont.)

SPECIAL LOFT PRIMARY COOLANT SYSTEM FEATURES FOR IMPROVED LOCE RESISTANCE

LOFT FEATURE	TYPICAL LPWR DESIGN	COMMENT	PRIORITY/ RECOMMENDATION
5. Alternate ECC Injection	Cold Leg ECC Injection (Some downcomer, hot leg, & upper head)	LOFT has the capability of injecting ECC in the cold and hot legs and upper and lower plenums. This may be of value if one ECC injection path was blocked. Selection of the ECC injection point is accomplished by remote actuation of valves except for the upper plenum injection in LOFT requires a change in piping configuration.	Low/Semiscale tests have indicated no appreciable differences exist due to ECC injection point.
6. Remote venting or reactor vessel head	None	This modification recently incorporated to permit remot refilling of the reactor vessel after recovery time from the blowdown portion of the LOCE.	Moderate/Could be used for remote venting and/or venting of any accumulated gases, e.g. hydrogen.

The important effect is that all of the recent small break analyses performed for LOFT, over a wide range of break sizes and calculations, do not predict core uncovery or heat up. Similar analyses performed for non vent valve LPWRs predict core uncover and heat up, in some instances in excess of 10CFR 50.46 requirement. It appears as though the relative elevation of the loop seal to the core is the main effect.

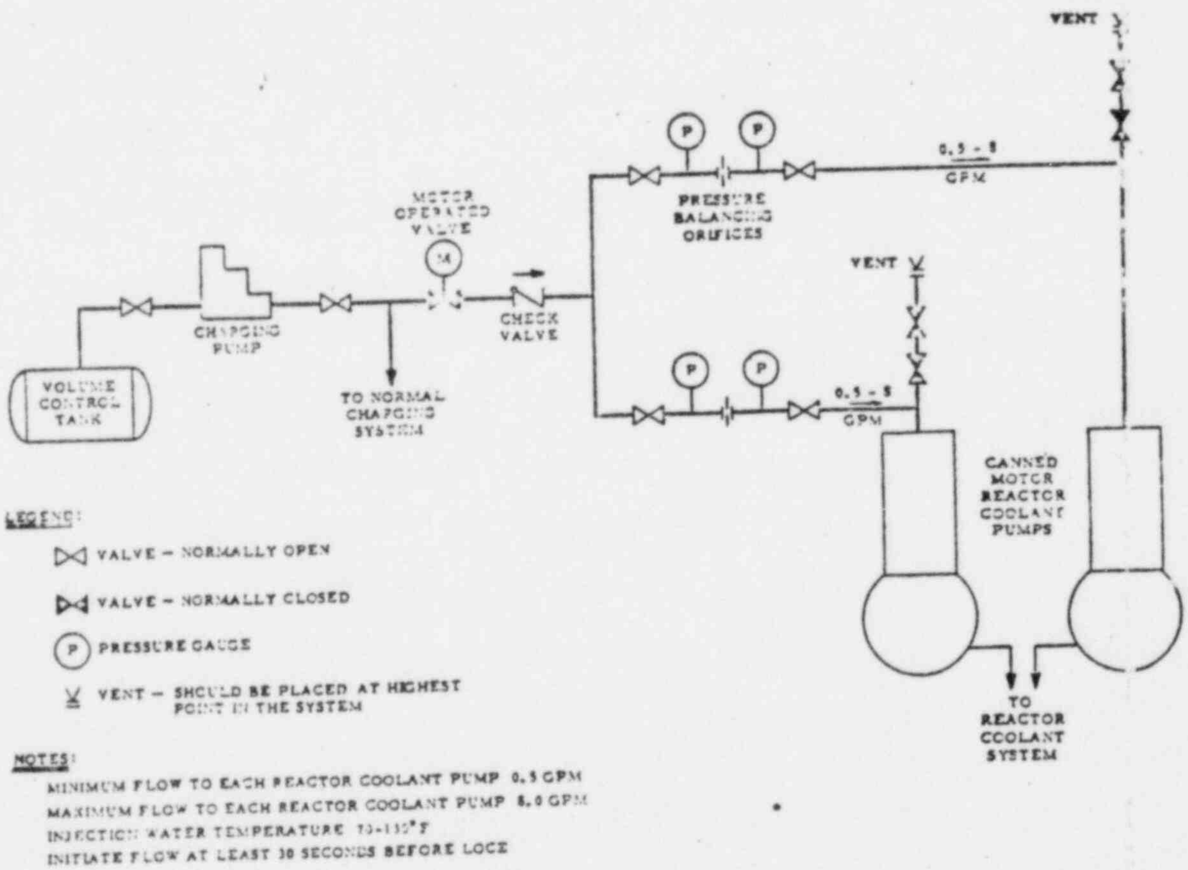
It appears that new LPWRs could significantly reduce risk of core damage for small breaks by lowering the core relative to the loop seal (or raising the loop seal relative to the core). For existing plants, the same effect could be accomplished by installing a cross tie between the hot leg and the cold leg, allowing flow from hot leg to cold leg only (check valve). This would require a relatively small line (4" to 12"). Vent valve plants would not require this modification. It need not be installed in each loop.

In order to determine the efficacy of this modification, safety analysis of plants with this design modification should be performed. This analysis must include potential risk increases introduced by the modification, e.g. increases core bypass, failure of the check valve, etc.

2.3.2 Reactor Coolant Pump Injection Water System

The reactor coolant pump water-injection system provides an external, separate water supply to the LOFT Primary Coolant Pumps during Loss-Of-Coolant-Accident experiments. Primary coolant pumps are typically designed to use the primary coolant as the source of water for lubricating bearings. During a LOCA, this source of water is removed, thereby endangering the operability of the pump. Water injection insures the operability of the pump.

The basic system shown in Figure 3 ties into the normal pump vent. During the LOFT experiments, the water injection system is initiated prior to the actual blowdown to preclude possible pump damage. However, the system



REACTOR COOLANT PUMP INJECTION WATER SYSTEM

Figure 3

would function adequately and provide protection to the pumps if the water injection commenced upon receipt of a low primary pressure signal. The simplicity and inexpensive components should allow retrofit to any existing commercial LPWR and use existing instrumentation for initiation. Normal HPIS pumps may be used.

To date, nine LOCE's have been completed on LOFT at normal operating temperatures and pressure (similar to the LPWR parameters) without noted pump degradation. It should also be noted that the pumps are tested after each LOCA experiment. It is not clear whether some or all LPWR's have this feature. Therefore, it is recommended that all LPWR's evaluate the capability of primary coolant pump operation without the availability of the primary coolant.

2.3.3 High Capacity/High Head HPIS and Charging Pumps

LOFT HPIS/Charging pumps are high head and high capacity positive displacement pumps as opposed to high head centrifugal pumps that are used on commercial reactors. This allows LOFT more flexibility in controlling pressure and inventory losses during a LOCA or operational transients.

2.4 Operations

Operations of the LOFT plant are typical of most reactor operations under normal operating conditions. Plant control is defined by a Plant Operation Manual. LOFT operation differs from an LPWR due to special procedures and training that is required for performance of a LOCE. Table IV is a summary of the operation functions that are different for LOFT. The Visitor Display Panel TV monitor in the containment vessel (C.V.), alternate actions, Joint Experiment Group, plant log and data monitor, and experiment safety analysis are all considered to be important features.

2.4.1 LOFT Visitor's Display Panel

The function of the Visitor's Display Panel is to sample selected reactor plant parameters periodically (usually one second intervals) and update the display to inform visitors of plant status preceding, during, and following a Loss-Of-Coolant-Experiment (LOCE).

TABLE IV

SPECIAL LOFT OPERATIONAL FEATURES FOR IMPROVED LOCE OPERATION

LOFT FEATURE	TYPICAL LPWR DESIGN	COMMENT	PRIORITY/ RECOMMENDATION
1. TV Cameras in CV, Monitors in MCR	None	These are used for surveillance. When fire alarms have occurred, these TVs have been used to assure that they were spurious alarms. The consequence if not used and with reactor at power is to SCRAM and make a reentry.	High/Could be used for visual surveillance within exclusion areas.
2. Visitors Display Room and Display Panel	None	Keeps traffic in main control room down during tests. LOFT has such a feature and if properly used could eliminate most visitors and nonoperation types from the control room.	High/Would allow those wishing to view events to do so without their added noise and confusion This is a big problem in LPWRs as well as LOFT.
3. Checking features built into the operating procedure	Unknown	Checks are provided in the Experimental Operating Procedure (EOP) to assure all systems are in readiness to support the test. The LOCE control system is setup and the system activated to assure it works. Valve positions are checked throughout the procedure. Steps are included to audit procedure for completeness during its execution.	Moderate/Not clear how to apply to LPWR.
4. Alternate Actions Built into EOP	Unknown	The EOP's main thrust is concerned with the expected actions, however, alternate actions are included to provide direction in the event expected action does not occur.	High/Procedure upgrade if applicable.
5. Joint Experiment Group (JEG)	None	The JEG composed of senior members of EG&G & DOE release approved procedure and reviews and approved changes to procedure.	High/Knowledgeable group in intimate contact with daily operation.
6. Additional Operator Information	None	Control room operators can call up on a terminal any of a number of preselected parameters being recorded on a disk. Calculated parameters are also included.	High/Special program in progress.

TABLE IV (Cont.)

SPECIAL LOFT OPERATIONAL FEATURES FOR IMPROVED LOCE OPERATION

LOFT FEATURE	TYPICAL LPWR DESIGN	COMMENT	PRIORITY/ RECOMMENDATION
7. Crew Training	Unknown	The operating crews are briefed on the LOCE operating procedure which stresses the evolutions to be conducted with emphasis on general test philosophy, prerequisite requirements, specific precautions, major milestones in the procedure and alternate actions to take in event test does not go as predicted. In addition, when a long time period has lapsed between tests, each crew goes through a "hands on" training by taking the reactor to a low power level (20%) and then going through casualty procedures. Finally a dry run of the test is conducted with the selected operating crew. All evolutions are either performed or simulated in an interpreted manner.	Moderate/Extensive training upgrades are in progress at LPWRs.
8. Experiment Safety Analysis	Single failure criteria	Includes multiple failures.	High

The panel is located in a visitor's room adjacent to the Main Control Room and allows visitors to witness the LOCE as it is being performed but does not require their presence in the Main Control Room, so interference with the operating crew is minimized. Plant parameters can be recorded on tape and displayed at a later date for further evaluation or replayed for the benefit of future visitors to demonstrate plant response during a LOCE.

During an accident situation, plant conditions could be recorded on tape allowing a replay to determine the series of events leading to the casualty condition. The visitor's room would also be a convenient location for an emergency management team to convene. Plant conditions could be observed minimizing interference with recovery efforts taking place in the Main Control Room while at the same time allowing close coordination and communication between Operations and Support organizations.

A display of this type could be designed for a power plant already in operation. Process instrumentation signals would have to be buffered and fed to a microprocessor to drive the indication on the panel.

A picture of the LOFT Display Panel and a listing of instruments being displayed is shown in Figure 4.

2.4.2 Television Monitors in the Containment

Television monitors take the place of an operator's eyes in assessing conditions inside the containment and aid him during normal and abnormal or emergency operation. They provide him with a more integrated, complete assessment of conditions and thereby allow him to make better decisions and control actions. During normal operation, properly placed cameras could be used to monitor areas which are inaccessible due to radiation, including the

LOFT INTEGRAL TEST SYSTEM

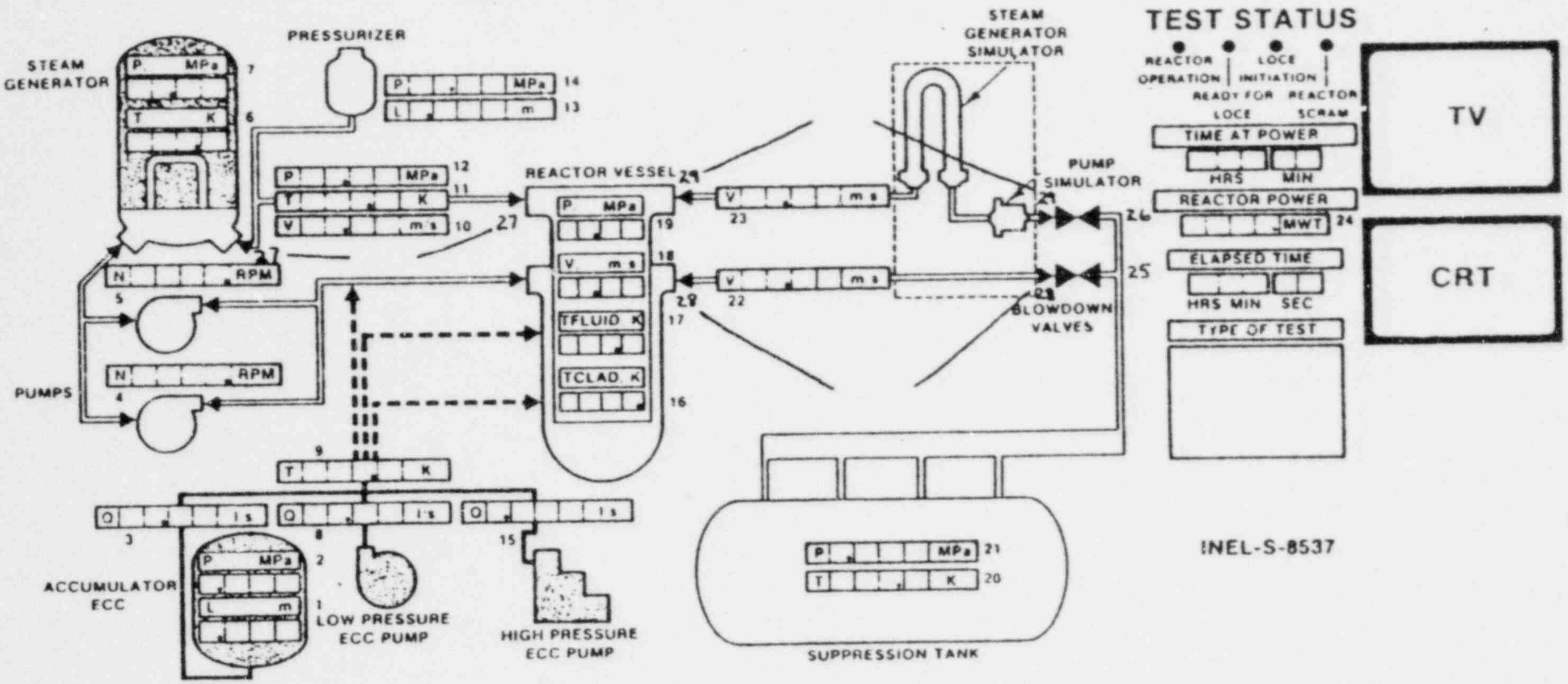


FIGURE 4

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reactor coolant pump motors, reactor coolant piping, and reactor vessel. During abnormal or emergency situations, the general location of small breaks and leaks could be found, the extent and severity of fires (or false alarms), and the level of fluid in the containment basement could be assessed. Television has been used to follow the progress of Loss-Of-Coolant-Experiments (LOCEs) to determine false fire alarms, and to assess the extent of an inadvertent containment spray. Few plants have such monitors; radiation, heat, and moisture resistant ones with zoom and light control and audio should be included at each loop, primary coolant motor, the pressurizer, basement, and containment dome.

2.4.3 Alternate Actions

During LOFT LOCEs, it is mandatory that the alternate actions be predefined in case the experiment does not go as anticipated. This allows alternate actions to be well thought out under calm conditions. Although all conceivable accidents cannot be covered, all plausible ones can. If LPWRs included alternate actions, the need for panic decisions would be reduced and well thoughtout procedures could be utilized almost immediately if an accident did occur.

2.4.4 Joint Experiment Group (JEG)

All LOFT tests are conducted under the supervision of the JEG. The JEG is composed of senior members from EG&G and DOE. The primary function of the JEG is to review, approve, and release Experiment Operating Procedures and changes to the procedures. During a test, the JEG is available in the control room for immediate consultation.

A group of senior people who are intimately familiar with the daily operation of an LPWR could be very beneficial in case of an accident. These people would be available on site for consultation and to assist in making decisions as to the next plant evolution that should be performed.

2.4.5 Additional Operator Information

Reactors typically use dial indicators for displaying control parameters. This requires appreciable space and sometimes reading errors occur. A parallel readout from a computer would allow digital display of selected parameters on a CRT. This eliminates the possibility of readout error and displays the denied parameters all together on the screen. Computed parameters can also be utilized in assessing plant operation. Historical information could also be made readily available to aid in evaluation degradation of components. Historical information could also be made readily available to aid in evaluation of the components.

2.4.6 Experiment Safety Analysis

LOFT performs an Experiment Safety Analysis for each experiment. This analysis is very detailed and examines multiple accidents occuring simultaneously. Typically, an FSAR does not consider multiple accidents.

2.4.7 Control Room Shielding, Isolation, and Ventilation

The LOFT control room is shielded more than an LPWR. In addition, it is isolated from the plant. Most LPWR control rooms could be susceptible to steam and contamination leaks, e.g., respirators were required in the control room at one time during the TMI incident. The LOFT control room is below the elevation of the reactor vessel and is located approximately 300 feet from the containment.

The ventilation system for the LOFT control room is designed so air intake would not be contaminated during a radiation release during an accident. Air intakes are located 180° apart and 300 feet from the facility. Except for stagnated air conditions, this guarantees an uncontaminated air supply to the control room.

2.4.8 Back-Up Power

The LOFT battery is much larger than an LPWR and supplies primarily safety related equipment and areas, expecially instrumentation and the control room. This assures that critical safety related items are always available to operators.

TABLE V

SPECIAL LOFT DATA RECORDING FEATURES FOR IMPROVED LOCE OPERATION

LOFT FEATURE	TYPICAL LPWR DESIGN	COMMENT	PRIORITY/ RECOMMENDATION
1. Continuous Recording on Disc of Selected Parameters	Limited Recording Capability	In the event of an incident data can be taken from the disc and converted into time plots of specific parameters, (30 plots available within 1/2 hour). These plots can then be reviewed to determine cause of incident.	Moderate/Incident Evaluation
2. Events Monitor	Limited	Prints out change in valve status, rods drop times, and bistable actuations. Will give an update when querried. Also will print out status of value position, listable position in comparison to a preprogrammed predicted valve.	Moderate/Operational and incident evaluation.
3. Plant Log and Data Computer	Limited	Records continuously over the previous shift so in case of a TMI or other transient detailed data with a common time base is retained.	Moderate/Ability to analyze "normal" Scrams and transient would be greatly improved.

TABLE VI

SPECIAL FEATURES FOR IMPROVED LOCE OPERATION

LOFT FEATURE	TYPICAL LPWR DESIGN	COMMENT	PRIORITY/ RECOMMENDATION
1. High Pressure Heat Ex Exchanger within containment paralleling steam generator. Canned pumps, etc. A good idea. Similar to BWR Isolation Condenser	None	To allow adequate core cooling in absence of steam generator heat rejection. LOFT has such a system in its navy-like cleanup system and it can handle up to 2-3% power plus pump heat.	Moderate/It would allow core cooling without having to put fluid into the auxiliary building; but multiple SG's available at operating plant.
2. Radiation Monitor on Containment Sump Pump Discharge Line	None	To defeat containment sump from discharging into auxiliary building if fluid is highly contaminated (LOFT does not have this)	High/May prevent spills and cleanup probems
3. Air Reservoirs in Containment (Large Ones)	None	Would allow air-operated valves to continue to function in case of loss of offsite power and air was lost to containment (i.e. air compressors are not now considered 'vital' equipment so they are not loaded.	Moderate/Prolonged loss of air to containment disables such things as primary coolant pump seal cooling (St. Lucie Unit 1). Useful in prolonged outages, earthquakes, etc. Not sure of back up capability at LPWRs.
4. S/G Blowdown Cross Tie	None	To refill steam generator in case of dry generator.	Low/If necessary, generator could be refilled with main feed which should be warm. If another generator is full, it could reject heat to cooldown.
5. Two Pressurizer Connections	One surge line (and spray lines)	Would allow vessel head venting and more meaningful pressurizer level.	

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TABLE VI (Cont.)

SPECIAL FEATURES FOR IMPROVED LOCE OPERATION

LOFT FEATURE	TYPICAL LPWR DESIGN	COMMENT	PRIORITY/ RECOMMENDATION
6. Silver Zeolite Filters	Unknown	The LOFT containment vessel atmosphere cleanup system, containing silver zeolite is highly effective for particulate and halogen removal prior to exhausting. Filter train can be used during operation instead of just a standby post-accident system. Expected life of halogen absorber is 20 years.	Moderate/Prevent potential releases as was seen at TMI.
7. Refueling cask for removing damaged fuel bundles	Pit Refueling	Prevents having to move heavily damaged bundles through the containment and into the refueling building, whose air cleanup is probably not able to handle large amounts of iodine should the bundle be further damaged in upending, etc. Also minimizes potential gaseous exposure to operator on refueling machine.	Moderate/Might be needed only occasionally as at TMI, but then would be indispensable.

2.5 Data Recording

Data recording on LOFT is accomplished on the DAVDS (Data Acquisition and Visual Display System). The DAVDS is comprised of four separate minicomputer systems plus a wide band system. The minicomputer systems are: (1) the Digital Data Acquisition and Processing System (DDAPS), (2) the Digital Data Acquisition System (DDAS), (3) the Plant Log and Data System (PLD), and (4) the Data Processing System (DPS). The primary recording system for LOCEs is the DDAPS with redundancy on the DDAS. The primary system for operator assistance is the PLD system which is also redundantly recorded on the DDAS. Table V summarizes the LOFT features. None of these features are rated as high priority.

2.6 Miscellaneous

Some LOFT features do not fit into the categories previously listed. This section includes those items. In addition, ideas that are not currently on LOFT but would be applicable to both LOFT and LPWRs are listed. Details of an LPWR concept using two connections between the reactor vessel and pressurizer is presented. This concept was presented in a memo to L. P. Leach by S. Z. Rouhani and is reproduced in this section. The miscellaneous LOFT features for improved LOCE resistance are presented in Table VI.

2.6.1 A PWR Concept with Two Connections Between the Reactor Vessel and Pressurizer

(a) Background

A careful review of the sequence of events in the Three Mile Island (TMI) Unit-2 incident indicates that the existence of vapor and non-condensible gasses inside the reactor vessel, in some period during the transient, caused a surge of coolant water into the pressurizer and gave dangerously wrong signals regarding the liquid level and liquid inventory in the primary system. This is a natural consequence of having only one hydraulic connection between the primary circulation system and the pressurizer vessel, usually at a point somewhat downstream of one of the outlet nozzles. This feature is common in all pressurized water reactor (PWR) designs. Analyses of LPWRs and LOFT L3-0 have shown that the problem is not related to a loop seal in the surge line; i.e. the steam flow is large enough to cause the TMI response even without a loop seal in the surge line.

(b) Proposed System

In order to avoid any gas or vapor trapping in the upper part of the reactor vessel; and, at the same time, to provide reliable operating conditions for the liquid level indicator(s) connected to the pressurizer, it appears necessary to have two different connections between the pressurizer and the upper plenum of the reactor vessel.

Figure 5 shows schematically such a system. The pressurizer has one connection between its top part with the top part of the reactor vessel (at its uppermost point) and another connection between its bottom part and another location in the upper plenum, preferably at a somewhat lower elevation compared to the end point of the first connection.

A mere addition of an extra piping connection between the upper end of the pressurizer and the upper plenum in the existing designs may to some extent serve the purpose of completing the hydraulic communication between the two vessels. However, the pressure drop between the upper plenum and the liquid connection point, after the hot-leg nozzle, will influence the position of liquid level inside the pressurizer and the extent of this influence will depend on the circulation rate in the loop. To avoid this difficulty and the regulation problems

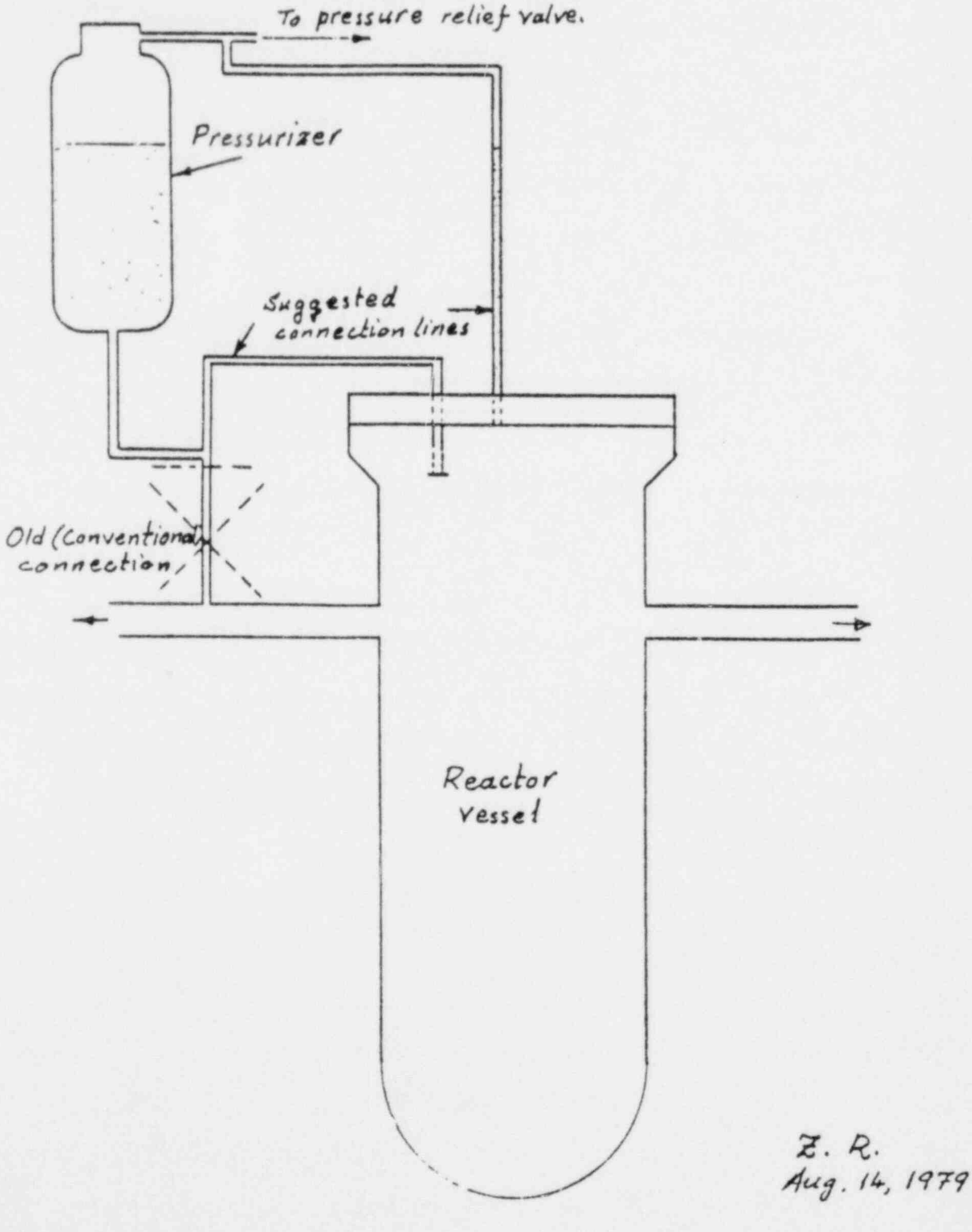

Fig 5 - PWR system with double hydraulic connections between pressurizer and upper plenum.

which may follow, it would be most suitable to bring both of the suggested connections from the pressurizer directly to the upper head of the reactor vessel. The function of the doubly connected pressurizer will be exactly the same in normal operations. But during a transient, this system functions quite differently compared to the single connection system.

If for any reason there happens to be some gas or vapor emerging from the core, it will rise through the upper plenum and flow directly through the vapor-leg connection into the vapor part of the pressurizer.

The first advantage of this system would be a direct indication of liquid inventory situation since the liquid inside the pressurizer will not be "trapped" and will quickly indicate the correct level which may warn of any water deficiency.

The second advantage is that the noncondensible gases may be blown off directly through the relief valve on the pressurizer; and in the case that a continued blowdown results in boiling inside the core, even that vapor will be led into the pressurizer with little risk for blocking the circulation paths.

(c) Suggested Work

(1) Analytical - Considering the results of detailed computations which were performed recently on TMI Unit-2 and the fact that with some minor alterations one could use the same code inputs to represent a doubly connected pressurizer system, it would be interesting to repeat some of the small break calculations in this system. Comparison of results with the old calculations could provide some interesting information. Later, similar modifications could be done in the inputs for analyzing the transient performances of Semiscale and LOFT, with a doubly connected pressurizer.

(2) Experimental - If time and budget considerations allow, it would be very informative to modify the existing experimental facilities of Semiscale and LOFT such that there will be two connection lines between their pressurizers and the upper plenum (as shown in Figure 5) and repeat some of the previous small break experiments.

A comparison of data from such experiments with the old ones may provide a guideline for potential improvements in the PWR system.

2.6.2 Radiation Monitor on Containment Sump Pump

One of the difficulties encountered during the TMI incident was the automatic pumping of contaminated water from the containment to the auxiliary building. TMI releases to the surrounding environment were from the auxiliary building. If a radiation monitor was available on the containment sump pump discharge, the automatic pumping feature could be overridden if radiation levels became high. The sump pump could then be manually actuated if conditions warranted it.

2.7 Conclusions and Recommendations

LOFT was designed to perform LOCA's. To allow repeated LOCE's, special features were incorporated into LOFT. These features are of particular interest to the nuclear industry for application to existing and future plants. Some of these features have a high priority for consideration by the nuclear power industry. These high priority features are summarized below in order of overall priority based on our assessment of maximum contribution to reactor safety. The order of implementation would be quite different based on ease and cost of implementation.

(1) unpressurized fuel rods

(2) vessel liquid level

(3) primary coolant pump loop seal

(4) expanded range instrumentation

(5) core exit thermocouples

(6) experiment safety analysis

(7) alternate actions

(8) subcooled meter

(9) pump parameters (expecially pump speed)

(10) nuclear hardened gamma densitometer

(11) high capacity/high head HPIS and charging pumps

(12) operator computer assistance

(13) TV cameras in containment

(14) visitor display room

(15) Joint Experiment Group

(16) primary coolant pump injection

(17) radiation monitor on containment sump pump

(18) instrument penetration cartridge

The items that would be easily implemented are:

(1) vessel liquid level (head to hot leg differential pressure or bottom of vessel to hot leg)

(2) expanded range instrumentation

(3) subcooled meter

(4) TV cameras in containment

(5) Joint Experiment Group

(6) alternate action

These items should be considered for early implementation with the balance considered for refueling and new construction.

This report should be revised semi-annually or as developments in the LOFT Program require.