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A RETRAN Model of the Calvert Cliffs-1 Pressurized Water Reactor for Assessing the Safety Implications of Control Systems

J-P. A. Renier
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A RETRAN MODEL OF THE CALVERT CLIFFS-1 PRESSURIZED WATER REACTOR FOR ASSESSING THE SAFETY IMPLICATIONS OF CONTROL SYSTEMS

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ACRONYMS

ac	alternating current
ADV	atmospheric steam dump valve
AFW	auxiliary feedwater
BG&E	Baltimore Gas and Electric
B&W	Babcock and Wilcox
C-E	Combustion Engineering
dc	direct current
dp	differential pressure
EFIC	emergency feedwater initiation and control
E/I	voltage-to-current
E/P	Electric-to-pneumatic
EPRI	Electric Power Research Institute
ESF	engineered safety features
ESFAS	engineered safety features actuation system
FMEA	Failure Mode and Effects Analysis
FSAR	final safety analysis report
FW	feedwater
gpm	gallons per minute
HP	high pressure
HPI	high-pressure injection
HPSI	high-pressure safety injection
I/P	current-to-pneumatic
kV	kilovolts
kW	kilowatts
LER	Licensee Event Report
LOCA	loss-of-coolant accident
LPI	low-pressure injection
MFIV	main feedwater isolation valve
MFW	main feedwater
NIS	nuclear instrumentation system
NNI	nonnuclear instrumentation
NRC	U.S. Nuclear Regulatory Commission
NSSS	nuclear steam supply system
ORNL	Oak Ridge National Laboratory

PORV	power-operated relief valve
psia	pounds per square inch (absolute)
psig	pounds per square inch (differential)
PTS	pressurized thermal shock
PWR	pressurized water reactor
RCS	reactor coolant system
SG	steam generator
SGIS	SG isolation signal
SGTR	SG tube rupture
SI	safety injection
SICS	safety implications of control systems
T_{avg}	temperature (average)
TBV	turbine bypass valve

ABSTRACT

The failure mode and effects analysis of Calvert Cliffs-1 identified sequences of events judged sufficiently complex to merit further analysis in detailed dynamic simulations. This report describes the RETRAN model developed for this purpose and the results obtained. The mathematical tool was RETRAN2/Mod3, the latest version of a widely used and extensively validated thermal-hydraulics production code obtained by license agreement with the developer, Electric Power Research Institute, and installed on the ORNL IBM-3033 computers. RETRAN2 is based on a first-principles methodology that treats two-phase flow with slip. Thermal equilibrium of phases is assumed except in the pressurizer, where non-equilibrium processes are important and special methodology is used. Heat transfer in solids is obtained from the conventional conduction equation. Point or 1-D kinetics is available for the reactor core. The fundamental methodology is supplemented with a broad list of process submodels that calculate heat transfer coefficients, fluid and metal state properties, choked flow, form and wall friction losses, and other parameters. Also supplied are component submodels for various types of valves and pumps, the latter of which incorporate four-quadrant characteristics for components in which two-phase or reverse flow may be expected, and head versus flow curves for others.

Extensive input allows the code to be highly particularized to a specific plant. The major investment in time and manpower occurs in setting up the base case; changes are comparatively easy to implement.

1. INTRODUCTION

This report describes a detailed RETRAN model used in dynamic simulations of the Calvert Cliffs-1 Nuclear Power Plant. The RETRAN model includes plant primary, secondary, control, and safety systems. These simulations were used to perform failure mode and effects analyses (FMEA) and to assess the safety implications of the control systems (SICS) of Calvert Cliffs-1.

The RETRAN-02/MOD3 computer code[1] was used in performing neutronic and thermal-hydraulics calculations. An extensive input setup to describe in detail the principal features of Calvert Cliffs-1 allowed the simulations to be tailored precisely to that specific nuclear power plant. Some results of the dynamic simulations using the RETRAN model for Calvert Cliffs-1 have been presented elsewhere.[2,3]

The Calvert Cliffs-1 power plant is a Combustion Engineering (C-E) pressurized water reactor (PWR) configured as shown in Fig. 1.1. The

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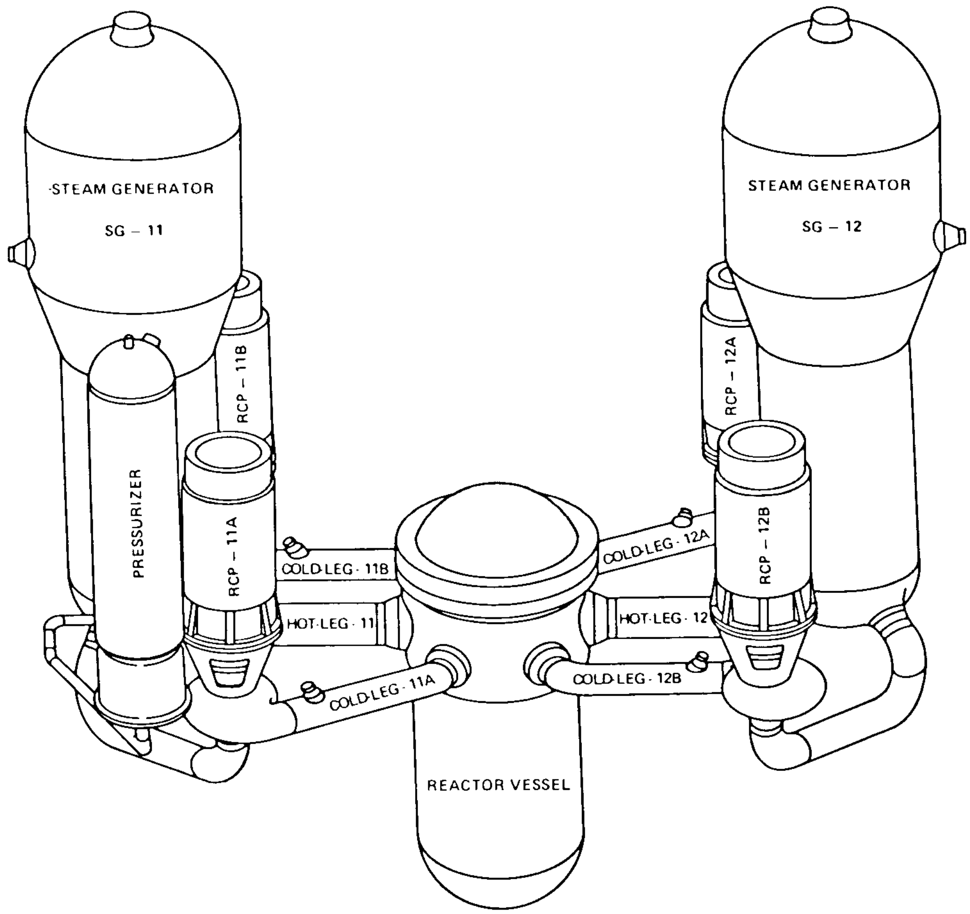

plant owner and operator, the Baltimore Gas & Electric Company (BG&E), and the plant vendor, C-E, provided numerous details of the primary, secondary, and control systems, which were incorporated into ORNL's Calvert Cliffs RETRAN model (Figs. 1.2 and 1.3). BG&E provided ORNL with a basic RETRAN input deck, which simulated principally the primary system. ORNL changed the deck extensively in the primary system for the FMEA and SICS studies. ORNL also added a complete secondary loop with the necessary control systems.

System descriptions and information were obtained from isometric piping drawings, system description and operating manuals, system specification sheets, and other materials provided by BG&E and C-E. Exact pipe lengths, volumes, diameters, and elevations have been preserved as much as possible unless otherwise stated.

Equipment failures and operator inactions were specified by the FMEA group at ORNL. The RETRAN model was a best-estimate model in the sense that every effort was made to simulate the real power plant as closely as possible, but taking into account the given failures.

All transients were initiated from full-power steady-state conditions. The RETRAN model is operational for transients at power and after a reactor trip.

Depending upon the initial conditions and required failures specified for the nuclear power plant simulations to be performed for the FMEA studies, portions of the RETRAN model shown in Fig. 1.3 were deleted or altered. This improved the running time on the IBM-3033 computers at ORNL for the specified transients. For instance, one alteration was deletion of the secondary system upstream of the main feedwater (MFW) pumps; the feedwater flow coming from the low-pressure feedtrain was then replaced by a RETRAN 'fill' option. Another alteration was deletion of the main steam system downstream of the main steam regulating valves.

As the Calvert Cliffs-1 RETRAN model evolved during the studies, it was necessary to rerun the steady-state calculations, followed by a 60-s 'null-transient,' before initiation of the transient could begin.

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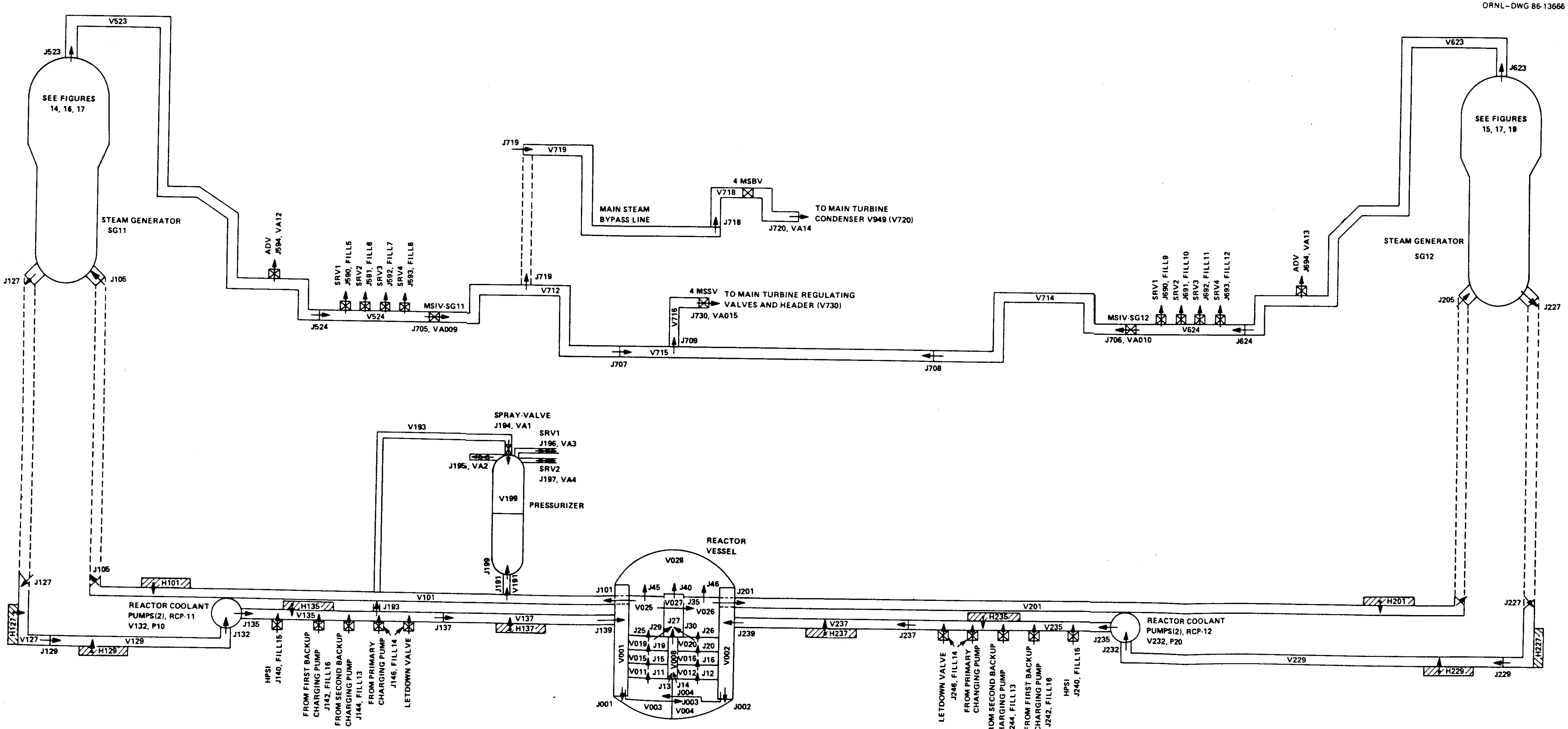

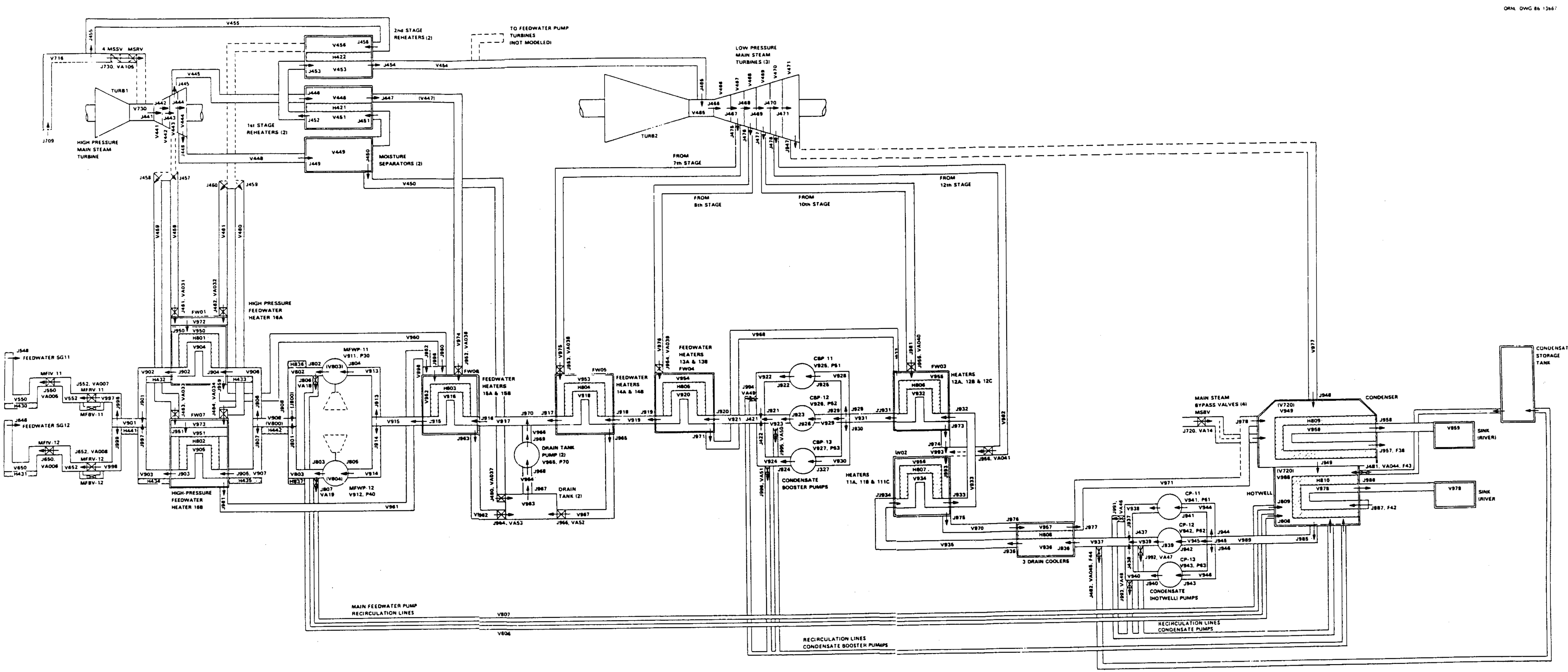

TO FEEDWATER PUMP TURBINES (NOT MODELED)
2nd STAGE REHEATERS (2)
1st STAGE REHEATERS (2)
MOISTURE SEPARATORS (2)
LOW PRESSURE MAIN STEAM TURBINES (2)
HIGH PRESSURE MAIN STEAM TURBINE
TURB1
TURB2
4 MSSV
MSRV
FROM 7th STAGE
FROM 8th STAGE
FROM 10th STAGE
FROM 12th STAGE
HIGH PRESSURE FEEDWATER HEATER 16A
HIGH-PRESSURE FEEDWATER HEATER 16B
FEEDWATER SG11
FEEDWATER SG12
MFWP-11
MFWP-12
FEEDWATER HEATERS 15A & 15B
FEEDWATER HEATERS 14A & 14B
FEEDWATER HEATERS 13A & 13B
DRAIN TANK PUMP (2)
DRAIN TANK (2)
CONDENSATE BOOSTER PUMPS
HEATERS 12A, 12B & 12C
HEATERS 11A, 11B & 11C
3 DRAIN COOLERS
CONDENSATE (HOTWELL) PUMPS
MAIN STEAM BYPASS VALVES (4)
CONDENSER
HOTWELL
SINK (RIVER)
CONDENSATE STORAGE TANK
MAIN FEEDWATER PUMP RECIRCULATION LINES
RECIRCULATION LINES CONDENSATE PUMPS
RECIRCULATION LINES CONDENSATE BOOSTER PUMPS

2. OVERVIEW OF THE MODEL

The ORNL simulation is based upon a Calvert Cliffs-1 RETRAN model provided by BG&E and previously used in their studies of certain aspects of plant dynamics. The BG&E model simulated principally the primary systems. The secondary side of each steam generator (SG) was represented by five nodes; the balance of plant was represented by boundary conditions. To treat all cases of interest to the Safety Implications of Control Systems (SICS) Program, it was necessary to expand portions of the model, principally the steam generator and control system simulations. The additions are based upon Calvert Cliffs-1 plant-specific information provided by BG&E and C-E.

The RETRAN nodal diagrams of the primary and secondary loops are shown in Figs. 1.2 and 1.3. The control systems were implemented using RETRAN's basic control modules. These systems control the various components in the RETRAN model, and they will be described later in this report. Because of the proprietary or confidential nature of some of the data used in the model, certain information in the nodal diagrams and in the control system diagrams will be omitted or shown only partially. The effect of heat capacity in the metal masses of the coolant pipes and components was included in the model, using RETRAN's heat conductor capability. Note that for the FMEA and SICS simulations, several control systems were modified or altered in order to simulate failures or improper operation of different portions of the control systems or modules in the power plant.

2.1 MODEL OF THE PRIMARY SIDE

In the primary side, the following major components were specifically modeled (see Fig. 1.2): a reactor vessel, two parallel heat transfer loops (each containing one steam generator), two reactor coolant cold legs and one hot leg per loop, and a pressurizer in one loop. The following components and operating details were modeled:

1. Reactor core, vessel and internals (see Fig. A.1.3 in Appendix A), including the regulating and safety control rods and the soluble boron injection and removal control systems (see Fig. A.1.5).

2. Two hot-leg loops: hot legs 11 and 12 (hot legs 21 and 22 in Calvert Cliffs-2). The hot legs will also be referenced as A and B.

3. Pressurizer (RETRAN volume number V199), including spray valve (RETRAN valve number VA001 at junction J194), heater and backup heaters, two pressure-operated relief valves (PORVs) (VA002 at J195), two pressurizer safety relief valves SRV1 (VA003 at J196) and SRV2 (VA004 at J197), and their associated control systems. [Note that the spray into the pressurizer gets water from cold leg 11 via the spray line (RETRAN volume node V193).]

4. Two steam generators (SG-11 and SG-12) of the U-tube type (SG-21 and SG-22 in Calvert Cliffs-2). The steam generators will also be referenced as SG-A and SG-B.

5. Four cold legs and four reactor coolant pumps. In the RETRAN model the cold legs and coolant pumps were combined into two cold legs with a coolant pump in each combined cold leg. (Cold legs 11 and 12, reactor coolant pumps 11 and 12 in Calvert Cliffs-1; cold legs 21 and 22, reactor coolant pumps 21 and 22 in unit 2)

6. Primary charging pump and first and second backup charging pumps, which introduce water into the primary coolant loops via the cold legs.

7. Letdown valves, which remove reactor coolant from the primary system via the cold legs and thus reduce water inventory in the primary system.

8. Soluble boron injection into or removal from the primary coolant system through the charging and letdown loops.

2.2 MODEL OF THE SECONDARY SIDE

In the secondary side, we have the following components in the RETRAN model (see Fig. 1.3):

1. Two steam generators (SG-11 and SG-12), including the downcomer, riser, steam separators, steam dryers, steam dome, recirculation flow, metal masses, and narrow-range and wide-range level control systems (see Figs. A.2.1 through A.2.6 in App. A).

2. Main steam line from the steam outlet of each steam generator.

3. Atmospheric dump valve in each main steam line.

4. Four main steam line safety relief valves in each main steam line.

5. Main steam isolation valve (MSIV) in each main steam line (see Fig. 1.2) (RETRAN valve number VA009 at junction J705 for SG-11, and valve VA010 at J706 for SG-12).

6. Main steam collector line (RETRAN volume V715), into which the steam of each of the main steam lines flows.

7. Four main steam stop valves (MSSVs) and main steam regulating valves (MSRV), which regulate steam flow into the high-pressure steam turbine.

8. Main steam bypass lines, which are connected to the main steam line coming from SG-11.

9. Four main steam bypass valves (MSBVs) (RETRAN valve number VA014 at junction J720) between the main steam bypass lines and the condenser hotwell unit (RETRAN volume V949/V720).

10. Auxiliary feedwater system (AFW) to each of the steam generators.

11. Main feedwater system (MFW) to each of the steam generators.

    In the MFW system in the secondary side (see Fig. 1.3), we have the following:

    - MFW pipe (RETRAN volume node V550 at junction J550) from MFW isolation valve (MFIV-11 or MFIV-A) to SG-11.
    - MFIV-11 valve (RETRAN valve number VA005 at junction J550) of SG-11 (MFIV-21 of SG-21 in unit 2).
    - Pipe (RETRAN volume node V552) from MFIV-11 to the MFW regulating valve (MFRV-11 or MFRV-A) and the MFW bypass valve (MFBV-11) (MFRV-21 and MFBV-21 in unit 2).
    - Pipe (RETRAN volume node V997) from the MFRV-11 valve to the collector pipe (RETRAN volume node V901) of the MFW pumps.
    - MFRV-11 and MFBV-11 valves (RETRAN valve number VA007 at junction J552) to SG-11 (MFRV-21 and MFBV-21 in unit 2).
    - Pipe (RETRAN volume node V997) from the MFRV-11 valve to the collector pipe (RETRAN volume node V901) of the MFW pumps.
    - Main-feedwater pipe (RETRAN volume node V650) from the MFW isolation valve (MFIV-12 or MFIV-B) to SG-12.
    - MFIV-12 valve (RETRAN valve number VA006 at junction J650) of SG-12 (MFIV-22 of SG-22 in unit 2).
    - Pipe (RETRAN volume node V652) from the MFIV-12 valve to the MFW regulating valve (MFRV-12 or MFRV-B) and the MFW bypass valve (MFBV-12 or MFBV-B).
    - MFRV-12 and MFBV-12 valves (RETRAN valve number VA008 at junction J652) to SG-12 (MFRV-22 and MFVB-22 in unit 2).
    - Pipe (RETRAN volume node V998) from the MFRV-12 valve to the collector pipe (RETRAN volume node V901) of the MFW pumps.
    - High-pressure FW heaters 16A and 16B. The steam to the shell side of these heaters comes from an intermediate stage (RETRAN volume node V443) of the high-pressure steam turbine and from the second stage (volume node V456) of the moisture separator reheater units. In the RETRAN model, these FW heaters were modeled as follows: for heater 16A, RETRAN FW heater FW01 using volume nodes V950 shell side and V904 tube side; for heater 16B, RETRAN FW heater FW07 using volume nodes V951 shell side and V905 tube side.

- Main feedwater pumps (RETRAN pump P30 at volume node V911 for MFWP-11 and pump P40 at volume node V912 for MFWP-12 in Fig. 1.3). In the plant, the MFW pumps are driven by small steam turbines. The steam to these turbines comes from the main steam lines, and their speed is controlled by steam regulating valves. In the RETRAN model, the small steam turbines for the MFW pumps were not modeled. The speed of the MFW pumps is directly controlled with the MFW pump control system (see Fig. A.3.5 in App. A). (MFWP-21 and MFWP-22 in unit 2)

- Main feedwater pumps MFWP-11 and MFWP-12 require a minimum flow while operating. In order to maintain this minimum flow when the water flow downstream of the pumps is lower than the minimum required flow, recirculation valves open up to recirculation lines connected to the hotwell. The recirculation valves were modulated with a control system built up from RETRAN's basic control modules (see Fig. A.3.6 in App. A).

- Low-pressure feedwater heaters 15A and 15B. In the RETRAN model they were modeled as one FW heater (RETRAN heater number FW06 using volume nodes V952 shell-side and V916 tube-side). The steam to the FW heater 15A comes from two sources:

  a. the drain from high-pressure FW heater 16A
  b. the steam from the first stage of main steam moisture separator reheater 1.

The steam to the FW heater 15B also comes from two sources:

  a. the drain of high-pressure FW heater 16B
  b. the steam from the first stage of the main steam moisture separator reheater 2.

- Two drain tanks. In the RETRAN model, the two drain tanks were combined into one RETRAN volume node V963. Drain tank number one is fed by

  a. the drain of feedwater heater 15A
  b. drain of the main steam moisture separator reheater unit 1
  c. the drain of feedwater heater 14A.

  Drain tank No. 2 is fed by

  a. the drain of FW heater 15B
  b. drain of the main steam moisture separator reheater unit 2
  c. the drain of feedwater heater 14B.

- Low-pressure FW heaters 14A and 14B. In the RETRAN model they were combined and modeled as one FW heater (RETRAN heater FW05 using volume nodes V953 shell-side and V918 tube-side). The steam to the FW heaters 14A and 14B comes from the 7th stage of the low-pressure steam turbines (see volume node V467 in Fig. 1.3).

- Low-pressure FW heaters 13A and 13B. In the RETRAN model, they were combined into one FW heater (RETRAN heater number FW04 using volume nodes V954 shell-side and V920 tube-side). The steam to FW heaters 13A and 13B comes from the 8th stage of the low-pressure steam turbines. The drain is fed to low-pressure FW heaters 12A, 12B, and 12C.

- Three condensate booster pumps CBP-11, CBP-12 and CBP-13. Condensate booster pump CBP-11 was modeled as RETRAN pump number P51 using volume node V925, CBP-12 as pump number P52 using volume node V926, and CBP-13 as pump number P53 using volume node V927. In order to maintain a minimum flow through the operating pumps, each condensate booster pump has a recirculation valve to a recirculation line, which is connected to the hotwell. The recirculation valves are represented in the RETRAN model as valve number VA049 at junction J994 for CBP-11, valve number VA050 at junction J995 for CBP-12, and valve number VA051 at junction J996 for CBP-13). The recirculation valves are modulated with the 'miniflow' control system of the condensate booster pumps. (The RETRAN controllers are shown in Fig. A.3.8 of App. A).

- Low-pressure FW heaters 12A, 12B, and 12C. In the RETRAN model, they were modeled as one FW heater (RETRAN FW heater number FW03 using volume nodes V955 shell-side and V932 tube-side). They are fed by the drain of FW heaters 13A and 13B, and the 10th stage of the low-pressure steam turbines (see RETRAN volume node V469 in Fig. 1.3).

- Feedwater heaters 11A, 11B and 11C. In the RETRAN model, they were combined into one FW heater, with RETRAN heater number FW02 using volume nodes V956 shell-side and V931 tube-side. The feedwater heaters 11 are fed by the drain of FW heater FW03 and by the 12th stage of the low-pressure steam turbines (see RETRAN volume node V470 in Fig. 1.3).

- Three drain coolers. In the RETRAN model they were combined as one drain cooler represented by volume nodes V936 tube side and V957 shell side.

- Three condensate (hotwell) pumps CP-11, CP-12, and CP-13. Condensate pump CP-11 was modeled as RETRAN pump P61 using volume node V941, CP-12 as pump P52 using volume node V942, and CP-13 as pump P53 using volume node V943. In order to maintain a minimum flow while operating, each condensate pump has a recirculation valve to the hotwell via recirculation lines. The recirculation valves are represented by RETRAN valve numbers VA046 at junction J991 for CP-11, VA047 at J992 for CP-12, and VA048 at J993 for CP-13 (see Fig. 1.3).

  The recirculation valves of the condensate pumps are modulated with the 'condensate-pump miniflow' control system, built up with

RETRAN's basic control modules. The miniflow controllers are displayed in Fig. A.3.7 in App. A.

- Three-shell, single-pass condenser-hotwell unit. In the RETRAN model it was modeled as one hotwell (RETRAN volume node V988) and one condenser (RETRAN volume node V949). The tube side of the condenser is fed by river water, whose flow is simulated by RETRAN fill number FILL38 at junction J957. After leaving the tube side of the condenser, the river water is fed into a RETRAN time-dependent (sink) volume node V959. The tube side of the hotwell is also fed by river water, whose flow is simulated by RETRAN fill number FILL42 at junction J987. After leaving the tube side of the hotwell, the river water is fed into a RETRAN time-dependent (sink) volume node V979.

  The water level in the hotwell is maintained between two set points. When the water level drops below the low-level alarm, the water inventory in the secondary system is increased by activating RETRAN valve VA044 at junction J481. The water originates from the condensate storage tank of the secondary system. When the water level in the hotwell exceeds the high-level alarm, water inventory in the secondary system is decreased by pumping water from the discharge section of condensate pumps CP-11, CP-12, and CP-13 to the condensate storage tank by opening a dump valve (RETRAN valve VA045 at junction J482 and RETRAN fill FILL44.) The condenser makeup and dump controller is shown in Fig. A.3.4 of App. A.

The main steam system in the secondary side, downstream of the four main steam stop valves (MSSV), includes the following (Fig. 1.3):

1. One main steam regulating valve (MSRV), represented by RETRAN valve VA015 at junction J730. The main steam regulating valve is modulated with a control system built up from RETRAN's basic control modules (not shown). In the RETRAN model the control system of the main steam stop valves (MSSVs) is imbedded inside the main steam regulating valve control system.

2. High-pressure steam turbine (HPT). In the RETRAN model the HPT is represented as turbine TURB1, comprising volume nodes V730, V441, V442, V443, and V444.

3. Two moisture separator reheater units, located between the HPT and the low-pressure steam turbines (LPTs). In the RETRAN model they were combined into one unit. The following volume nodes were used:

   - moisture separator units were represented by volume node V449.
   - first-stage reheaters were represented by volume nodes V446 and V451.
   - second stage reheaters were represented by volume nodes V456 and V453.

The steam output of the moisture separator reheater units was fed into the header of the three LPTs.

4. Three LPTs. The LPTs were placed on the same shaft as the high-pressure main steam turbine. In the RETRAN model the three LPTs were combined into one turbine, RETRAN turbine TURB2, composed of RETRAN volume nodes V465, V466, V467, V468, V469, V470, and V471. The exhaust of the three LPTs was fed into the 'three-shell' condenser-hotwell unit.

The turbines are 1800-rpm tandem compound units, made by the General Electric Co. for Calvert Cliffs-1 and by the Westinghouse Corp. for Calvert Cliffs-2.

During the studies, it was observed that successful achievement of a convergent solution in the steady-state option of RETRAN depended on the proper sequence of the RETRAN fluid volumes and flow junctions. It was found that the RETRAN nodes and junctions must be sequentially numbered following the fluid flow; otherwise, the steady-state solution might fail. A preprocessor was subsequently written which renumbered RETRAN volumes and junctions sequentially following the actual fluid flow in the different thermal-hydraulic loops. Also, RETRAN control blocks 702xxx and 703xxx were renumbered automatically in the preprocessor following the flow of information that was given in the controllers. Note that these controllers were built up with RETRAN's basic control blocks.

See Appendix A for further details of model modeling.

3. MODEL VALIDATION

The RETRAN2/Mod3 code that provided the mathematical framework for the modeling described here has received extensive validation against a broad spectrum of both process and systems data. The code in its present and previous editions has been used worldwide for many years to study PWR and BWR dynamics.

The Calvert Cliffs model supplied to ORNL was previously validated by BG&E against an asymmetric cooldown event that occurred at Calvert Cliffs-2, sister plant to unit 1, on October 11, 1983.[3] Parameters compared included pressurizer pressure and water level, loop A hot- and cold-leg coolant temperatures, loop B secondary pressure, and water level in both generators. The model showed generally good agreement with the data.

The data for this transient were supplied to ORNL and were used to revalidate the ORNL expanded model. Dominant features of the transient included loss of one FW pump and high-flow failure of the other, which caused underfill of one generator and overfill of the other. Key events are listed in Table 3.1. The transient was initiated when steam generator main feedwater pump 22 tripped on low oil pressure. Operators began reducing reactor power and closing the turbine throttle valves, with the intent of achieving the 70% power level allowed with operation of the remaining MFW pump. Because of a mismatch between reactor and turbine runbacks, the reactor tripped on low water level in SG-22 at 62 s into the transient. Nominally, MFW regulating valves ramp back to 5% open on reactor trip. However, MFW regulating valve 21 to SG-21 failed fully open instead, and the MFW pump 21 governing valve stuck on high-speed stop, resulting in maximum FW flow from pump 21 to SG-21. Operators isolated the pump 340 s into the transient.

The four turbine bypass valves (with a combined capacity of 40% of full power steam flow) cycled following reactor trip, and one failed partially open until isolated by operators at 300 s. This failure resulted in continued cooldown and depressurization of the primary and secondary systems.

Operators later initiated auxiliary feedwater (AFW) to SG-22 and isolated auxiliary flow to SG-21; the blowdown system was used to reduce the level in SG-21.

Table 3.1. Sequence of events in the asymmetric cooldown transient at Calvert Cliffs-2, October 11, 1983

Event	Time (s)
MFW pump 22 trips	0
Operators reduce reactor power and throttle turbine	0+
Reactor trips on low water level in SG-22	62
MFW regulating valve 21 fails open; main feedwater pump 21 sticks on high-speed stop	62+
Turbine bypass valve sticks open	62+
Operators isolate bypass valve	300
Operators isolate MFW pump 21	340
Auxiliary feedwater to SG-21 isolated, auxiliary flow to SG-22 initiated	340+

Comparisons of plant data with the expanded RETRAN simulation are shown in Figs. 3.1 through 3.10. The revised model shows the same level of agreement with data as the original version. The ORNL version replaces boundary conditions on reactor power and FW flow with actual simulations. Comparisons of these parameters with data (Figs. 3.1, 3.6, and 3.8) are specific tests of the model revisions. The agreement is generally good. The simulated water level in SG-21 (Fig. 3.7) shows a "well" during the portion of the transient when the second MFW pump trips and flow rapidly decreases to near zero. The measured values do not show this "well," which suggests that the level instrument is effectively high-frequency filtered in a way not included in the model. Elsewhere the simulated level measure is suitable.

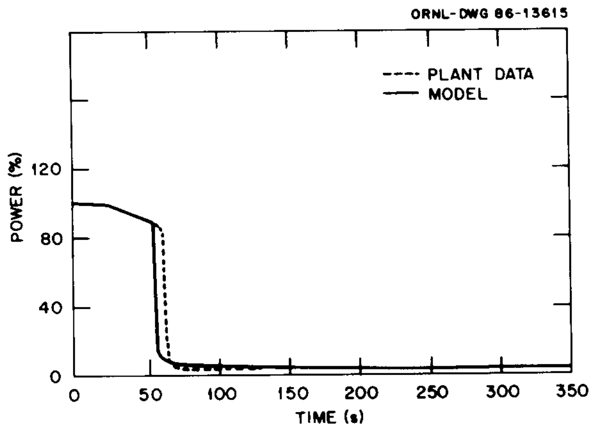

Fig. 3.1. Calvert Cliffs-2 asymmetric cooldown event, October 11, 1983. Reactor power.

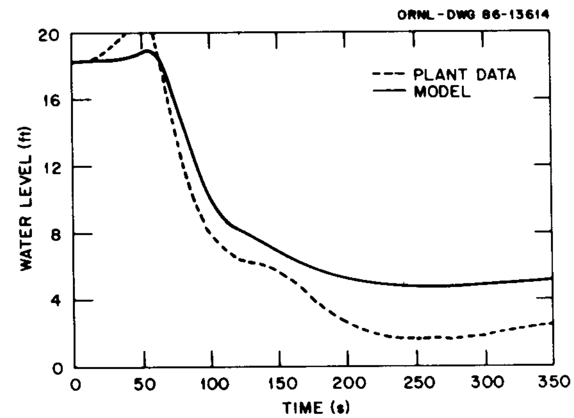

Fig. 3.2. Calvert Cliffs-2 asymmetric cooldown event, October 11, 1983. Pressurizer water level.

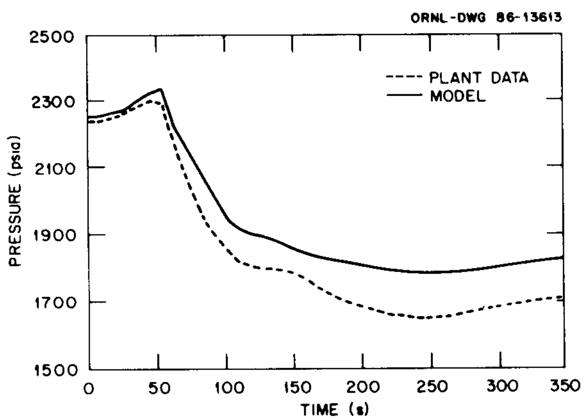

Fig. 3.3. Calvert Cliffs-2 asymmetric cooldown event, October 11, 1983. Pressurizer pressure.

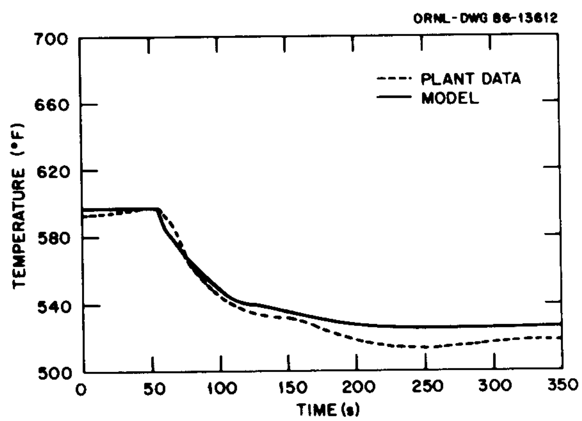

Fig. 3.4. Calvert Cliffs-2 asymmetric cooldown event, October 11, 1983. Hot-leg temperature.

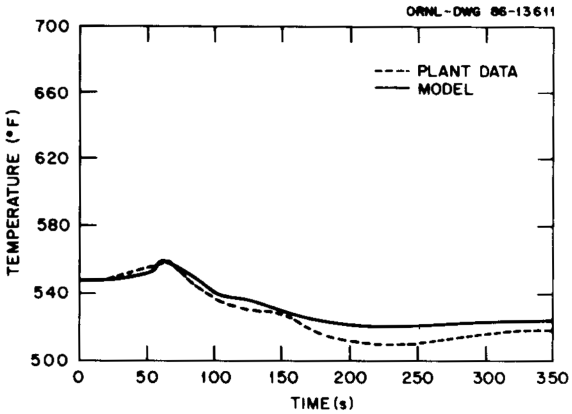

Fig. 3.5. Calvert Cliffs-2 asymmetric cooldown event, October 11, 1983. Cold-leg temperature.

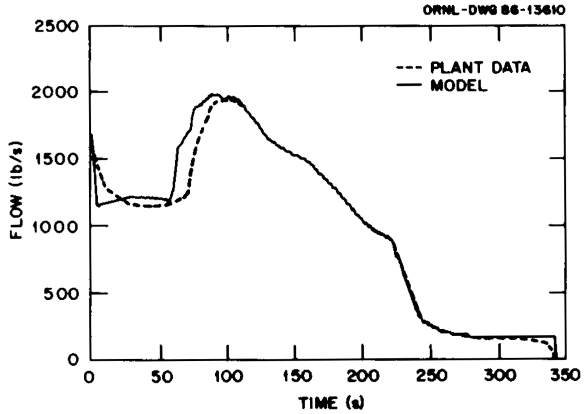

Fig. 3.6. Calvert Cliffs-2 asymmetric cooldown event, October 11, 1983. Feedwater flow to SG 21.

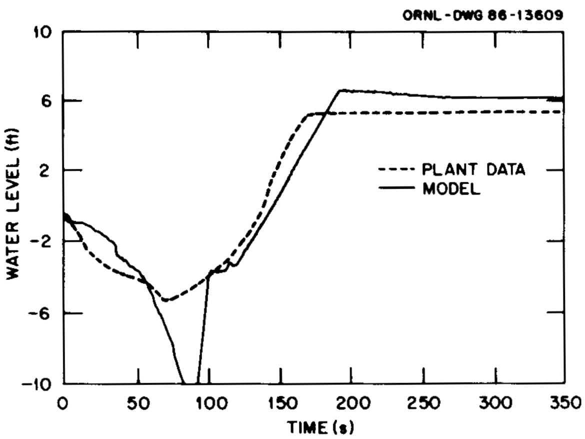

Fig. 3.7. Calvert Cliffs-2 asymmetric cooldown event, October 11, 1983. Water level in SG 21.

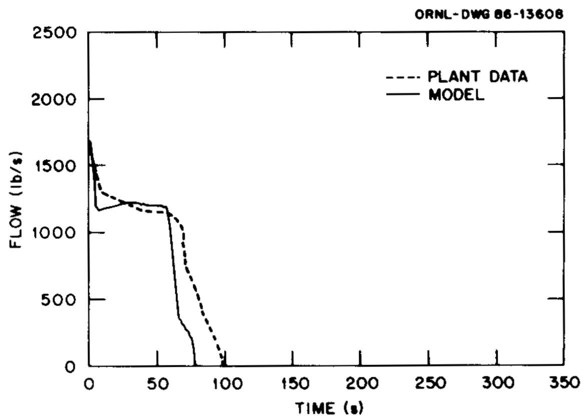

Fig. 3.8. Calvert Cliffs-2 asymmetric cooldown event, October 11, 1983. Feedwater flow to SG 22.

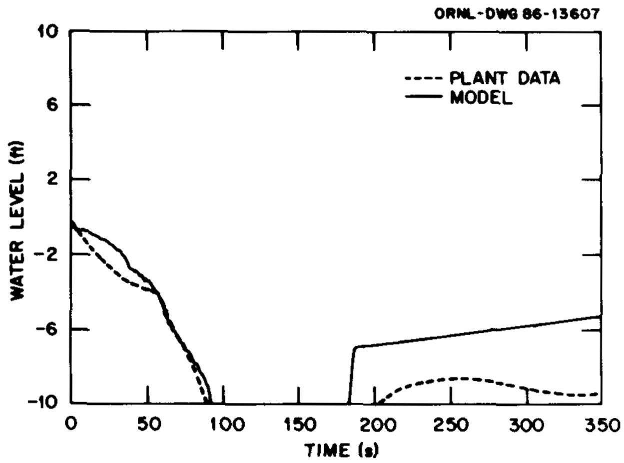

Fig. 3.9. Calvert Cliffs-2 asymmetric cooldown event, October 11, 1983. Water level in SG 22.

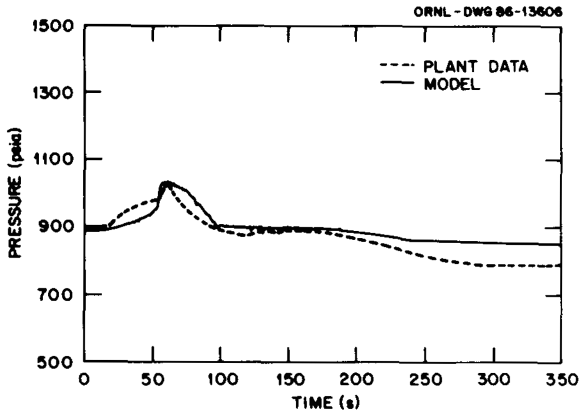

Fig. 3.10. Calvert Cliffs-2 asymmetric cooldown event, October 11, 1983. Pressure in SG 22.

4. TRANSIENTS RUN WITH THE MODEL

The RETRAN model has been used to investigate three categories of scenarios: overfill of the steam generators, dryout of steam generators, and primary-side depressurization that may uncover the core. The following cases have been run:

4.1 OVERFEED

- failure high of SG-A steam flow reading at 1940 lb/s (nominal reading is 1640 lb/s); SG-A high-level turbine trip defeated.
- failure low of SG-A water level reading 10 in. below set point; SG high-level turbine trip defeated.
- SG-A MFW regulating valve 11 failed full open in 1.5 s.
- SG-A MFW regulating valve 11 failed full open in 1.5 s; MFW isolation valve 12 failed open.
- SG-A MFW regulating valve 11 frozen in place on reactor/turbine trip.
- SG-A MFW regulating valve 11 frozen in place on reactor/turbine trip; MFW isolation valve 11 failed open.
- SG-A MFW regulating valve 11 failed full open in 1.5 s; with recent Calvert Cliffs-1 design changes, MFW isolation valves do not close on SG low-low level.
- SG-A MFW regulating valve 11 frozen in place on reactor/turbine trip; with recent Calvert Cliffs-1 design changes, MFW isolation valves do not close on SG low-low level trip.

4.2 DRYOUT

- failure low of SG-A steam flow reading at 1110 lb/s.
- failure high of SG-A level reading (narrow range) 10 in. above set point; low water level (narrow range) reactor trip defeated; low-low level AFW actuation trip (wide range) not failed.
- failure high of SG-A level reading 10 in. above set point on both the wide-range and narrow-range scales; low level and low-low level trips defeated.
- SG-A MFW regulating valve 11 failed completely closed (no leakage) in 5 s.

4.3 PRIMARY-SIDE DEPRESSURIZATION

- failure of both PORVs open.
- failure of one PORV open.
- small break of 0.0015 ft^2 in hot leg of loop A.

The first eight cases assessed whether the stipulated malfunctions of SG controls could initiate an overfill event. The next four investigated whether stipulated failures of SG controls could induce dryout. The last three explored whether small-break LOCAs on the primary side could result in core uncovery.

The model initially included closure of the main feedwater isolation valves on low-low SG water level trip (and AFW actuation), which until recently was the design of Calvert Cliffs-1. Closure of isolation valves on low-low trip has been deactivated, a change which was discovered midway through the series of runs. Cases thought to be potentially affected by this change were repeated as noted in the above descriptions.

5. RESULTS OF THE CALCULATIONS

5.1 OVERFEED TRANSIENTS

Flow to the generators is modulated by two error signals: steam flow is compared with feedwater flow, and generator water level is compared with level set point. The sum of these errors is sent to the controllers of the MFW valves. For the overfill case in which steam flow reading failed high at 1940 lb/s (compared with nominal 1640 lb/s), the control system initially acted to increase feedwater flow (Note that in the plotted results the code uses the first 60 s to establish nominal steady state; thus the transients begin at 60 s.) However, the resulting increase in steam generator level nullified the steam flow error after approximately 1 min. Flow initially increased approximately 10% and then was restored to near nominal. There were negligible variations in primary pressure and temperature, and minor variations in SG level. This event did not result in overfill or overcooling.

In the second overfill study, the SG-A level reading was failed 10 in. below set point. The failure dominated the transient and was not compensated by the resulting feedwater flow-steamflow error. High-level trip was defeated. Steam generator A moisture separators and steam dome were flooded in 10 min. (Fig. 5.1.1), at which time the liquid-steam mixture began injecting into the steam line (Fig. 5.1.2). Steam quality decreased to 85% (Fig. 5.1.3),and liquid content in the pipe between generator and turbine was approximately 1%. Since, because of pressure tap location, the level reading saturated before the SG was full, outlet quality provides a clearer indication of when the SG actually filled. Average core coolant temperature (Fig. 5.1.4) and power (Fig. 5.1.5) varied negligibly during the overfill, in part because of the slow rate of fill. When water began injecting into the steam line, pressure (Fig. 5.1.6) and feedflow to the generator (Fig. 5.1.7) varied slightly. The overfill did not result in overcooling of the primary.

In the previous two overfeed studies, the error signal was of such size that the SG-A feedwater valve did not fail full open. In the next case the valve was postulated to fail full open in 1.5 s, thereby initiating presumably the maximum rate of overfeed. Steam generator A filled to the 50-in. high-level trip in 2 min. (Fig. 5.1.8), at which time the turbine tripped followed by a reactor trip. The MFW valve to SG-B closed and the MFW bypass valve to SG-B opened to 5%, causing a small additional flow to SG-A (Fig. 5.1.9). Imbalances between FW flow and steam generation in SG-B caused its water level to drop to the low-low level set point 3 min. into the overfill (Fig. 5.1.10), at which time auxiliary feedwater was initiated. A minute later, as previously scheduled at Calvert Cliffs-1, the MFW isolation valves to both generators closed and overfill was effectively terminated (Fig. 5.1.9). No water was injected into the steam line. Minimum average core coolant temperature was 530°F (Fig. 5.1.11). Minimum primary pressure was 1750 psig (Fig. 5.1.12). Minimum pressurizer level was 3 ft (Fig. 5.1.13).

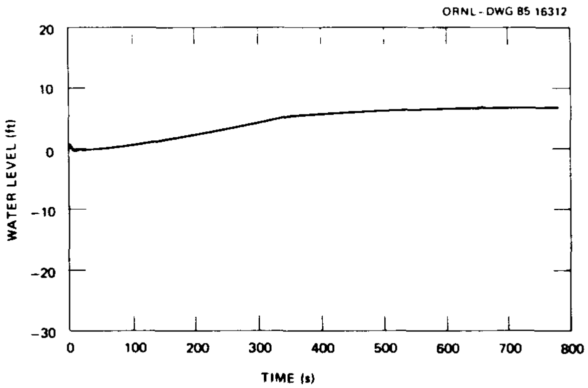

Fig. 5.1.1. SG-A water level with SG-A measured water level reading failed 10 in. below set point.

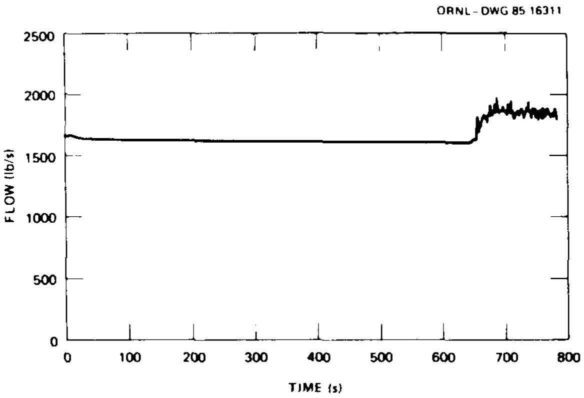

Fig. 5.1.2. SG-A steam flow with SG-A measured water level reading failed 10 in. below set point.

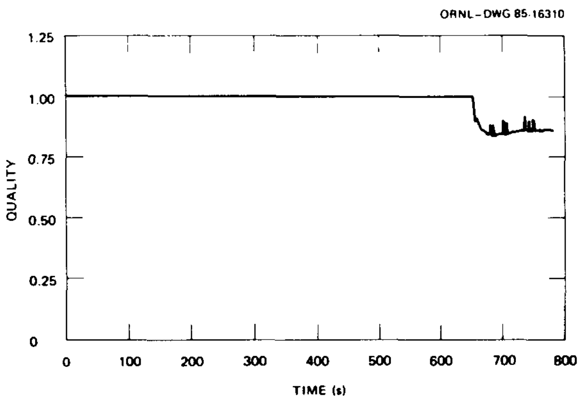

Fig. 5.1.3. SG-A outlet quality with SG-A measured water level reading failed 10 in. below set point.

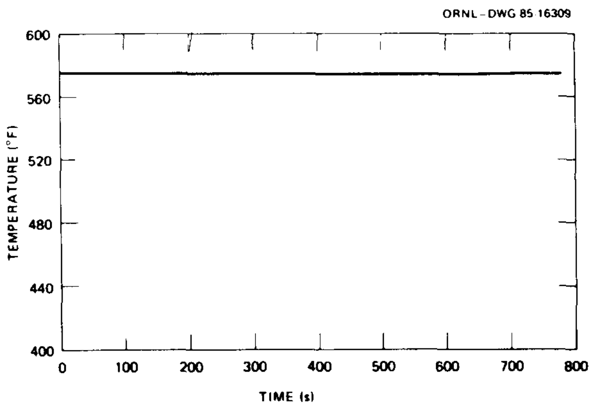

Fig. 5.1.4. Average core coolant temperature with SG-A measured water level reading failed 10 in. below set point.

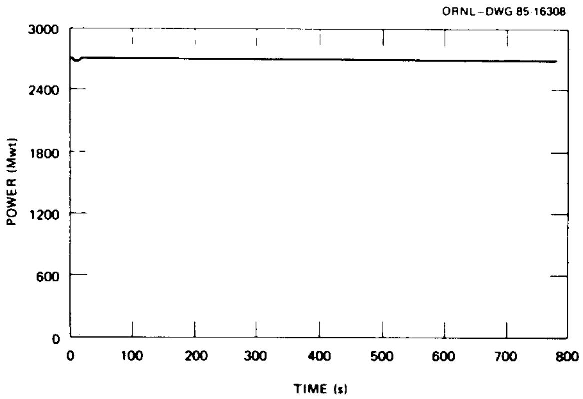

Fig. 5.1.5. Reactor power with SG-A measured water level reading failed 10 in. below set point.

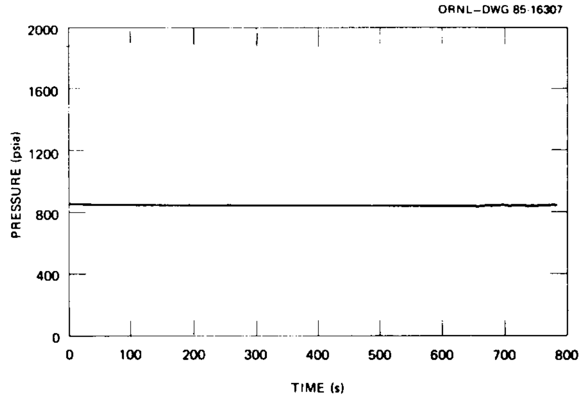

Fig. 5.1.6. Steam line A pressure with SG-A measured water level reading failed 10 in. below set point.

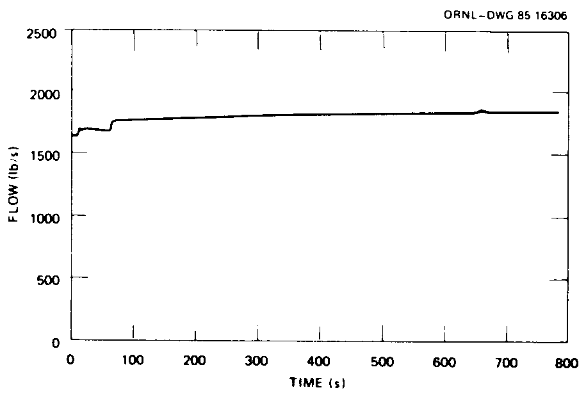

Fig. 5.1.7. SG-A FW flow with SG-A measured water level reading failed 10 in. below set point.

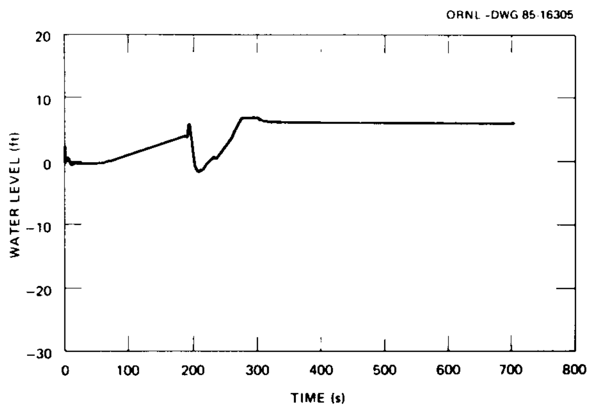

Fig. 5.1.8. SG-A water level with SG-A MFW valve failed full open in 1.5 s.

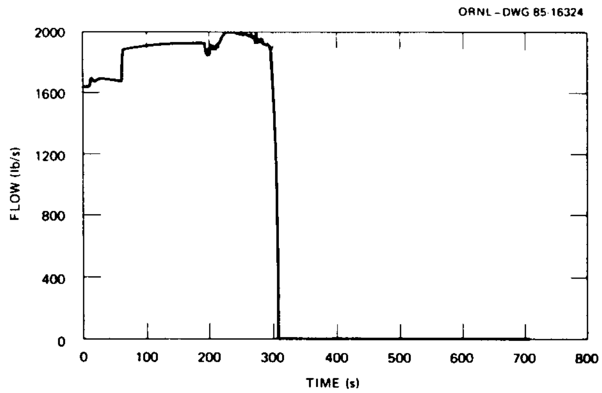

Fig. 5.1.9. SG-A FW flow with SG-A MFW valve failed full open in 1.5 s.

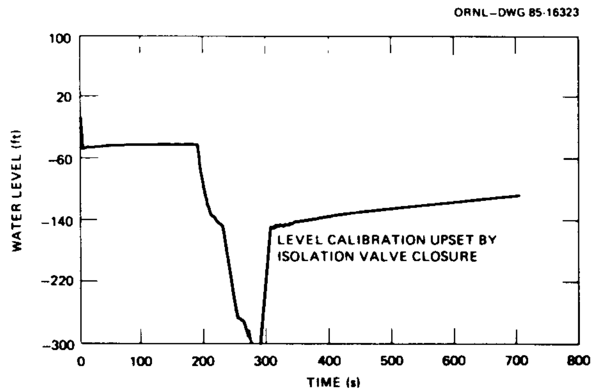

Fig. 5.1.10. SG-B wide-range water level with SG-A MFW valve failed full open in 1.5 s.

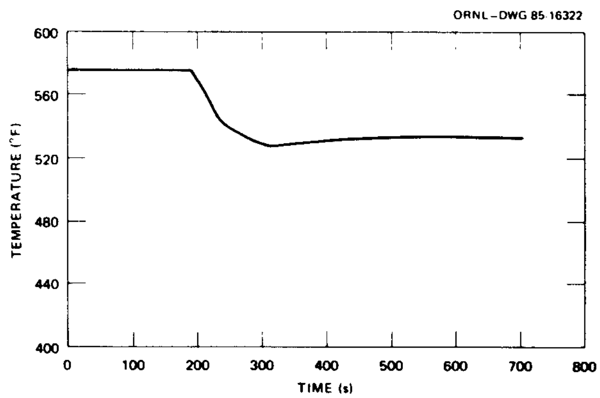

Fig. 5.1.11. Average core coolant temperature with SG-A MFW valve failed full open in 1.5 s.

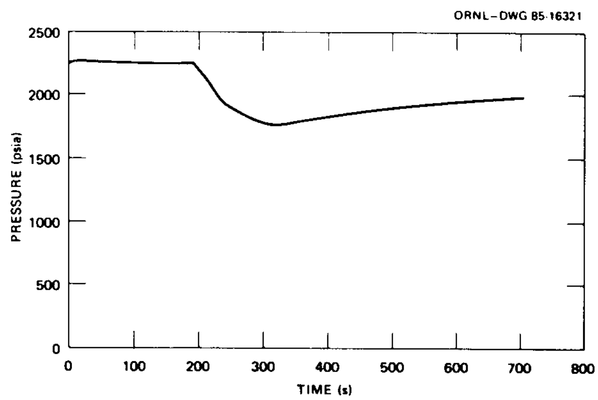

Fig. 5.1.12. Pressurizer pressure (psia) with SG-A MFW valve failed full open in 1.5 s.

The fourth overfeed case postulated that the MFW regulating valve failed full open and that the associated MFW isolation valve failed to close. As in the previous case, the reactor tripped on high SG level. The generator filled completely in 4.5 min. Because the reference pressure tap is several feet below the top of the SG, the level measurement saturated before the generator was full (Fig. 5.1.14). The abrupt drop in SG outlet quality (Fig. 5.1.15) indicated when the generator was actually full. Shortly thereafter, water was injected into the steam line (Fig. 5.1.16). Modest overcooling as a result of the overfill is apparent in the drop in core temperature, pressure, and pressurizer level (Figs. 5.1.17 - 5.1.19), although most of the variation is the nominal result of reactor trip.

In the fifth overfeed case, the MFW valve to SG-A was postulated to fail in place when the reactor and turbine tripped. Principal results were similar to the third case in which the valve failed full open without failure of the isolation valve. Steam generator A filled to 45 in. on the narrow-range scale in 95 s. (Readings immediately after reactor/turbine trip appeared distorted by disturbances in feedwater and steam flows and hence in pressure differentials.) Steam generator B water level dropped to the low-low (wide-range) level trip 45 s after onset of the transient. Main feedwater isolation valves closed 60 s later and terminated the overfill (Fig. 5.1.20). Temperature and other variations on the primary side were similar to those of the third case (Fig. 5.1.21).

When the previous case was repeated with MFW isolation valve A failed open, the feedwater pumps tripped in 1.7 min. on high pump outlet pressure and terminated the overfill at 45 in., before any water could be injected into the steam line.

The preceding two cases, which tripped MFW isolation valve B on low-low SG level, were repeated with the recent Calvert Cliffs-1 design change in the RETRAN model, in which the feedwater isolation valves no longer actuate on low-low level. In the rerun of failure of main feedwater valve A full open in 1.5 s, the results did not differ significantly from those with the closure of the main feedwater isolation valves on low-low level. Generator A filled in 4.5 min. after onset of the transient and 2.4 min. after the reactor tripped on high generator water level (Fig. 5.1.22). Minor cooling of the primary occurred (Figs. 5.1.23 through 5.1.25).

In the second of the reruns, MFW valve A failed in place on reactor trip. Steam generator A filled and began spilling pure water into the steamline in 3 min. after onset of the transient (Fig. 5.1.26), sooner than in the preceding case because in the former, the turbine and reactor did not trip until SG high level was reached. Minor cooling of the primary occurred (Figs. 5.1.27 through 5.1.29).

In the original and rerun cases of main feedwater regulating valve A failure, main feedwater valve B closed on reactor trip. MFW pump runback rate was such that pump outlet pressure increased significantly.

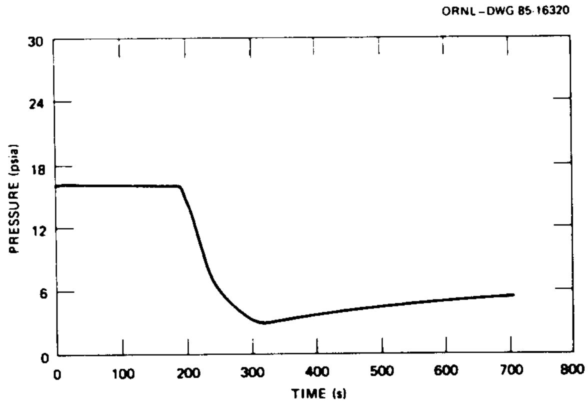

Fig. 5.1.13. Pressurizer water level with SG-A MFW valve failed full open in 1.5 s.

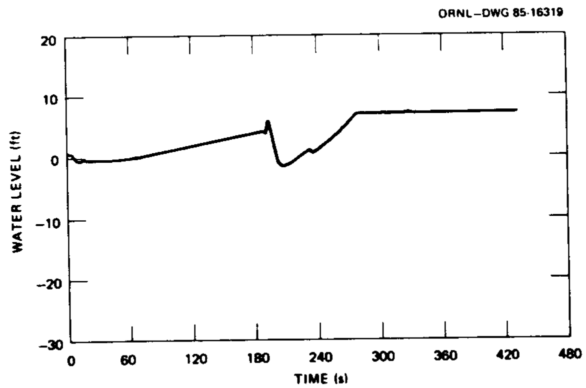

Fig. 5.1.14. SG-A water level with SG-A MFW failed open in 1.5 s; MFW isolation valve failed open.

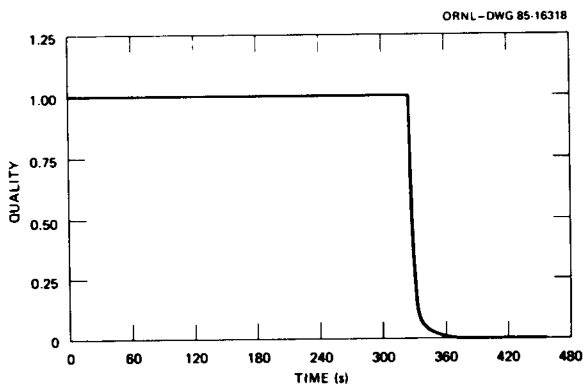

Fig. 5.1.15. SG-A outlet steam quality with SG-A MFW valve failed open in 1.5 s and MFW isolation valve failed open.

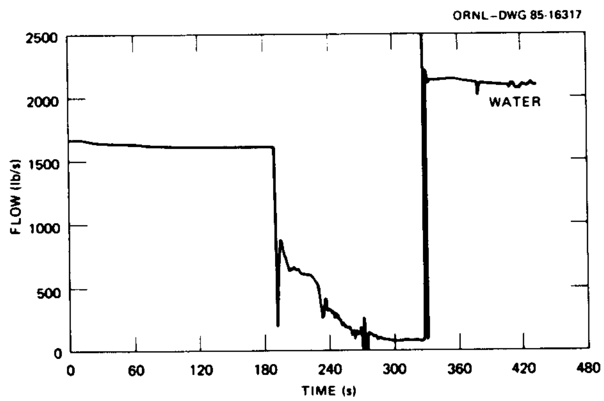

Fig. 5.1.16. SG-A exit steam flow with SG-A MFW valve failed open in 1.5 s and MFW isolation valve failed open.

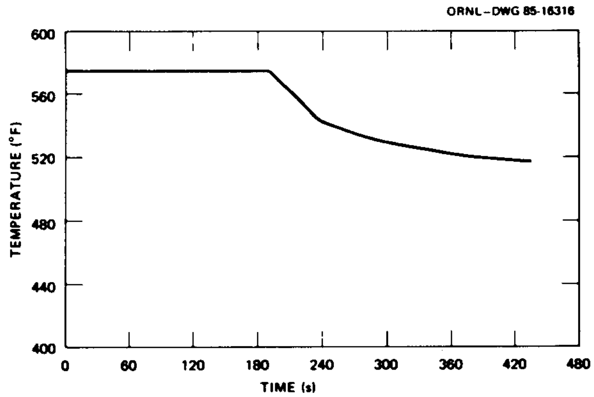

Fig. 5.1.17. Average core coolant temperature with SG-A MFW valve failed open in 1.5 s and MFW isolation valve failed open.

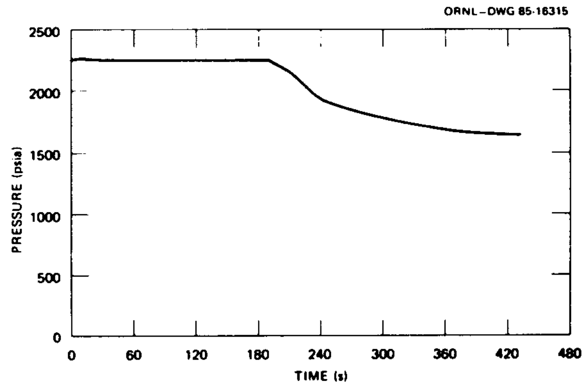

Fig. 5.1.18. Pressurizer pressure with SG-A MFW valve failed open in 1.5 s and MFW isolation valve failed open.

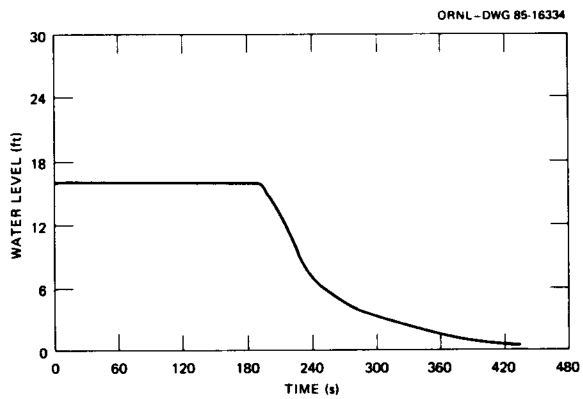

Fig. 5.1.19. Pressurizer water level with SG-A MFW valve failed open in 1.5 s and MFW isolation valve failed open.

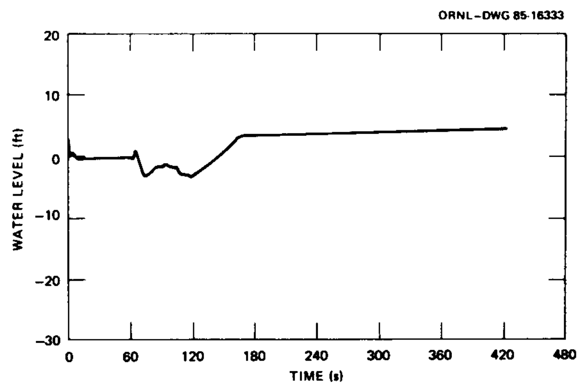

Fig. 5.1.20. SG-A water level with SG-A MFW valve frozen in place on reactor/turbine trip.

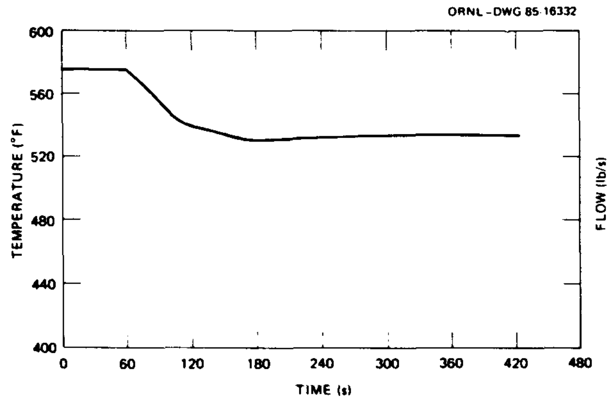

Fig. 5.1.21. Average core coolant temperature with SG-A MFW valve frozen in place on reactor/turbine trip.

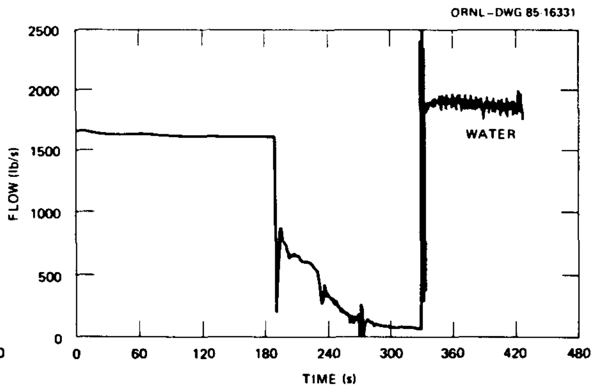

Fig. 5.1.22. SG-A exit steam flow with SG-A MFW valve failed full open in 1.5 s (run repeated with revised operation of MFIV).

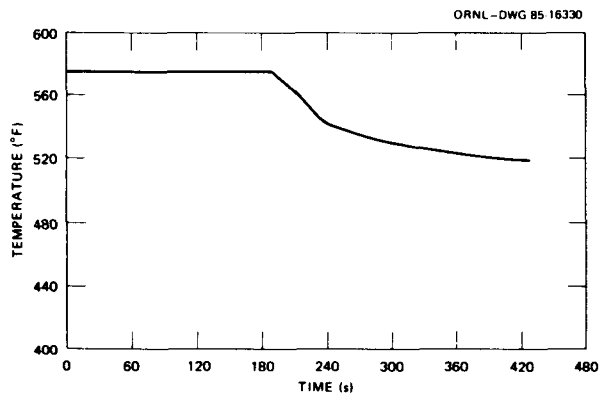

Fig. 5.1.23. Average core coolant temperature with SG-A MFW valve failed full open in 1.5 s (run repeated with revised operation of MFIV).

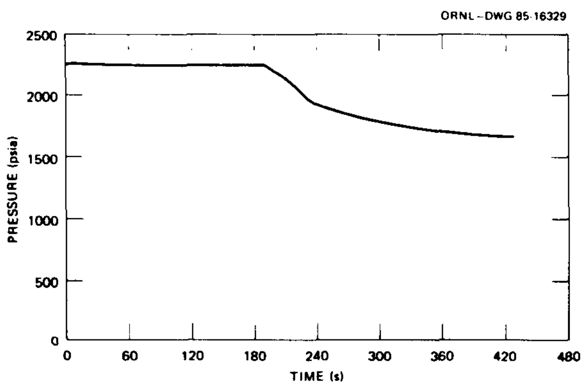

Fig. 5.1.24. Pressurizer pressure with SG-A MFW valve failed full open in 1.5 s (run repeated with revised operation of MFIV).

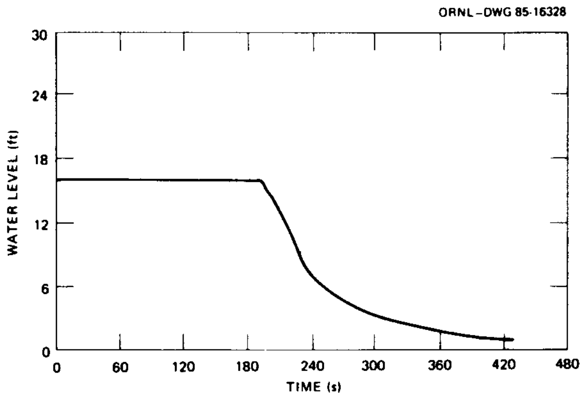

Fig. 5.1.25. Pressurizer water level with SG-A MFW valve failed full open in 1.5 s (run repeated with revised operation of MFIV).

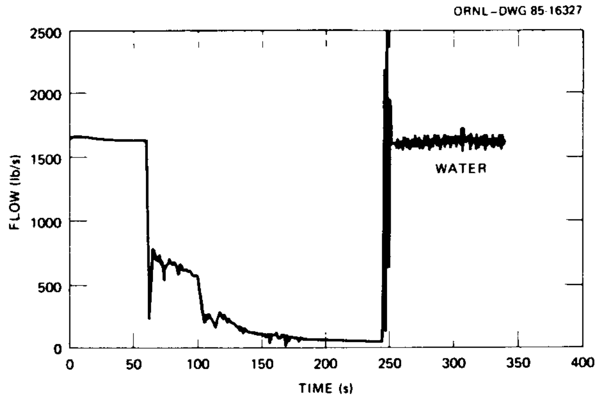

Fig. 5.1.26. SG-A exit steam flow with SG-A MFW valve failed in place on reactor trip (run repeated with revised operation of MFIV).

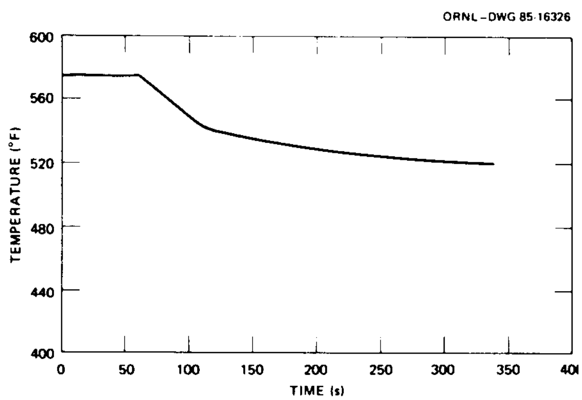

Fig. 5.1.27. Average core coolant temperature with SG-A MFW valve failed in place on reactor trip (run repeated with revised operation of MFIV).

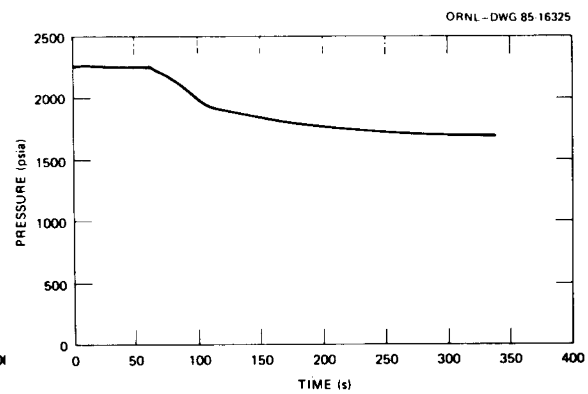

Fig. 5.1.28. Pressurizer pressure with SG-A MFW valve failed in place on reactor trip (run repeated with revised operation of MFIV).

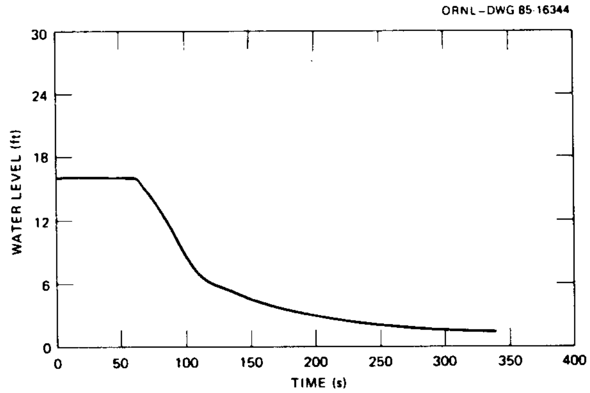

Fig. 5.1.29. Pressurizer water level with SG-A MFW valve failed in place on reactor trip (run repeated with revised operation of MFIV).

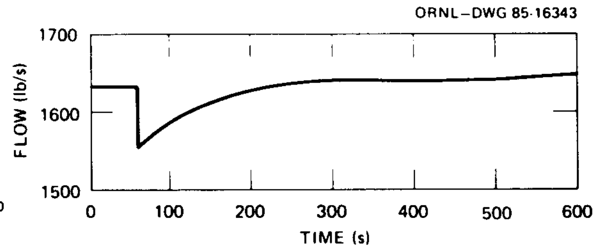

Fig. 5.2.1. SG-A FW flow with SG-A steam flow reading failed low at 1110 lb/s.

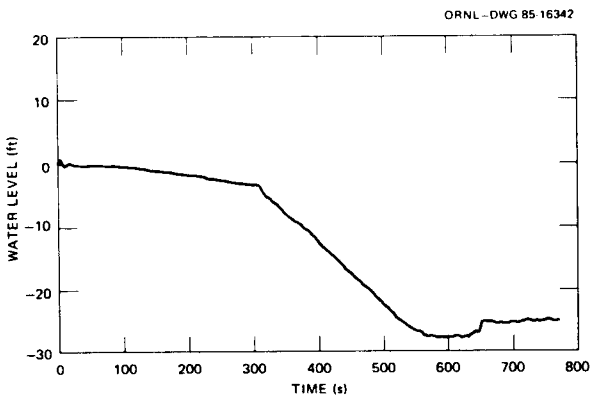

Fig. 5.2.2. SG-A measured water level with SG-A measured level failed 10 in. above set point and low and low-low level trips failed.

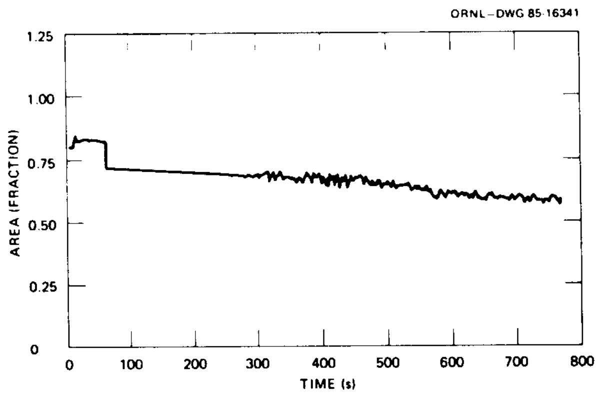

Fig. 5.2.3. MFW valve A area with SG-A measured level failed 10 in. above set point and low and low-low level trips failed.

When MFW regulating valve A failed full open, with or without isolation valve B closure, feedflow was always sufficient to hold MFW pump outlet pressure below the high-pressure trip. When MFW valve A failed in place, the high-pressure trip was exceeded if the B isolation valve further restricted flow by blocking the bypass valve. Feedwater recirculation was included in the calculations but was not sufficient in some cases to prevent the high-pressure trip of the MFW pumps.

5.2 DRYOUT TRANSIENTS

In the first dryout study the SG-A steam flow reading was failed low at 1110 lb/s. As in the overfeed event in which the steam flow reading failed high, the resulting water level error nullified the flow error after approximately 1 min. Feed flow decreased approximately 10% and then returned to near nominal (Fig. 5.2.1). Effects on the primary side were negligible.

In the second dryout case, the SG-A narrow-range (operating scale) water level reading was failed high at 10 in. above set point. Reactor trip on low level, also read on the narrow-range scale, was defeated. Generator inventory depleted until the low-low level set point, read on the wide-range scale, was reached in 3.7 min, at which time the AFW system was activated, and then the reactor tripped. Pressures and temperatures on the primary side experienced only minor variations during the partial dryout.

The third dryout study postulated the failures of the second case plus the following. Since the auxiliary feedwater (AFW) system is turned on when the low-low level limit is reached, this case assumed in addition that the low-low level reading failed 10 in. above set point. With this combination of failures, SG-A level depleted approximately 335 in. during the first 10 min. of the transient and then stabilized (Fig. 5.2.2), largely because of the low gain of the MFW regulating valve controller. The valve initially closed sharply from 82% open to 71% in response to the proportional part (Figs. 5.2.3, 5.2.4). The integral is small (0.1 repeat per min.), and subsequent closure was so slow that after 12 min. the opening decreased only to 60%. Pressurizer pressure stabilized at 2285 psia (Fig. 5.2.5), core average temperature at 578°F (Fig. 5.2.6), and power at 91% (Fig. 5.2.7). Simple extrapolation of the results suggests that further significant depletion of the generator will be long-term, requiring perhaps an hour.

The fourth dryout case postulated that the SG-A MFW valve failed closed in approximately 5 s (Fig. 5.2.8); valve leakage was assumed negligible. After another 22 s, SG-A water level decreased to the low level set point (Figs. 5.2.9, 5.2.10) and tripped the reactor (Fig. 5.2.11). Low-low level trip (wide-range scale) was reached 24 s later, and auxiliary feedwater was started (Fig. 5.2.8). During the following 2 min, system variables stabilized (Figs. 5.2.12 through 5.2.15). The

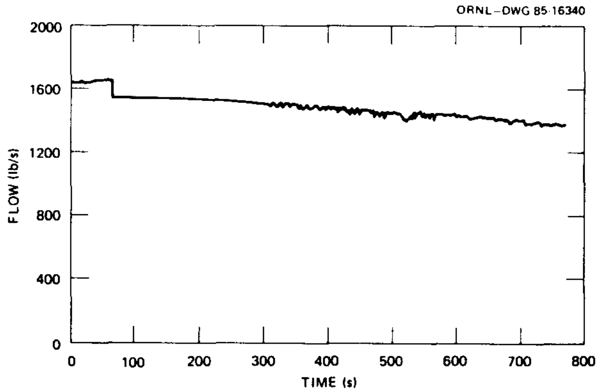

Fig. 5.2.4. SG-A FW flow with SG-A measured level failed 10 in. above set point and low and low-low level trips failed.

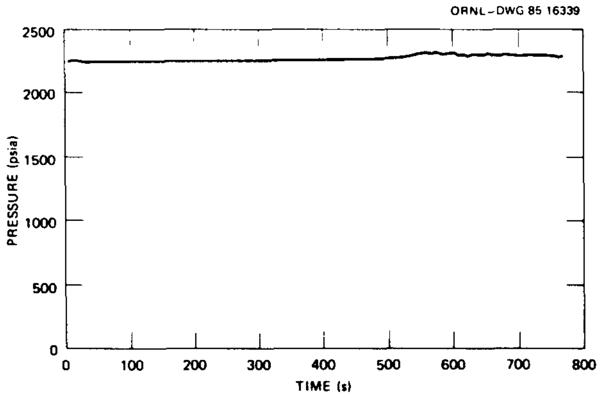

Fig. 5.2.5. Pressurizer pressure with SG-A measured level failed 10 in. above set point and low and low-low level trips failed.

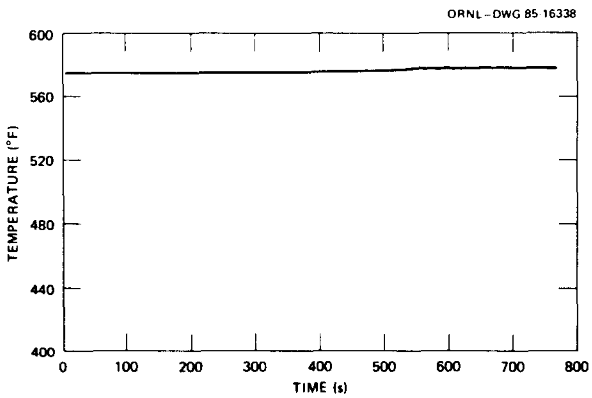

Fig. 5.2.6. Average core coolant temperature with SG-A measured level failed 10 in. above set point and low and low-low level trips failed.

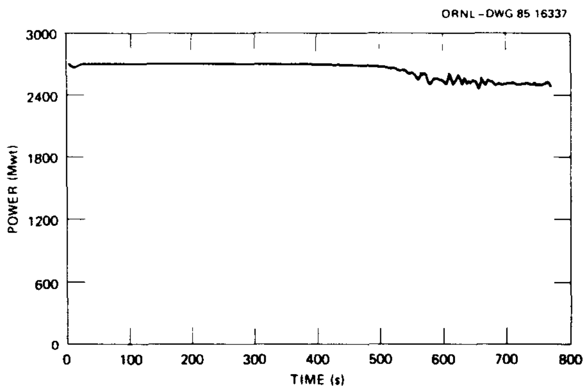

Fig. 5.2.7. Reactor power with SG-A measured level failed 10 in. above set point and low and low-low level trips failed.

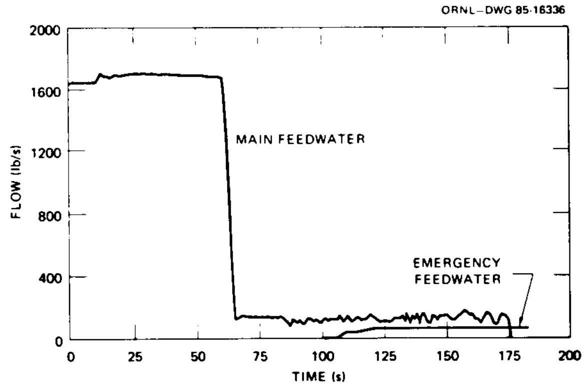

Fig. 5.2.8. SG-A FW flow with MFW valve A failed closed in 5 s.

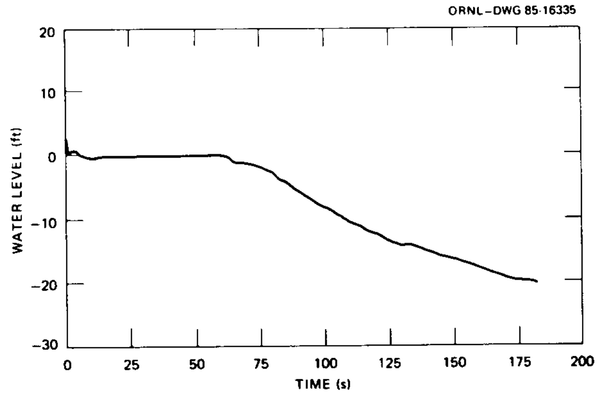

Fig. 5.2.9. SG-A water level (narrow range) with MFW valve A failed closed in 5 s.

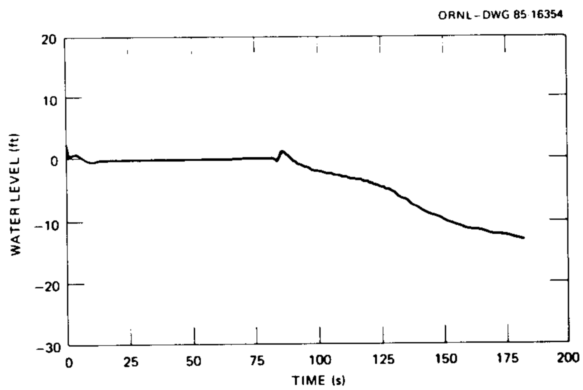

Fig. 5.2.10. SG-B water level (narrow range) with MFW valve A failed closed in 5 s.

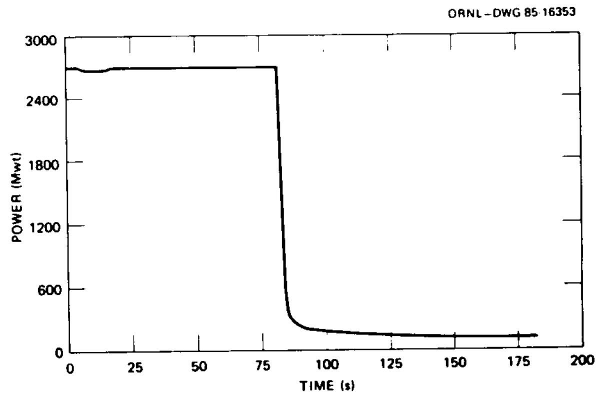

Fig. 5.2.11. Reactor power with MFW valve A failed closed in 5 s.

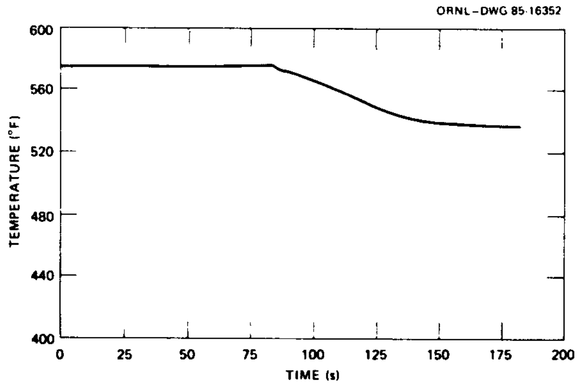

Fig. 5.2.12. Average core coolant temperature with MFW valve A failed closed in 5 s.

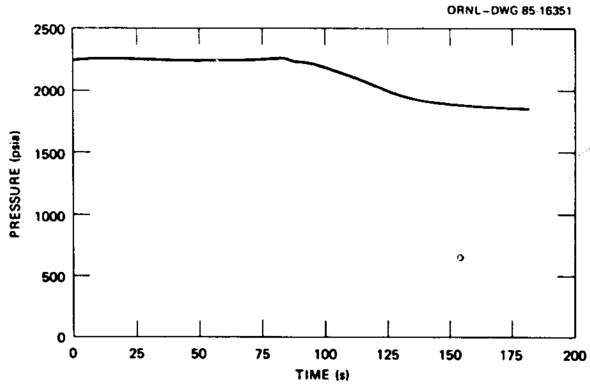

Fig. 5.2.13. Pressurizer pressure with MFW valve A failed closed in 5 s.

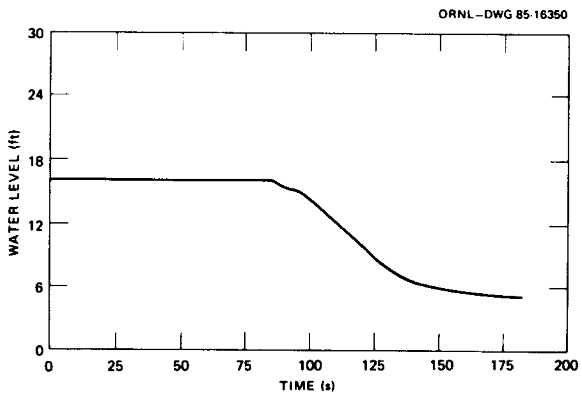

Fig. 5.2.14. Pressurizer water level with MFW valve A failed closed in 5 s.

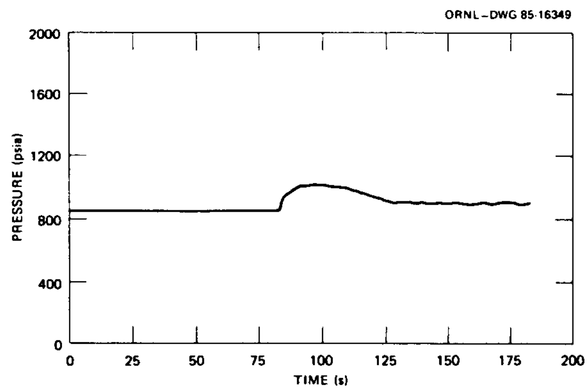

Fig. 5.2.15. SG-A steam pressure with MFW valve A failed closed in 5 s.

principal effect of the postulated MFW valve failure appears to be initially more rapid depletion of the inventory in SG-A. Following a reactor trip (which would normally close the MFW valves) and then an emergency (auxiliary) feedwater trip, the transient appeared to converge toward typical trip conditions.

5.3 PRIMARY-SIDE DEPRESSURIZATION TRANSIENTS

In the first depressurization study, both PORVs were postulated to fail open. This corresponds to a small break of 0.015 ft^2. In the first 1.5 min of the transient, the primary side depressurized to 1070 psia (Fig. 5.3.1). The reactor (Fig. 5.3.2) tripped at setpoint (see Appendix A.1.7) and the high-pressure safety injection system tripped on at the set point pressure of 1740 psia. Following the initial rapid depressurization, the pressurizer went solid (Fig. 5.3.3), and at 7 min loss of inventory became balanced by makeup/high-pressure injection. Primary pressure stabilized at approximately 700 psia, and a steam bubble formed in the header above the core. Partial voiding occurred in the collectors and in the hot legs. The saturated fluid was subcooled in the generator. Voiding of the core did not occur. At the end of 7 min the system appeared to have stabilized in this configuration (Figs. 5.3.4 and 5.3.5).

In the second system depressurization study, one PORV was postulated to fail open. The primary system depressurized less rapidly, as expected, but approximately 3 min into the transient, pressure decreased below the high-pressure safety injection system pump deadhead and injection began to counter the leak (Fig. 5.3.6). The pressurizer went solid in 5 min (Fig. 5.3.7), and the average reactor coolant temperature slowly dropped to 520°F (Fig. 5.3.8). Voiding of the upper head occurred (Fig. 5.3.9). During the 2 min before the pressurizer went solid there was voiding of a few percent in the hot leg of loop B and in the control rod shroud region above the core. When the pressurizer went solid and pressure leveled off with temperature still declining slowly, the hot-leg and shroud voids collapsed. The system appeared stable, and no voiding of the core occurred.

In the third depressurization case, a small break of 0.0015 ft^2 was introduced in the hot leg of loop A. This corresponded to a leak an order of magnitude smaller than the two-PORV failure. The leak was larger than the makeup system could compensate but sufficiently small that the pressure did not promptly drop to the high-pressure injection set point. Primary pressure (Fig. 5.3.10) and inventory (Fig. 5.3.11) declined gradually for 20.5 min until pressurizer low water level tripped the heaters. The rate of pressure decrease then approximately doubled. Temperature variations were minor (Fig. 5.3.12). After 30.5 min, the reactor tripped on low pressure setpoint (Fig. 5.3.13). Pressurizer water level was 2.2 ft. On reactor trip, the water level dropped to 4 in. Primary pressure rapidly fell below the 1275 psig high-pressure safety injection system deadhead, and net loss of inventory was terminated. Just prior to the reactor trip (when the

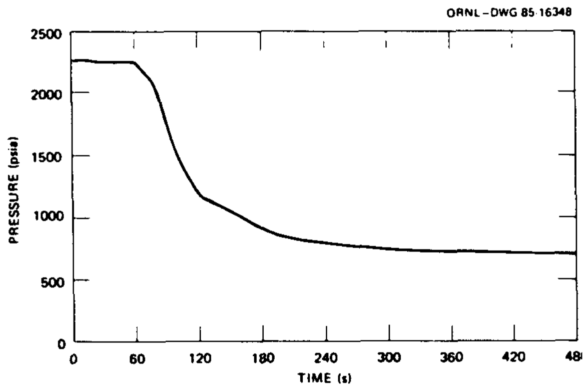

Fig. 5.3.1. Pressurizer pressure with both PORVs failed open.

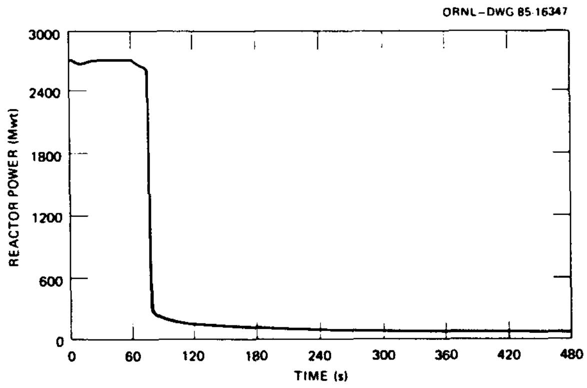

Fig. 5.3.2. Reactor power with both PORVs failed open.

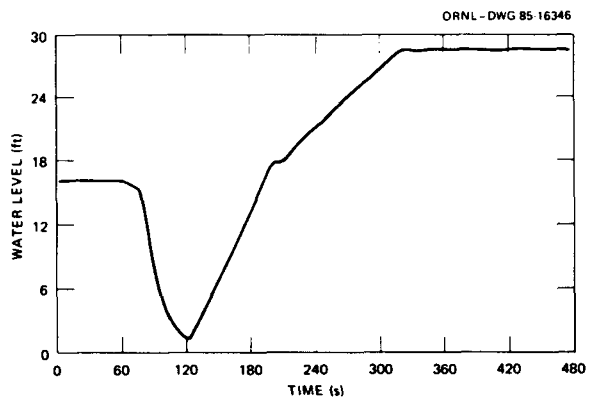

Fig. 5.3.3. Pressurizer water level with both PORVs failed open.

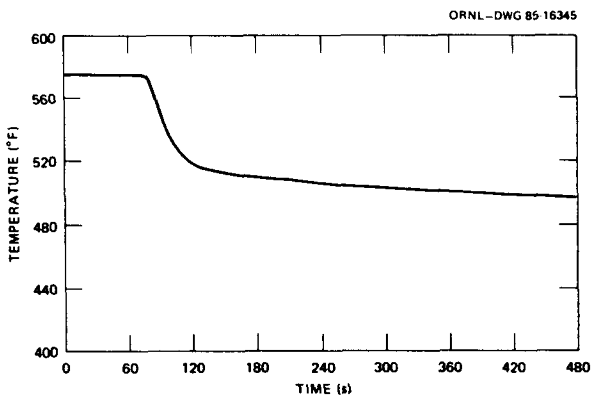

Fig. 5.3.4. Average core coolant temperature with both PORVs failed open.

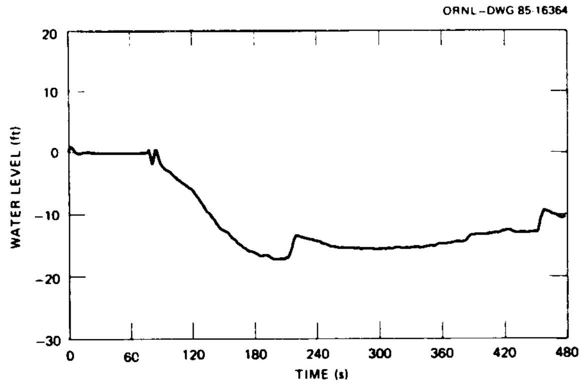

Fig. 5.3.5. SG-A water level with both PORVs failed open.

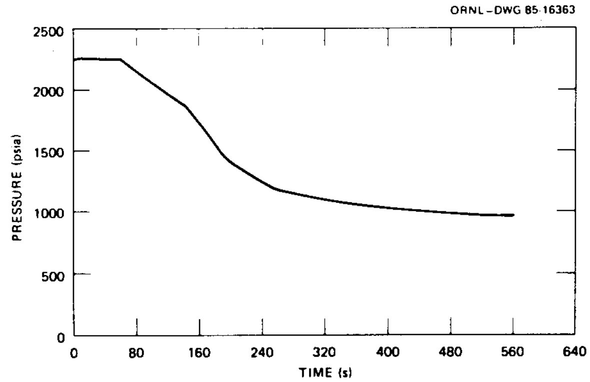

Fig. 5.3.6. Pressurizer pressure with one PORV failed open.

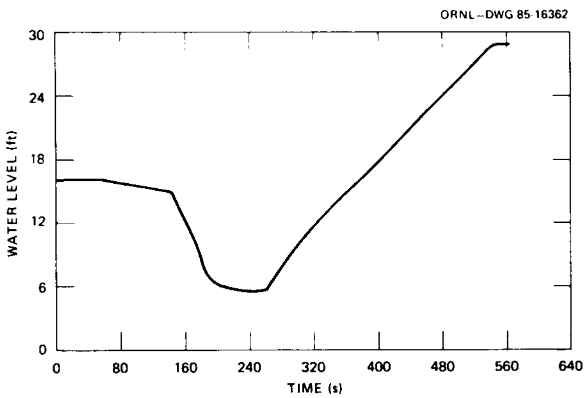

Fig. 5.3.7. Pressurizer water level with one PORV failed open.

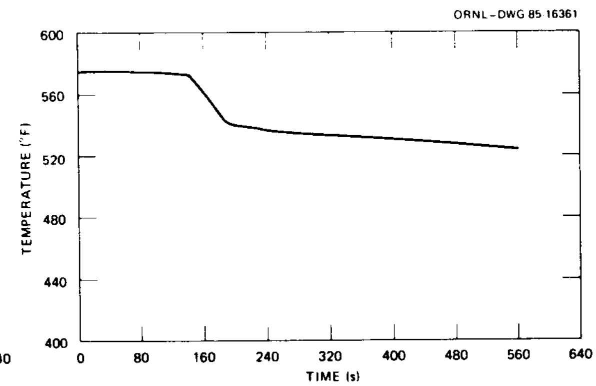

Fig. 5.3.8. Average core coolant temperature with one PORV failed open.

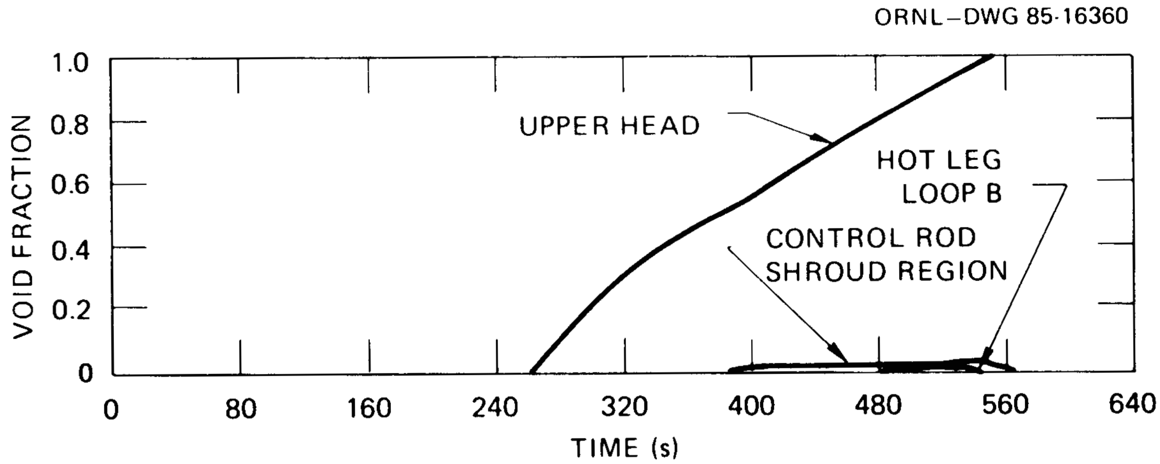

Fig. 5.3.9. Steam volume fraction with one PORV failed open.

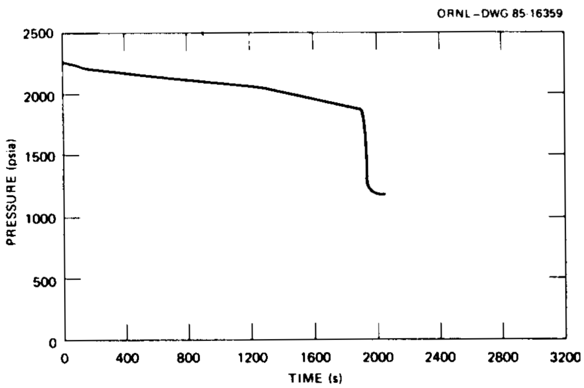

Fig. 5.3.10. Pressurizer pressure with small break (0.0015 ft²) in loop A hot leg.

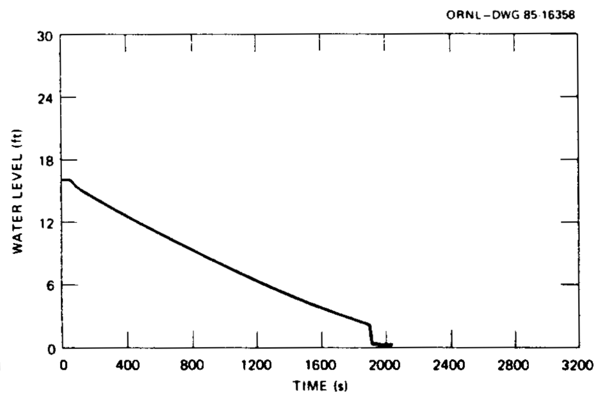

Fig. 5.3.11. Pressurizer water level with small break (0.0015 ft²) in loop A hot leg.

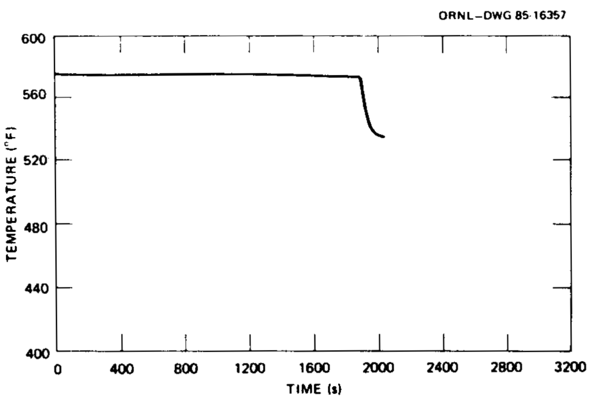

Fig. 5.3.12. Average core coolant temperature with small break (0.0015 ft²) in loop A hot leg.

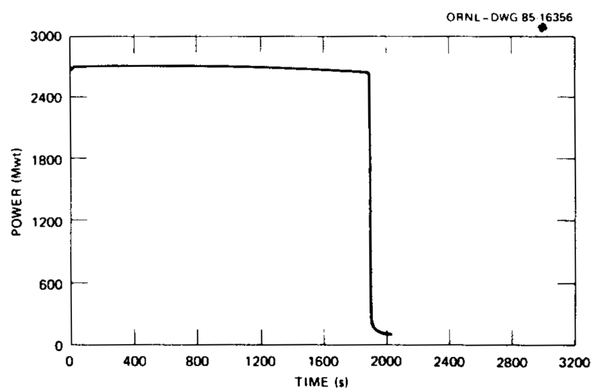

Fig. 5.3.13. Reactor power with small break (0.0015 ft²) in loop A hot leg.

pressure was 1882 psia), the leak, makeup, and high-pressure injection rates were 23.5 lb/s, 13.4 lb/s, and 0 respectively. Shortly after the reactor trip (when the pressure was 1184 psia), the respective rates were 16.1 lb/s, 18.2 lb/s, and 50.4 lb/s. The sharp depressurization on reactor trip caused a maximum voiding of 25% in the upper head of the reactor vessel (Fig. 5.3.14). No other voiding in the vessel occurred.

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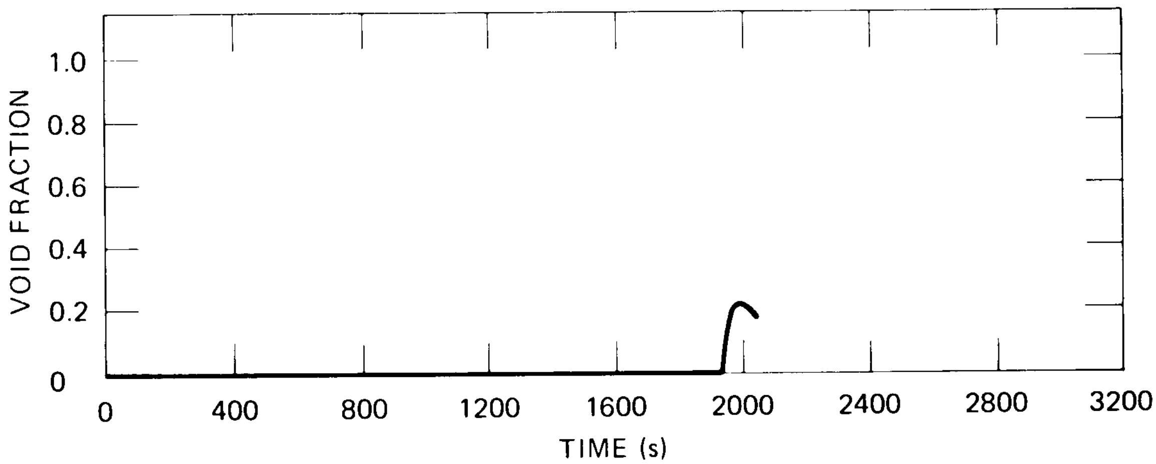

Fig. 5.3.14. Voiding in vessel upper head with small break ($0.0015\ ft^2$) in loop A hot leg.

6. CONCLUSIONS

The overfill studies indicate that the postulated control failures will result in only minor pressure and temperature variations on the primary side.

For failure high of the steam flow reading, the resulting error in generator water level appears to counteract the false flow signal and largely nullify the effects after small variations in feedwater flow.

When the generator water level reading fails low and induces overfill in combination with high-level trip failure, the principal consequence appears to be the sizable quantity of water injected into the steam line. Effects on the primary side were small. While the calculation predicts injection of water into the steam line, it does not predict the extent (if any) to which phase separation occurs and water accumulates and loads the pipe.

With the previous Calvert Cliffs-1 design (MFW isolation valve closes on low-low SG water level), failure of MFW regulating valve to SG-A full open or failure in place on reactor trip filled SG-A to the 45- to 72-in. range, at which point the overfill was terminated when low-low level in SG-B tripped the MFW isolation valves. No water was injected into the steam line. Primary side variations were largely the consequence of reactor trip rather than the modest overfill. In order to completely fill the generator, it was necessary to further postulate failure of MFW isolation valve SG-A in combination with MFW regulating valve SG-A failing full open. Then SG-A filled in 4.5 min, and water was pumped into the steam line. Modest cooling of the primary occurred. When the MFW valve failed in place and the MFW isolation valve failed open, the MFW pumps tripped on high outlet pressure and terminated the overfill without water injection into the steam line.

With the recent design change at Calvert Cliffs-1 (isolation valves not actuated on low-low generator level), failure of SG-A main feedwater regulating valve either full open or in place on reactor trip resulted in filling SG-A and spilling water into the steam line in 3 to 4.5 min. Cooling of the primary was minor.

Failure high of the SG-A steam flow reading did not lead to dryout, because of the compensating error signal in the level measurement. When only the operating-level reading and low-level trip were failed, dryout was truncated by actuation of the AFW system at the low-low level set point on the wide-range scale. When both the wide- and narrow-range readings were failed, generator inventory depleted further but dryout did not occur during the first 12 min because of the small gain of the MFW regulating valve controller. The system stabilized, and indications were that total dryout would have a significantly more long-range effect under the postulated failures. When mechanical or other failures caused the MFW valve to SG-A to close in a few seconds, reactor trip on low level and AFW trip on low-low level occurred within 1 min, truncated the dryout, and established typical trip conditions.

Failure of both PORVs in an open position depressurized the primary side to ~700 psia, at which point the high-pressure safety injection equilibrated with the leak. Voiding occurred above but not in the core. Failure of one PORV open initiated the high-pressure safety injection ~3 min into the transient. Primary pressure bottomed out near 950 psig. No voiding of the core occurred. The transient was essentially a milder version of the two-PORV-failure case. A leak an order of magnitude smaller in the hot leg, larger than the makeup could compensate but small enough to produce slow depressurization, caused the pressurizer water level to drop to 2.2 ft before the reactor tripped on low pressure after 30 min. The rapid drop in pressure on reactor trip initiated the high-pressure safety injection system and terminated net inventory loss. Minimum pressurizer water level was ~4 in. Some voiding in the upper head of the reactor vessel occurred. These depressurization calculations, simulating SB-LOCAs in the range 0.0015 to 0.015 ft^2, do not evidence a critical size break in which primary inventory would deplete to the extent of core uncovery before actuating the high-pressure safety injection system.

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2. S. J. Ball et al., "An Assessment of the Safety Implications of Control at the Calvert-Cliffs-1 Nuclear Plant, NUREG/CR-4265, ORNL/TM-9640, Oak Ridge National Laboratory, 1985.

3. S. M. Mirsky and T. L. Cook, "RETRAN Analysis of a Calvert Cliffs Multiple Secondary Side Malfunction Event," Baltimore Gas and Electric Company, ANS Third International Conference on Reactor Thermal Hydraulics, 1985.

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Finally, we wish to thank S. J. Ball, R. S. Stone, and L. C. Oakes of the ORNL Instrumentation and Controls Division for their steadfast support.

APPENDIX A

MODELING DETAILS

LIST OF APPENDIX A FIGURES

APPENDIX A

MODELING DETAILS

A.1 PRIMARY SYSTEM

The RETRAN model of the Calvert Cliffs-1 primary system model includes the following components:

- reactor vessel
- reactor coolant pumps
- hot legs and cold legs
- pressurizer
- charging pumps and letdown valves
- high-pressure safety injection system
- primary side of the steam generators

A schematic diagram of the primary system is displayed in Fig. A.1.1. The modeling of the different components of the primary system is displayed in the RETRAN nodal diagram in Fig. A.1.2.

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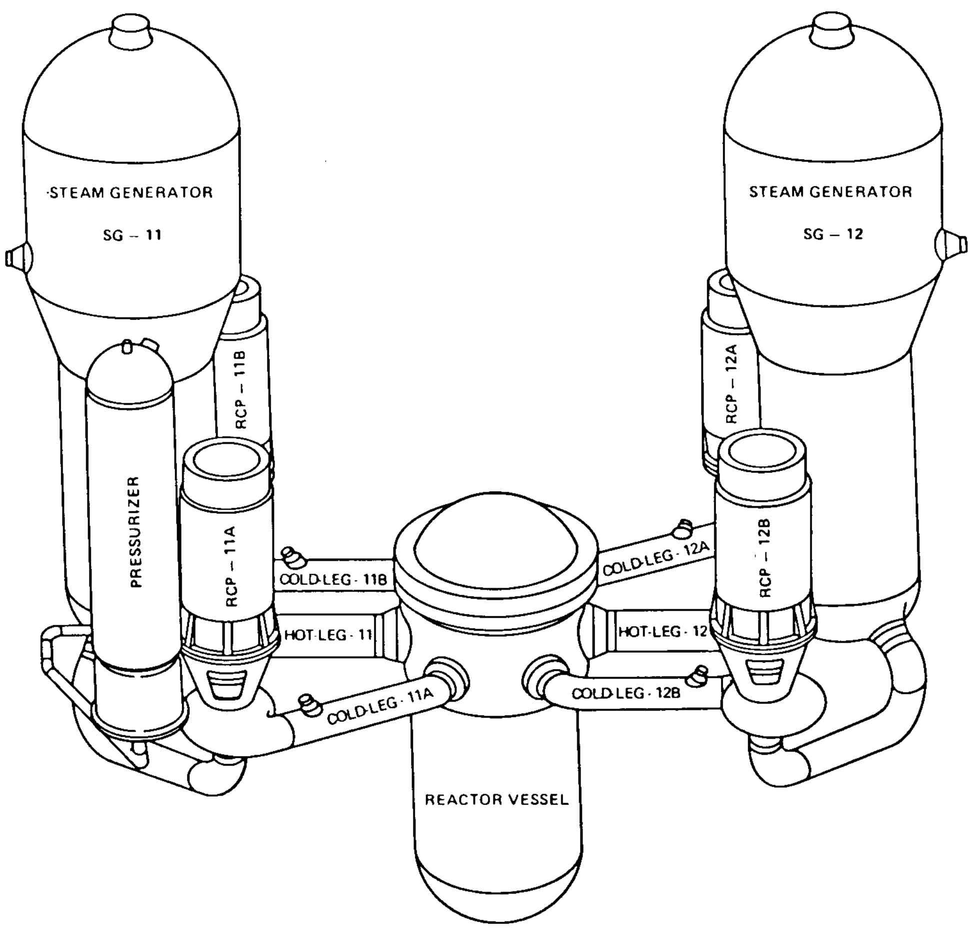

Fig. A.1.1. Schematic diagram of the Calvert Cliffs-1 primary system.

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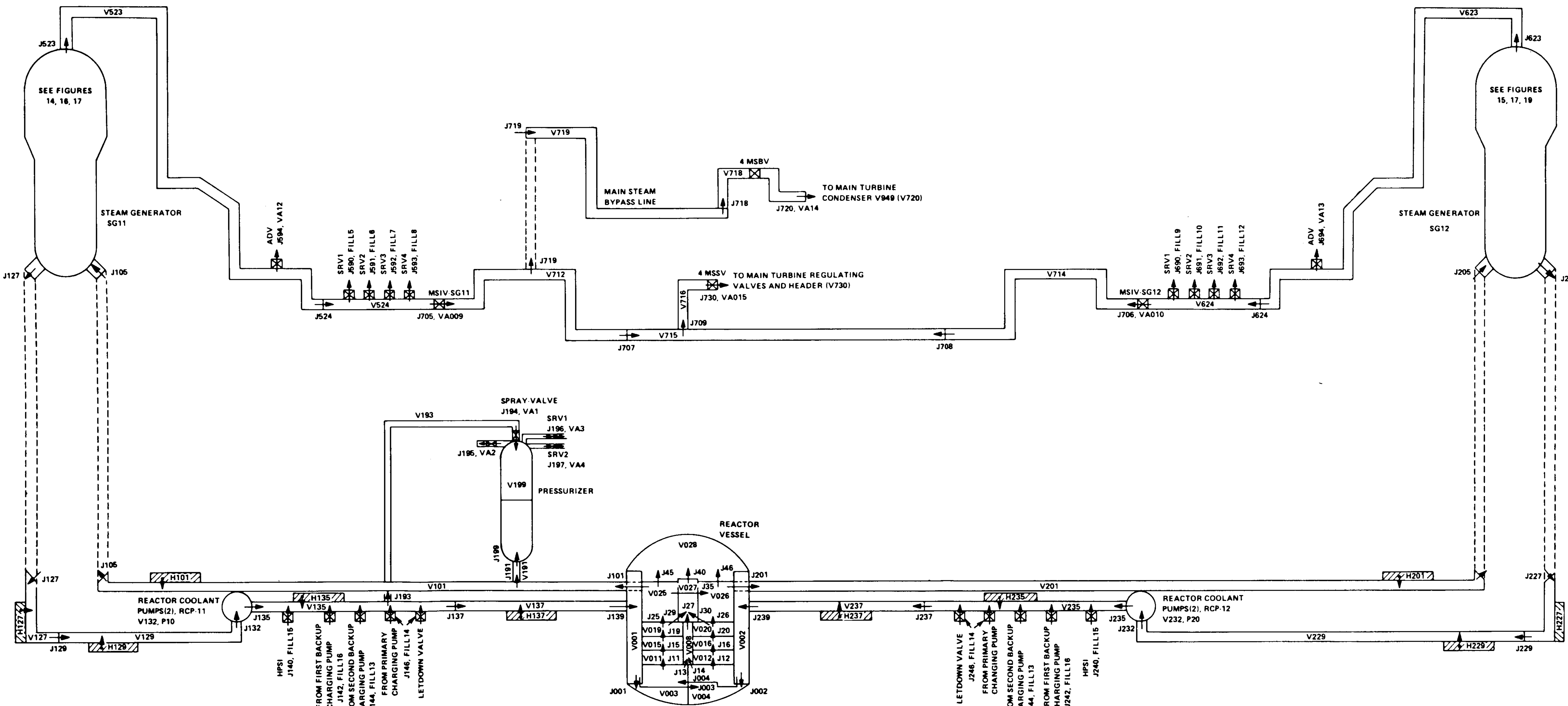

Fig. A.1.2. RETRAN nodal diagram of the primary system.

A.1.1 REACTOR VESSEL

Sections inside the reactor vessel were modeled as follows (see Fig. A.1.3):

1. The downcomer was subdivided into two symmetrical volumes (RETRAN volumes nodes V001 and V002).

2. The active reactor core was subdivided into two symmetrical core regions and a core-bypass region, which included the control rod guide tubes. Each reactor core region was subdivided into the following nodes :

   a. For core-volume-set 1, three RETRAN volume nodes (V11, V15 and V19) for core-region 1, and three RETRAN volume nodes (V12, V16 and V20) for core-region 2, each 3.80 ft high.

   b. For core-volume-set 2, three RETRAN volume nodes (V11, V13, V15, V17 and V19) for core-region 1, and three RETRAN volume nodes (V12, V14, V16, V18 and V20) for core region 2, each 2.28 ft high.

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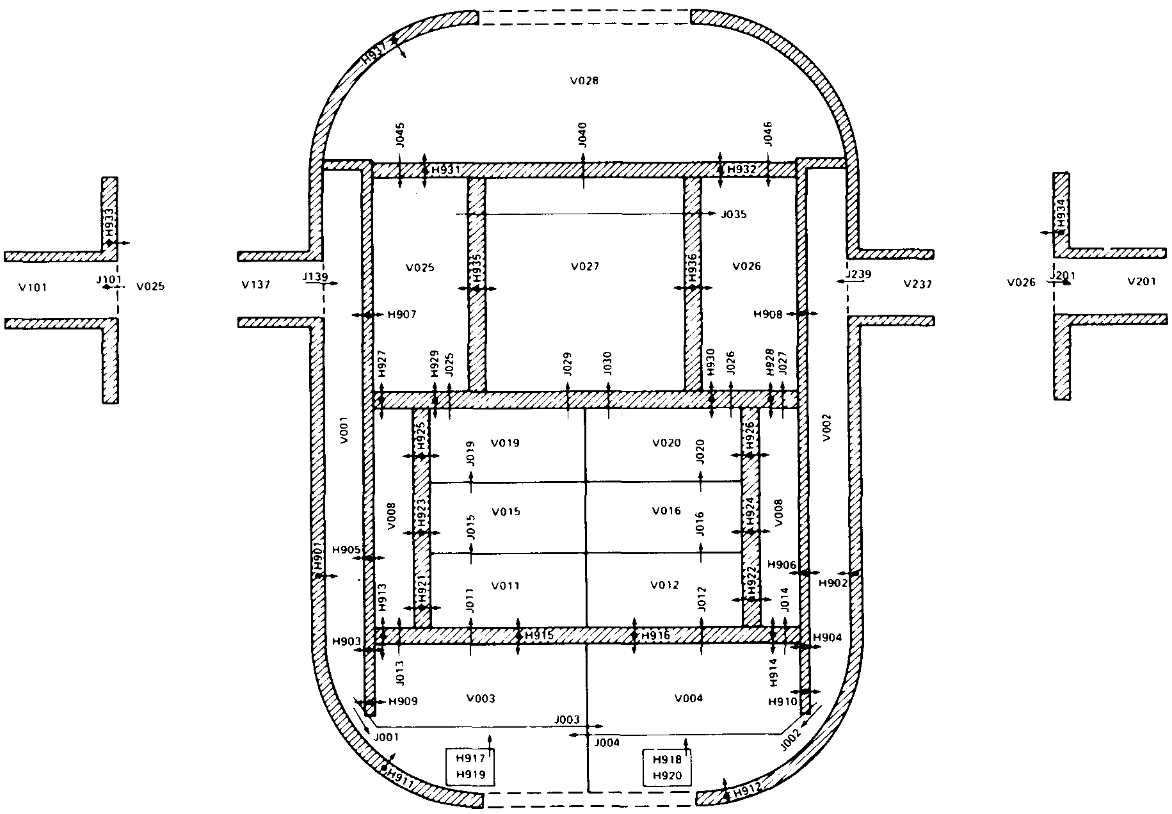

Fig. A.1.3. RETRAN nodal diagram of the reactor pressure vessel, core, and internals.

c. The core-bypass region was modeled with one RETRAN volume node (V008).

3. The lower plenum was subdivided into two symmetrical regions (RETRAN volume nodes V003 and V004). The flow through volume node V003 was channeled as follows (at 100% full-power steady-state):

    18688 lbm/s (48.4%) to core region 1
    618 lbm/s (1.6%) to core-bypass region

    and the flow through RETRAN volume node V004 was as follows:

    18688 lbm/s (48.4%) to core region 2
    618 lbm/s (1.6%) to core-bypass region.

    Since interloop mixing was assumed in the lower plenum, the flow from RETRAN volume node V001 (downcomer) was channeled into the lower plenum as follows:

    junction J001 (V001 to V003): 14093 lbm/s or 36.5%
    junction J003 (V001 to V004): 5213 lbm/s or 13.5%

    and the flow from volume node V002 (downcomer) :

    junction J002 (V002 to V004): 14093 lbm/s or 36.5%
    junction J004 (V002 to V003): 5213 lbm/s or 13.5%

4. The upper plenum was subdivided into two symmetrical RETRAN volume nodes, V025 and V026, fed by the flow from core regions 1 and 2. No interloop mixing between the upper plenum regions was assumed at 100% full power. However, junctions were installed in the model in order to allow intermixing during transients.

5. The flow from the core-bypass region was channeled into the upper plenum (435 lbm/s to volume node V025, 435 lbm/s to volume node V026) and 364 lbm/s to the region in which the control element assemblies (CEAs) are located. The flow from the CEA region was channeled into the upper head region (volume node V028), and the flow through the heating core region was channeled into the upper plenum regions (volume nodes V025 and V026).

6. The flow through the upper plenum regions is channeled into the hot legs (volume nodes V101 and V201), 19305 lbm/s into hot leg 11 and 19305 lbm/s into hot leg 12.

A.1.2 REACTOR CORE

The reactor core contains 217 fuel assemblies and 85 control element assemblies (CEAs). Reactor power is controlled primarily by moving the control element assemblies and by removing or adding soluble boron to the primary loop water.

1. The CEAs are subdivided into eight groups or banks, five regulating banks and three safety shutdown banks. Note that all CEAs of a particular bank are moved in unison. At power, the different regulating CEA banks are moved relative to each other in a preset way; the maximum allowable insertion (or bite) depends on the power level, fuel cycle, and time within a fuel cycle.

   The prescribed movement of the different banks is designed to attain power distributions within acceptable limits set by nuclear heat flux factors and departure nucleate boiling ratio (DNBRs).

   At power, the five regulating CEA banks in the RETRAN model move at a rate of 35 in./min. At shutdown upon a reactor scram command, the five regulating and three shutdown CEA banks are inserted into the core at a speed of 50 in./s.

   A typical power-dependent CEA insertion scheme is shown in Fig. A.1.4. This figure shows the maximum insertion or bite. It

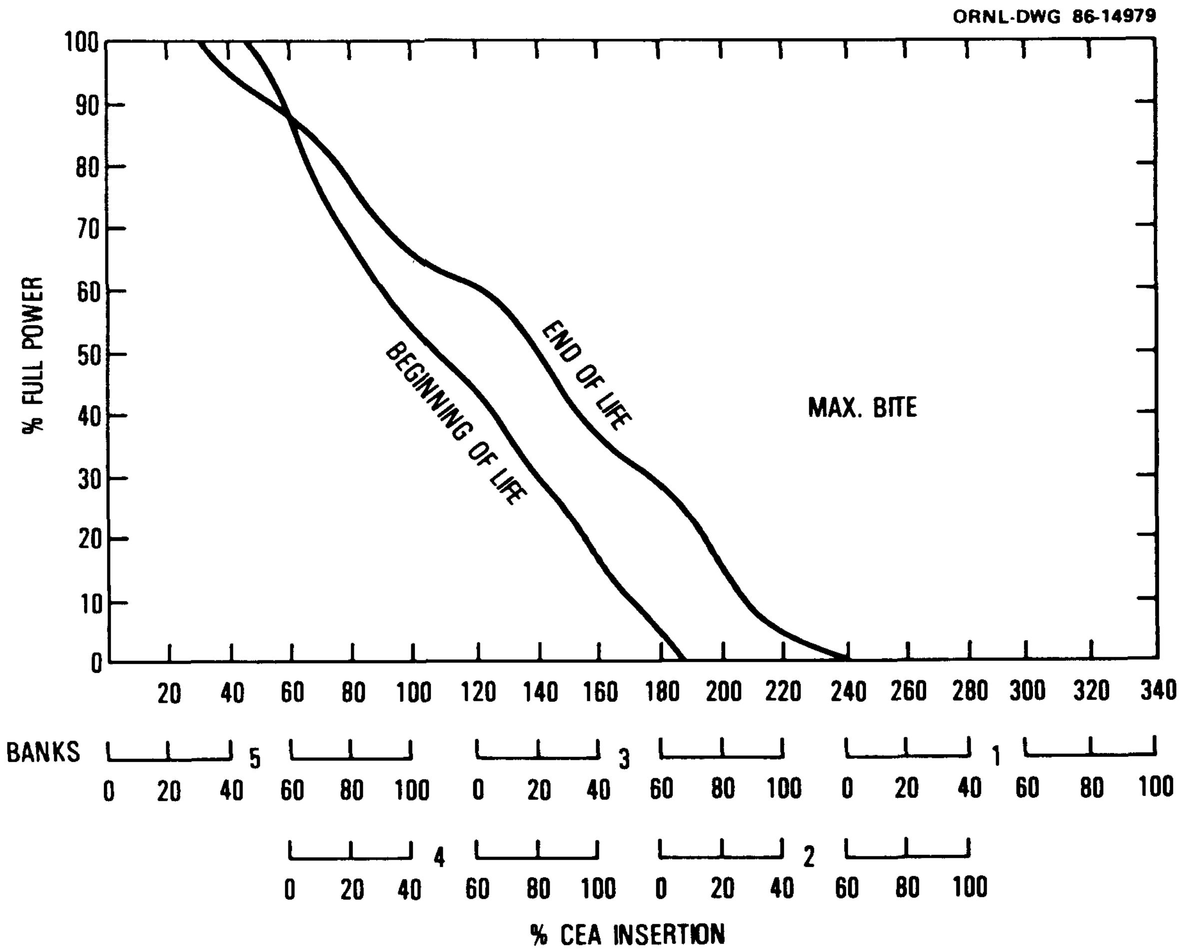

Fig. A.1.4. Typical power-dependent CEA insertion limits.

also shows that only when CEA regulating bank 5 has been inserted 60% into the core, is bank 4 allowed to move in, and only when bank 4 has been inserted 60% into the core is bank 3 allowed to move in. Note that upon a reactor scram signal, all regulating control element assemblies are inserted at the maximum insertion speed.

In the RETRAN model, reactor power level can be controlled by the automatic reactor power controller. This controller activates movement of the regulating CEA banks when the power error (actual power minus desired given power level) exceeds typically ±0.5%, and it deactivates when the absolute power error is less than 0.2%.

Note that in the Calvert Cliffs-1 nuclear power plant, the automatic reactor power controller was deactivated in 1983, and was replaced by a "permissiveness" signal given by the reactor operator. In the Calvert Cliffs-1 reactor transient studies, the operator was simulated by this automatic controller in those transients where the operator is allowed to adjust power.

2. Soluble boron is inserted into the primary system with the help of the boric acid pumps. These pumps have a design capacity of 143 gallons per minute (gpm) each and are fed by fluid containing 12 wt % boric acid. Their exhaust is fed into a pipe upstream from the makeup pumps.

Note that for the steady-state solution of the RETRAN model, the makeup flow equals the letdown flow out of the primary loop. Removal or insertion of soluble boron in the primary system is thus performed by adding through the makeup pumps fluid containing less or more wt % soluble boron than the boron level in the letdown fluid.

During the approach to full power, the model positioned the CEA bank 5 regulating control element assemblies 20 in. into the core (approximately half the distance of the maximum allowable bite). Soluble boron content in the primary loop was then adjusted by activating or deactivating the boric acid pumps through the controller system. Also, when regulation of reactor power during a transient was used in a calculation, and when the regulating control element assemblies were inserted to their maximum allowable limit, the model would also activate regulation of the soluble boron content in the primary loop.

The reactivities due to the five regulating CEA banks, the three shutdown safety banks and the soluble boron in the primary system were taken at the beginning-of-cycle (BOC) of cycle 6 of Calvert Cliffs-1 at hot full power (HFP). The point kinetics option in RETRAN was used.

The standard set of delayed neutron fractions and lifetimes, available in RETRAN, were used. Also the ANSI decay fractions and lifetimes were used.

The RETRAN control diagrams of the five regulating CEA banks, the three shutdown/safety banks, and the boron injection are displayed in Fig. A.1.5.

A.1.3 REACTOR COOLANT PUMPS

In each of the four cold legs is an identical reactor coolant pump (RCP) (see Fig. A.1.1). They are single-speed centrifugal pumps, used to circulate reactor coolant through the core and to heat the reactor coolant during plant startup to achieve hot-zero-power status (HZP).

Each pump motor has a flywheel to increase the inertia of the pumps. They also possess non-reverse rotation devices to prevent reverse rotation, which might occur if one RCP is stopped and one or more pumps are operating in the other cold-legs.

Rated RCP speed is 883 rpm, and rated flow per pump is 92,825 gpm. The head, power, and torque versus flowrate curves of the pumps were provided by BG&E and were converted into RETRAN-compatible homologous curves.

In the RETRAN model, the four cold legs were combined into two cold legs, and the four RCPs were combined into two pumps, RETRAN pump P10 using volume node V132 and pump P20 using volume node V232 (see Figs. A.1.1 and A.1.2). Rated flow, torque, and inertia were thus doubled.

The following RCP trips were used in the model:

a. operator trip 30 s after initiation of a high-pressure safety injection (HPSI) signal, and

b. operator trip when the pressurizer (PZR) pressure drops below 1300 psia.

A.1.4 HOT LEGS AND COLD LEGS

a. Hot legs: Two pipe sections, each 42 in. ID, connect the reactor vessel outlets to the SG primary coolant inlet nozzle (RETRAN volume nodes V101 and V201 in Fig. A.1.2).

b. Cold legs: Four pipe sections, each 30 in. ID, connect the SG primary coolant outlets to the RCPs; and four pipe sections, each 30 in. ID, connect the pumps to the reactor vessel inlets. In the RETRAN model (Fig. A.1.2), the four cold legs were combined into two cold legs, each containing a pump made up of two RCPs. Thus we have

   1. Cold leg 11 : using RETRAN volume nodes V127 and V129, pump P10 (using volume node V132), and volume nodes V135 and V137.

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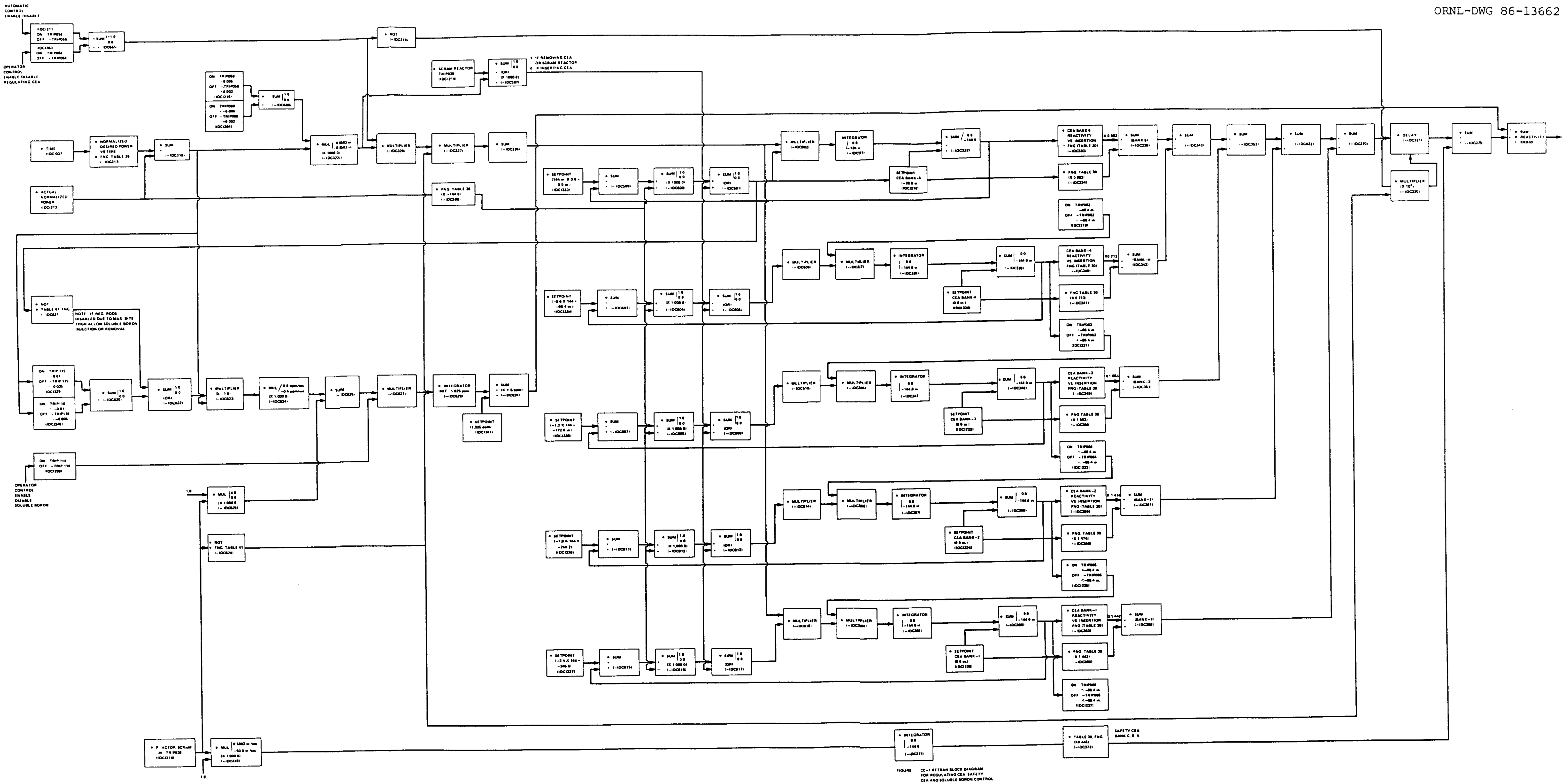

Fig. A.1.5. RETRAN controller for reactor reactivity control.

2. Cold leg 12 : using RETRAN volume nodes V227 and V229, pump P20 (using volume node V232), and volume nodes V235 and V237.

The flow through each of the cold legs in the RETRAN model is ~19,305 lbm/s.

A.1.5 PRESSURIZER, CHARGING PUMPS, AND LETDOWN VALVES

The pressurizer (PZR) is a tank ~30 ft high that pressurizes the primary system. It has a total volume of ~1500 ft^3.

The PZR is represented by a non-equilibrium RETRAN volume node V199 (see Fig. A.1.2) using the RETRAN pressurizer model, which includes the spray valve, heaters, power-operated-relief valves (PORVs), safety-relief valves (SRV1 and SRV2) and a surge line. It is connected to one of the hot legs (volume node V101) of the primary system via the surge line (volume node V191).

The RETRAN pressurizer model allows two separate thermal-hydraulics regions (vapor and liquid), which do not have to be in thermal equilibrium. Rainout out of the vapor region and flashing from the liquid into the vapor region are allowed. The spray, via the spray valve (RETRAN valve VA001 at junction J194) enters the PZR at the top. It enables water to mix with the vapor region and thus condense vapor in the vapor region, followed by the deposit of fluid in the liquid region. The spray line to the spray valve is connected to one of the cold legs (volume node V193) of the primary system.

In the pressurizer of Calvert Cliffs-1, there is a continuous spray flow of 1.5 gpm and a maximum flow of ~375 gpm when the spray valve is fully open. The steady-state solution using the RETRAN pressurizer model precludes the use of "initial spray" and "heaters on" options during steady-state iterations. After the steady-state solution is obtained in RETRAN, only then do the controls of the spray valve and the pressurizer heaters become active. To circumvent the problem of not having spray or heaters on in obtaining the steady-state solution using RETRAN, a null-transient was run after obtaining the steady-state solution in order to let the RETRAN model settle down to a true steady state with spray and heaters on.

The pressurizer controller can be subdivided as having two functions:

1. Maintain primary coolant pressure between two set points by activating spray and/or pressurizer heaters.

2. Maintain the proper coolant inventory in the primary system by either discharging through the letdown valves (at RETRAN junctions J146 and J246) or injecting coolant with activation of the charging pumps.

The level set points are programmed to be a function of coolant average temperatures. For example, at hot full power the pressurizer 'zero' mixture level is 16.0 ft, whereas at hot zero power the set point is 9.2 ft. (Note that in the RETRAN pressurizer model of Calvert Cliffs-2, the 'zero-level' set point at hot full power is at 18.2 ft.)

The level controller in the pressurizer compares the measured and programmed level set points. It generates a signal for regulating the letdown control valves at RETRAN junctions J146 and J246 (see Fig. A.1.2). In addition, this level controller starts and stops the charging pumps at low- or high-level set points of the pressurizer.

Note that upstream of these charging pumps, which form a part of the chemical and volume control system, soluble boron can be injected through the RETRAN controller that injects or removes soluble boron from the primary coolant (see RETRAN control diagram in Fig. A.1.5).

The control diagrams of the RETRAN model that simulates the pressurizer controller are shown in Figs. A.1.6, A.1.7, and A.1.8. The pressurizer pressure set point at which the spray valve opens is 2300 psia. All backup heaters are turned on if the pressure in the pressurizer drops below 2200 psia. All pressurizer heaters are turned on if the relative level exceeds +13 in. (relative to the pressurizer zero-level set point). All backup heaters are turned off if the pressure exceeds 2225 psia. All pressurizer heaters are turned off if the relative level drops below +9 in. If the pressurizer level drops below 5.65 ft, all heaters are turned off to prevent damage to the heaters. Also, all heaters in the pressurizer are turned off if the high-pressure safety injection (HPSI) signal is activated.

The proportional heaters are operated gradually. They are at their maximum when the pressurizer pressure drops below 2225 psia, and they are turned off when the pressure exceeds 2275 psia. Note that the proportional heaters in the pressurizer were not modeled. It was assumed that the power removed by the letdown fluid is compensated by the heat introduced by the proportional heaters.

The letdown valves are opened gradually as a function of the pressurizer level. At a relative pressurizer level of -4 in., the opening of the letdown valves (see RETRAN junctions J146 and J246 in Fig. A.1.2) is at its minimum; at a relative level of +32 in., the letdown valves are fully open. Upon a HPSI signal, the letdown valves are closed.

Note that the main charging pump is always in operation. At equilibrium, injection of fluid into the primary system from the main charging pump is compensated by the removal of fluid through the letdown valves. Upon a HPSI signal, a net flow into the primary system is obtained since the letdown valves are then closed. The maximum letdown flowrate is 128 gpm.

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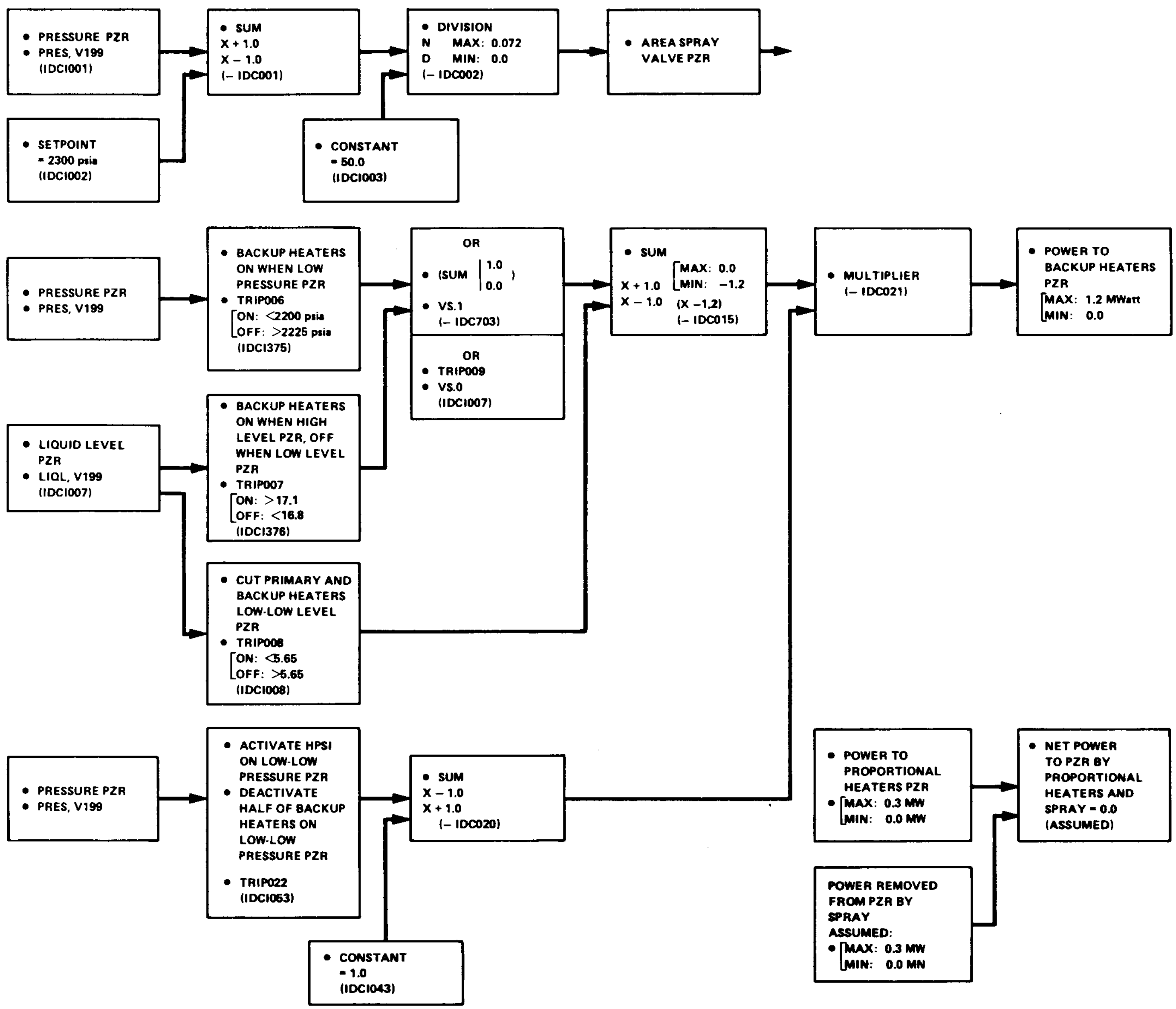

Fig. A.1.6. RETRAN controllers for spray valves and pressurizer heaters.

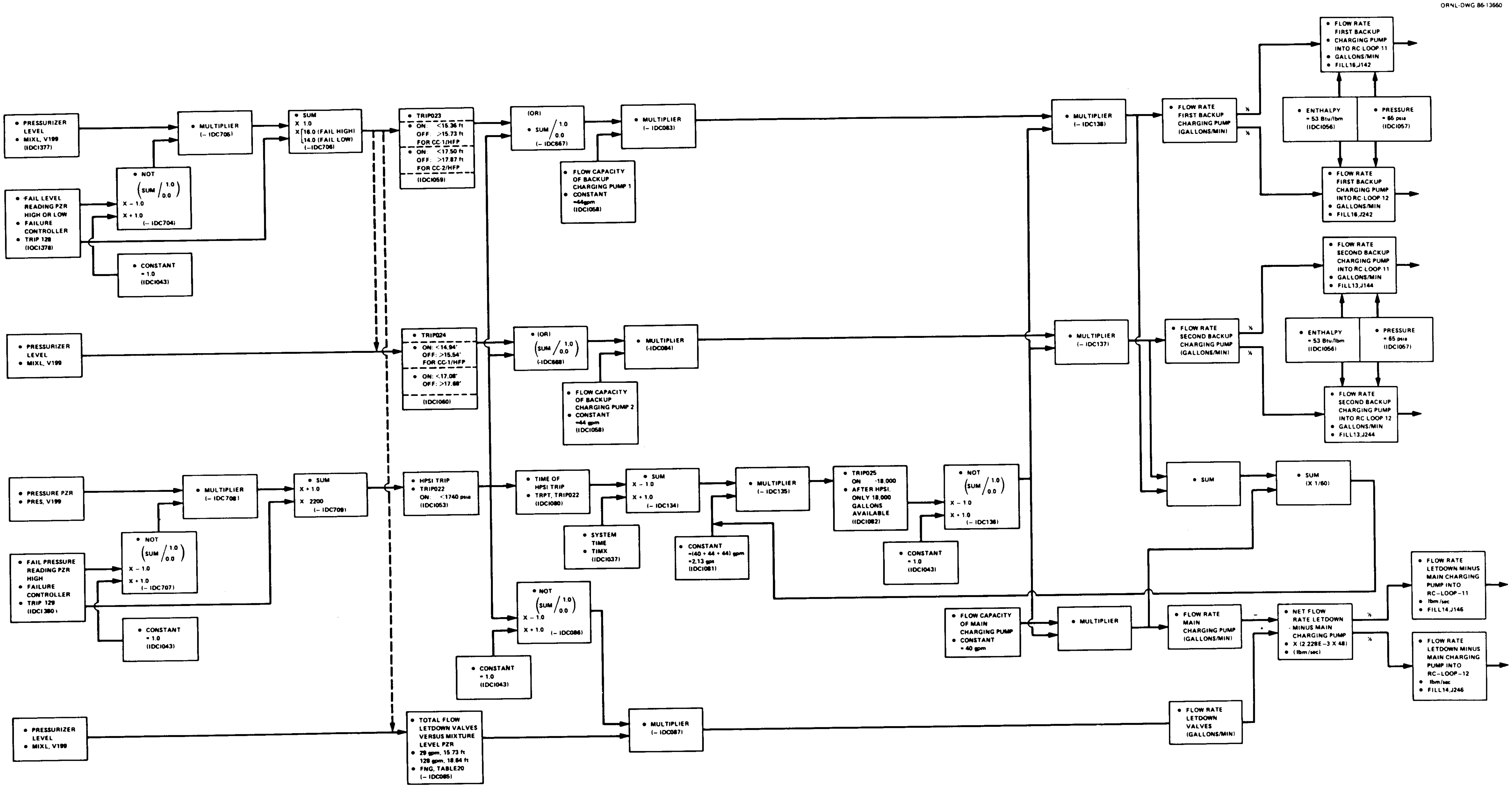

Fig. A.1.7. RETRAN controllers for charging pumps and letdown valves.

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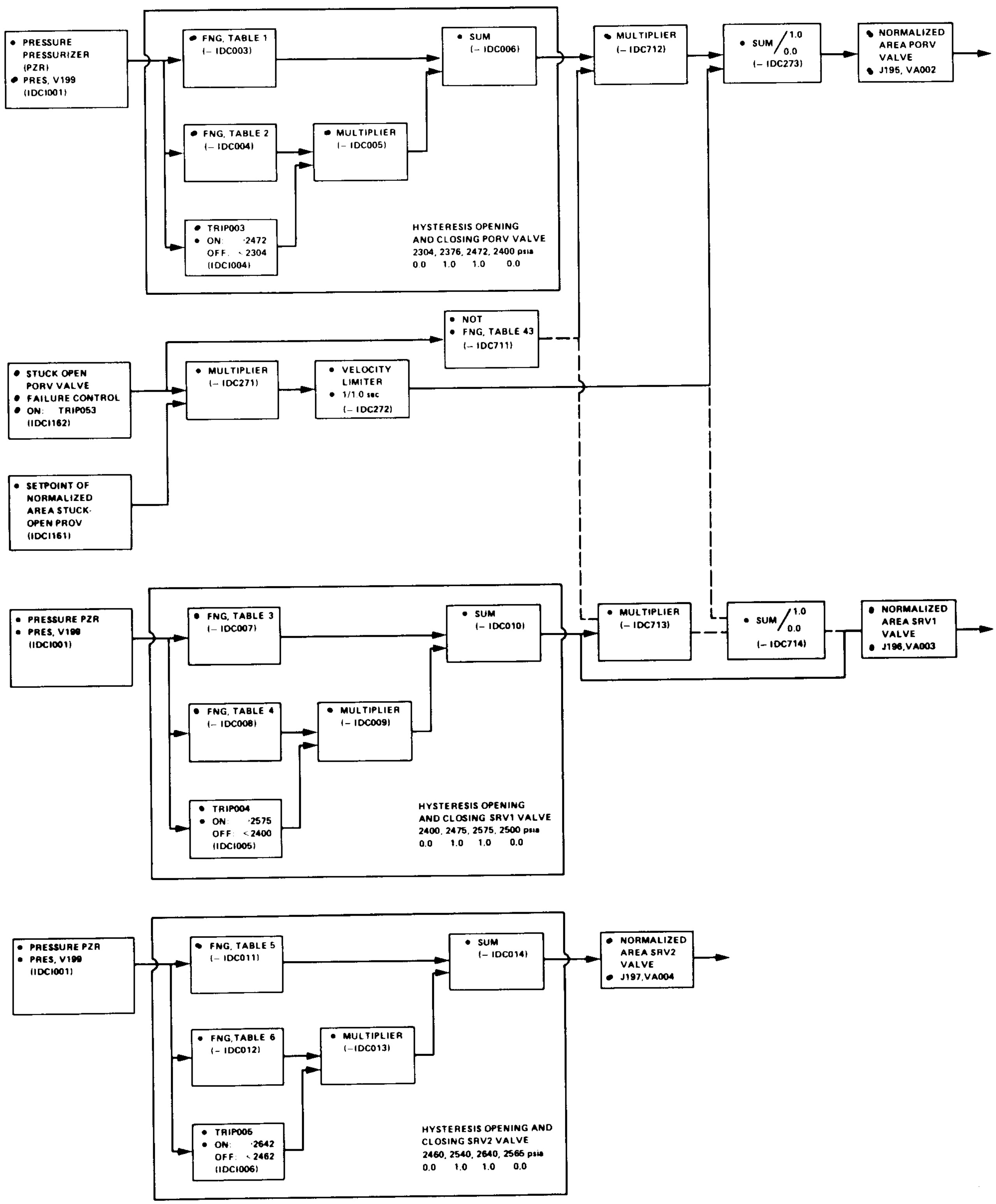

Fig. A.1.8. RETRAN controllers for the PORV and pressurizer safety relief valves.

Set points for the second backup charging pump are as follows:

- on at a pressurizer relative level of -13.5 in.
- off at a pressurizer relative level of -6.25 in.

Since there is a limited supply of coolant available upstream from the charging pumps once the HPSI system is activated, and since the maximum flow from the primary and backup charging pumps is ~128 gpm, the charging pumps will stop at ~2.35 h after activation of the HPSI system.

In the RETRAN model, the PORVs and pressurizer safety relief valves are directly vented inside the containment building. For these valves the 'choked flow' option is used in RETRAN. The PORV relief lines, quench tank, and rupture disc were not modeled. This is adequate if vapor is released through the valves. If, however, fluid is released, the relief lines and quench tank should be modeled. Note that a quench tank is provided to receive, condense, and cool the discharge from the PORVs and pressurizer safety relief valves.

The RETRAN control diagrams for simulating operation of the PORVs (RETRAN valve VA002 at junction J195 in Fig. A.1.2) and the safety relief valves SRV1 and SRV2 (RETRAN valves VA003 at J196 for SRV1 and VA004 at J197 for SRV2) are shown in Fig. A.1.8. A hysteresis type opening was implemented. The hysteresis set points are based on an accumulation pressure of 1.03 times set pressure and a blowdown pressure of 0.96 times set pressure.

The following set pressures were used in the RETRAN model:

- PORVs: 2400 psia
- Pressurizer safety relief valve SRV1: 2500 psia
- Pressurizer safety relief valve SRV2: 2565 psia

A.1.6 HIGH-PRESSURE SAFETY INJECTION SYSTEM

The high-pressure safety injection (HPSI) system injects water into the cold legs of the primary system when pressurizer pressure drops below 1740 psia. In the RETRAN model the injection is done at junction J140 for cold-leg 11 and at junction J240 for cold leg 12 (see Fig. A.1.2).

The HPSI signal also activates the primary and first- and second-backup charging pumps (which also inject water into the primary system via the cold legs), and closes the letdown valves at RETRAN junctions J146 and J246 (see Fig. A.1.7).

The HPSI signal system draws its water from the refueling water storage tank (RWT). The flowrate from the HPSI system, through RETRAN junctions J140 and J240, is dependent on the pressure in the cold legs. The net flow from the pumps of the HPSI system through RETRAN junctions J140 and J240 stays zero until pressure in the cold leg drops below ~1285 psia.

Below this level the flowrate from the HPSI pumps into the primary system gradually increases with decreasing pressure. For example, at a downstream pressure of 1000 psia, the net flowrate is ~320 gpm per HPSI pump. Note that the relationship between the net flowrate and the downstream pressure is not linear.

The RETRAN controller that simulates operation of the HPSI system is shown in Fig. A.1.9.

A.1.7 REACTOR SCRAM

The reactor control system will insert all safety and regulating control element assemblies (CEAs) into the reactor core at a maximum speed of 50 in./s when one of the following conditions occurs:

- High pressure in the reactor coolant loop of SG-11: pressure in RETRAN volume node V101 is greater than 2400 psia.

- High pressure in the reactor coolant loop of SG-12: pressure in RETRAN volume node V201 is greater than 2400 psia.

- Low pressure in the primary system: if the pressure drops below a variable set pressure.

  $$P = X1 * A1 * QR1 + X2 * Tin - X3,$$

  where X1, X2, X3 = constant values
  Tin = reactor coolant temperature at the reactor core inlet
  QR1 = reactor-power-dependent value.

  For example, for a reactor coolant temperature of 562°F and at a relative reactor power of 100%, the low-pressure set point below which the reactor will scram is ~2055 psia. The RETRAN control system that implements this variable low-pressure set point to initiate a reactor scram is shown in Fig. A.1.10.

- Low-pressure trip when the pressure in pressurizer node V199 drops below 1875 psia.

- Steam generator isolation signal (SGIS) for either steam generator: RETRAN trip TRIP020.

- Auxiliary feedwater trip signal: RETRAN trip TRIP030.

- Main steam turbine trip: RETRAN trip number TRIP039.

- Manual reactor scram signal: RETRAN trip number TRIP038.

- Reactor scram when the change in reactor power is positive and exceeds 5%/min. The RETRAN control diagram is shown in Fig. A.1.11.

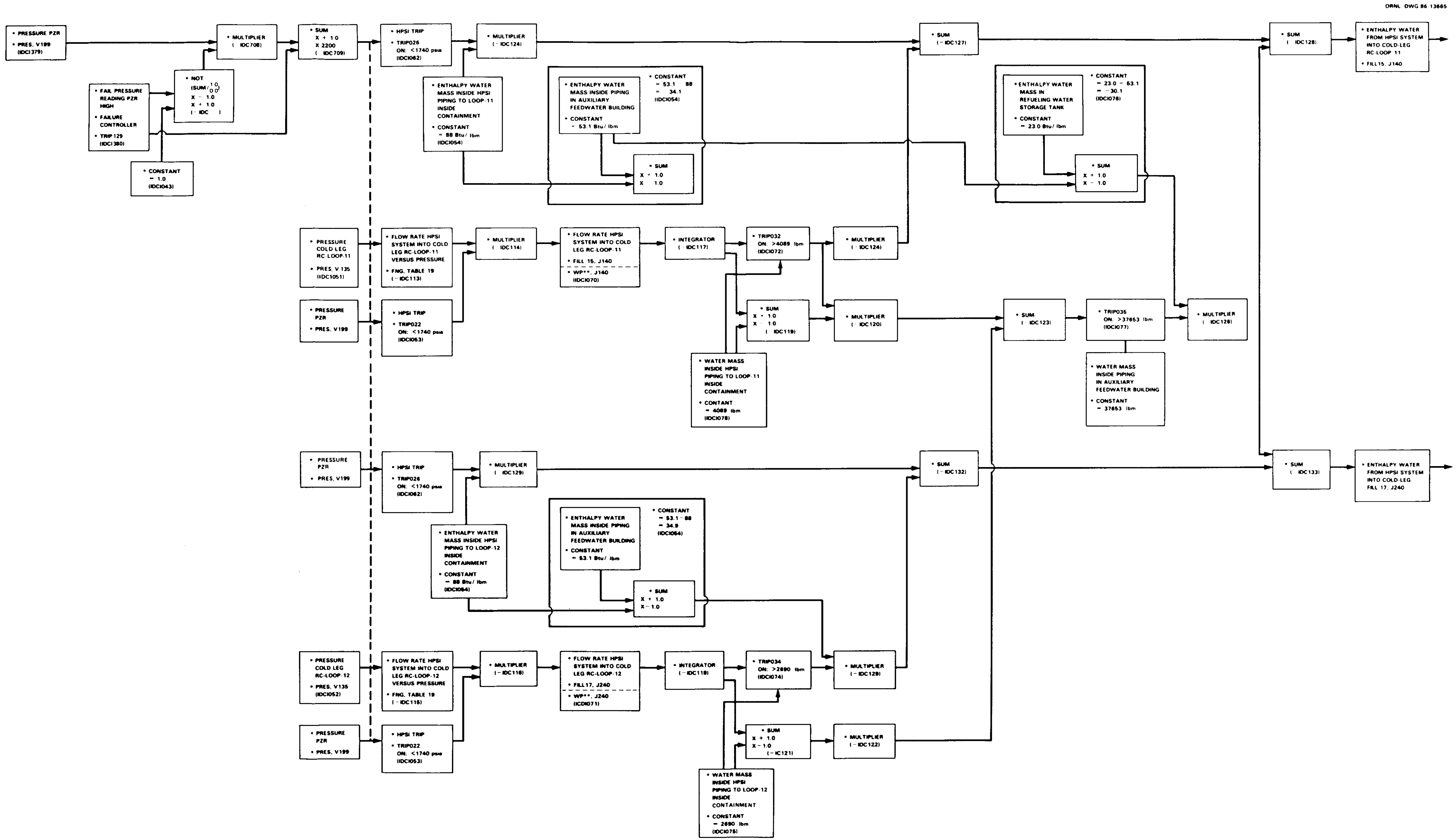

Fig. A.1.9. RETRAN controller for the high-pressure safety injection system.

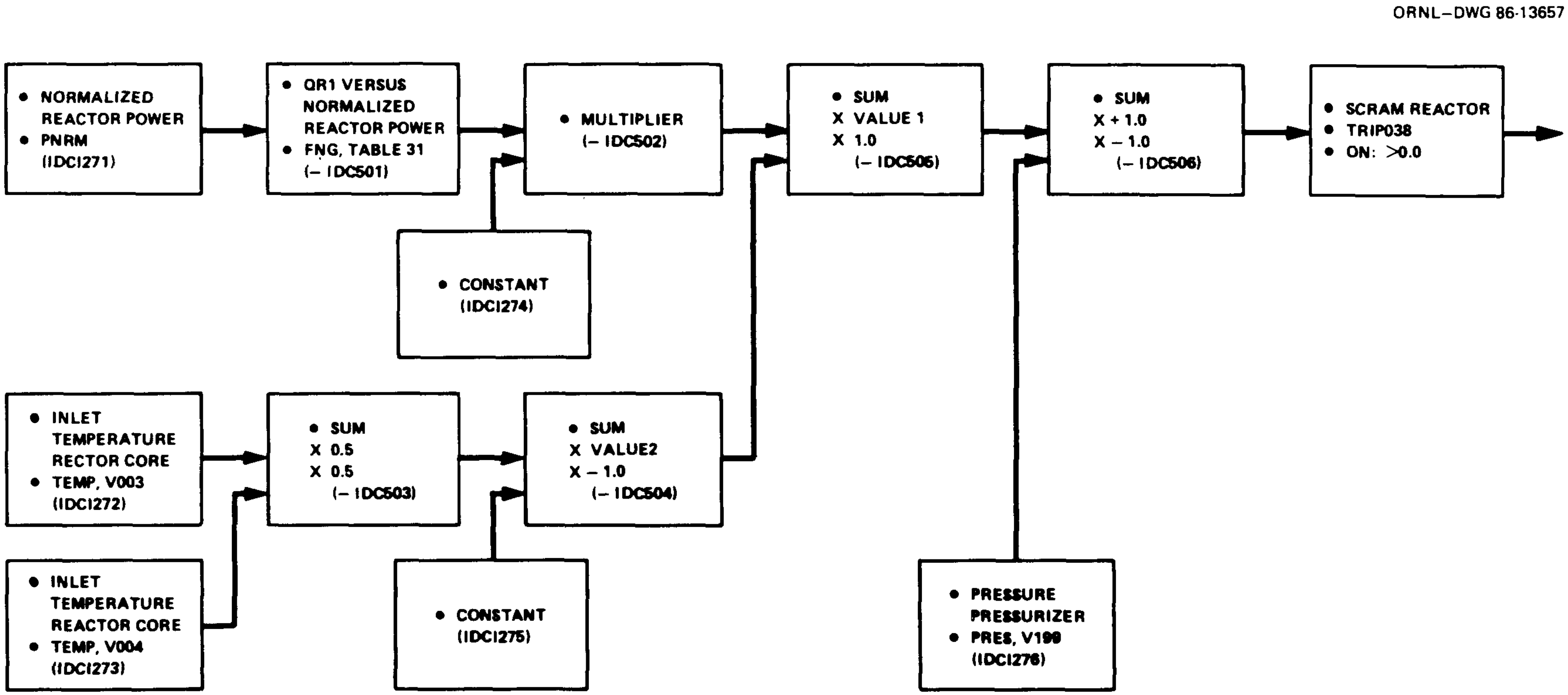

Fig. A.1.10. RETRAN controller for the variable set point of primary system pressure to initiate a reactor scram.

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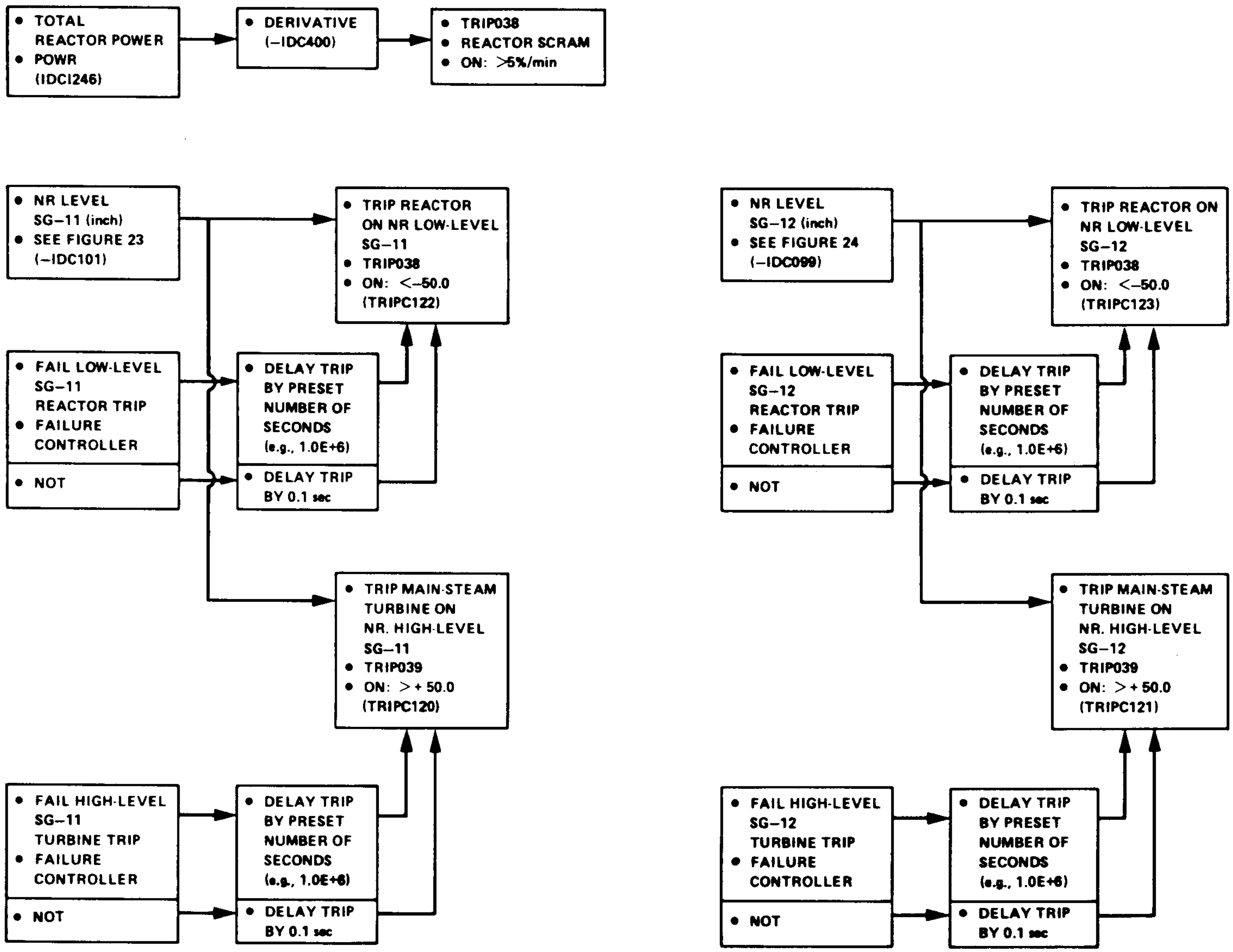

Fig. A.1.11. Various RETRAN controllers for initiation of reactor scram and a main steam turbine trip.

- Reactor trip when the narrow-range level in SG-11 or SG-12 drops below the -50 in. set point (see Fig. A.1.11).

A.1.8 MAIN TURBINE TRIP

The main steam turbines are tripped by closing the four main steam stop valves (MSSVs) represented in Fig. A.1.12 as RETRAN valve number VA015 at junction J730. The main steam turbines will trip under the following conditions:

1. at 0.1 s after initiation of a reactor scram.

2. on manual main steam turbine trip.

3. on low vacuum trip in the condenser-hotwell unit. This trip is initiated if the pressure in RETRAN volume node V949 exceeds a given set point of ~5 psia.

4. on turbine overspeed. (The turbine overspeed trip has not yet been implemented in the RETRAN model.)

5. The narrow-range level in SG-11 or SG-12 exceeds the set point of +50 in. (see Fig. A.1.11).

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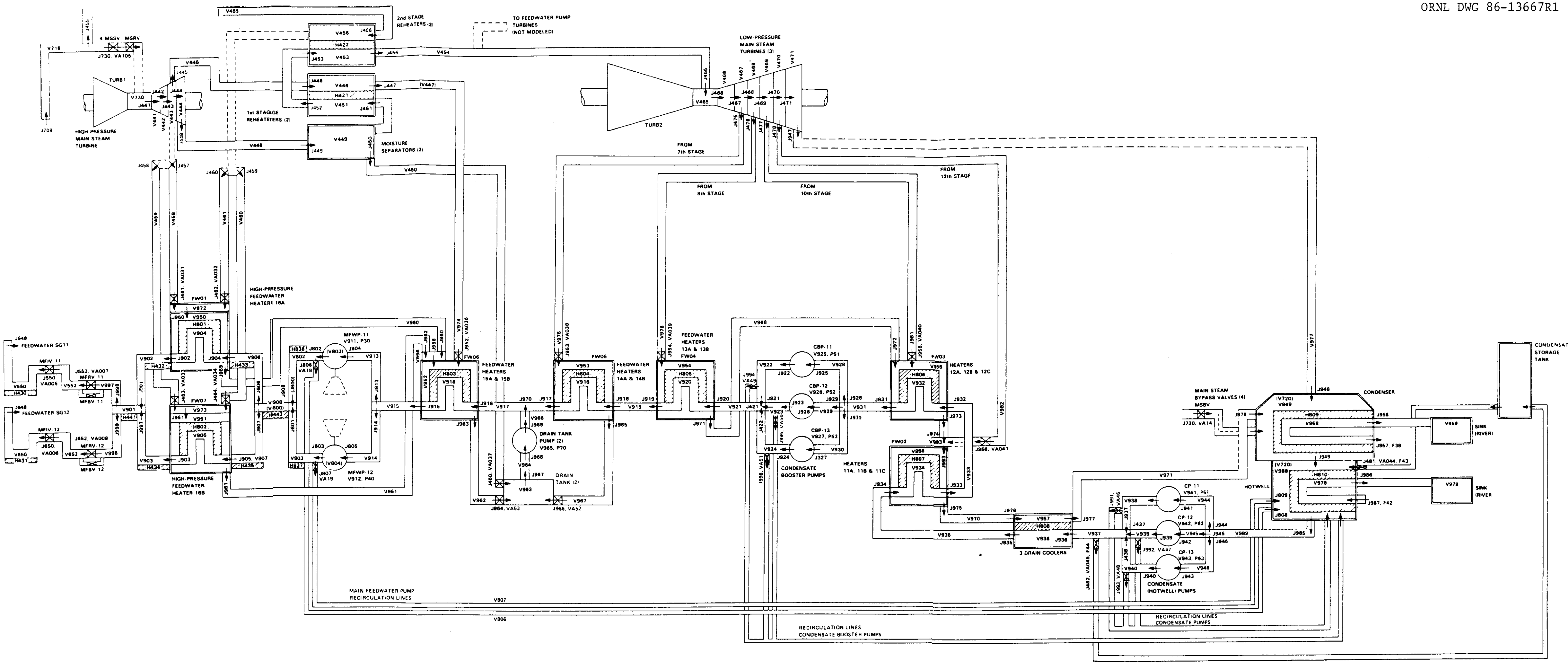

Fig. A.1.12. RETRAN nodal diagram of the secondary system.

A.2 STEAM GENERATORS

In Calvert Cliffs-1 two steam generators, SG-11 and SG-12 are used in parallel to transfer the heat generated in the reactor core, via the primary coolant, to the water of the secondary system. The steam-generators have a 'U-tube' heat exchanger with the reactor coolant on the tube side. The feedwater coming from the secondary system is transformed into a water/steam mixture in the shell side. In the simulations for Calvert Cliffs-2, two identical steam generators, SG-21 and SG-22 were assumed.

Three different RETRAN nodal diagrams of the steam generators have been used in the power plant simulations:

a. Steam generator nodal diagram with one volume node in the downcomer, one volume node in the riser, and six volume nodes in the tube side (see Fig. A.2.1 for SG-11 and Fig. A.2.2 for SG-12).

b. Steam generator nodal diagram with four volume nodes in the downcomer, four volume nodes in the riser and six volume nodes in the tube side (see Fig. A.2.3 for SG-11 and Fig. A.2.4 for SG-12).

c. Steam generator nodal diagram with six volume nodes in the downcomer, six volume nodes in the riser and six volume nodes in the tube side (see Fig. A.2.5 for SG-11 and Fig. A.2.6 for SG-12).

Reactor coolant flows via the hot legs into SG-11 and SG-12 (see RETRAN volume nodes V101 and V201 in Fig. A.1.2). For SG-11/SG-12, the primary coolant flows into the steam generators at RETRAN junction J105-SG11/J205-SG12, goes through the tube side, and then exits the generator at RETRAN junctions J127-SG11/J227-SG12.

In the secondary side, feedwater enters the steam generators through the feedwater inlet nozzle at junction J548-SG11/J648-SG12 and is distributed to a feedring with holes at the bottom, mixes with hot water coming from the SG centrifugal steam separators and steam dryers via junction J541-SG11/J641-SG12, and then flows down the downcomer.

For SG-11, the downcomer is represented by RETRAN volume node V501 (Fig. A.2.1); volume nodes V501, V502, V503, and V531 (Fig. A.2.3); and volume nodes V501, V502, V503, V504, V531, and V532 (Fig. A.2.5). The downcomer for SG-12 is represented by RETRAN volume node V601 (Fig. A.2.2); volume nodes V601, V602, V603, and V631 (Fig. A.2.4); and volume nodes V601, V602, V603, V604, V631, and V632 (see Fig. A.2.6).

The feedwater then goes up the shell side of the vertical U-tubes (called the riser), where it picks up heat from the primary coolant and transforms itself into a water/steam mixture.

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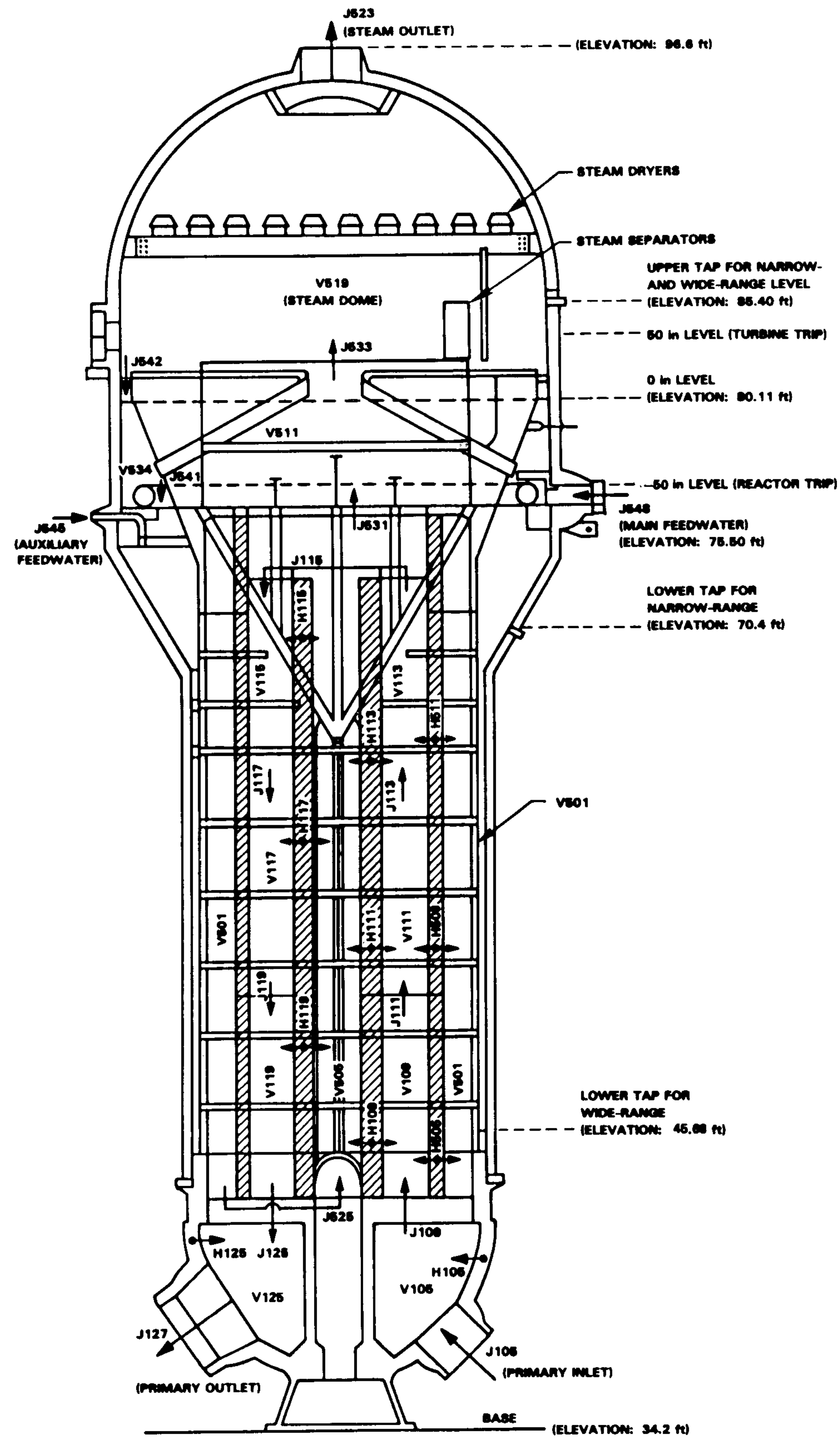

Fig. A.2.1. Nodal diagram of steam generator SG-11 with one riser node and one downcomer node.

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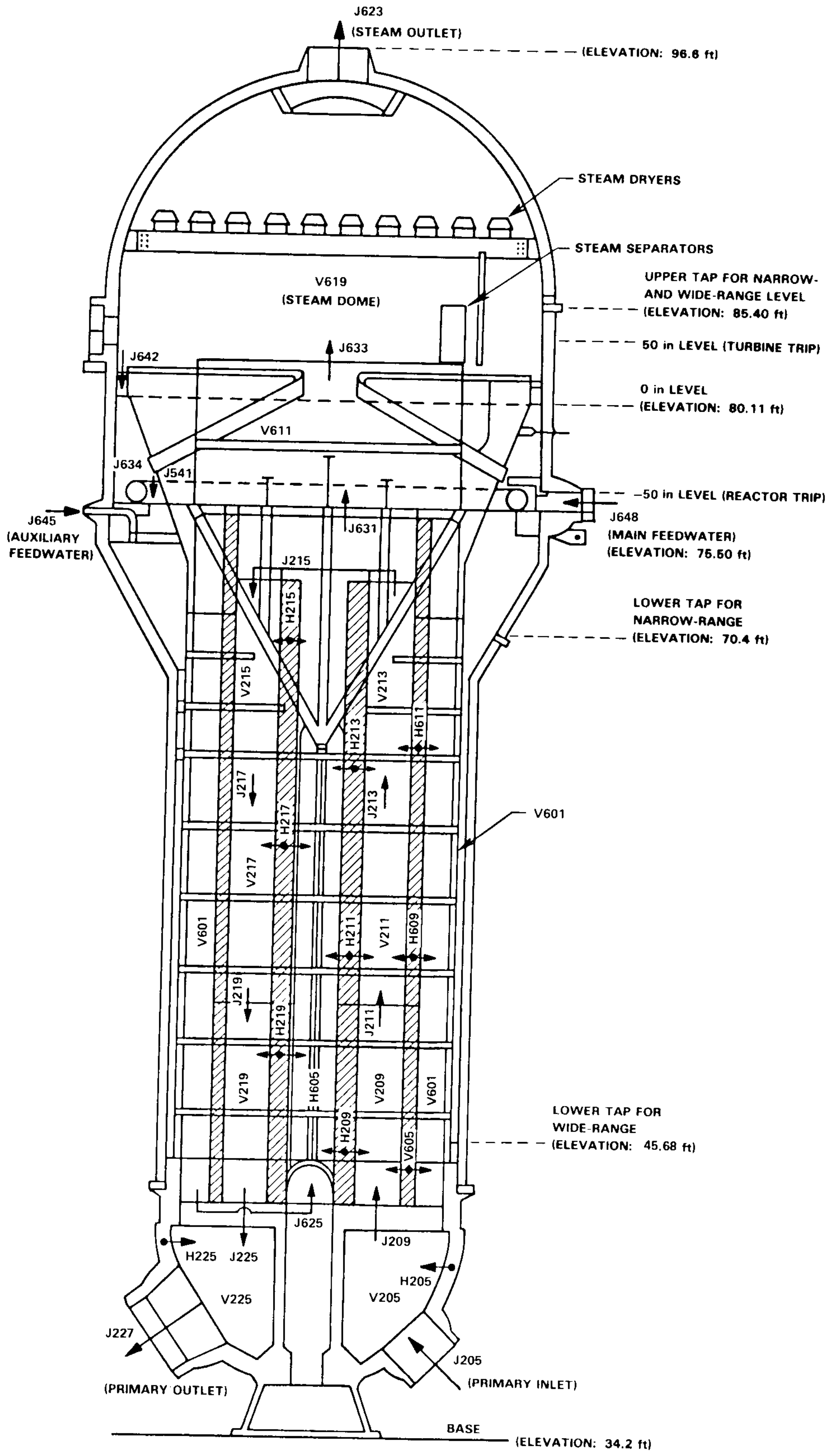

Fig. A.2.2. Nodal diagram of steam generator SG-12 with one riser node and one downcomer node.

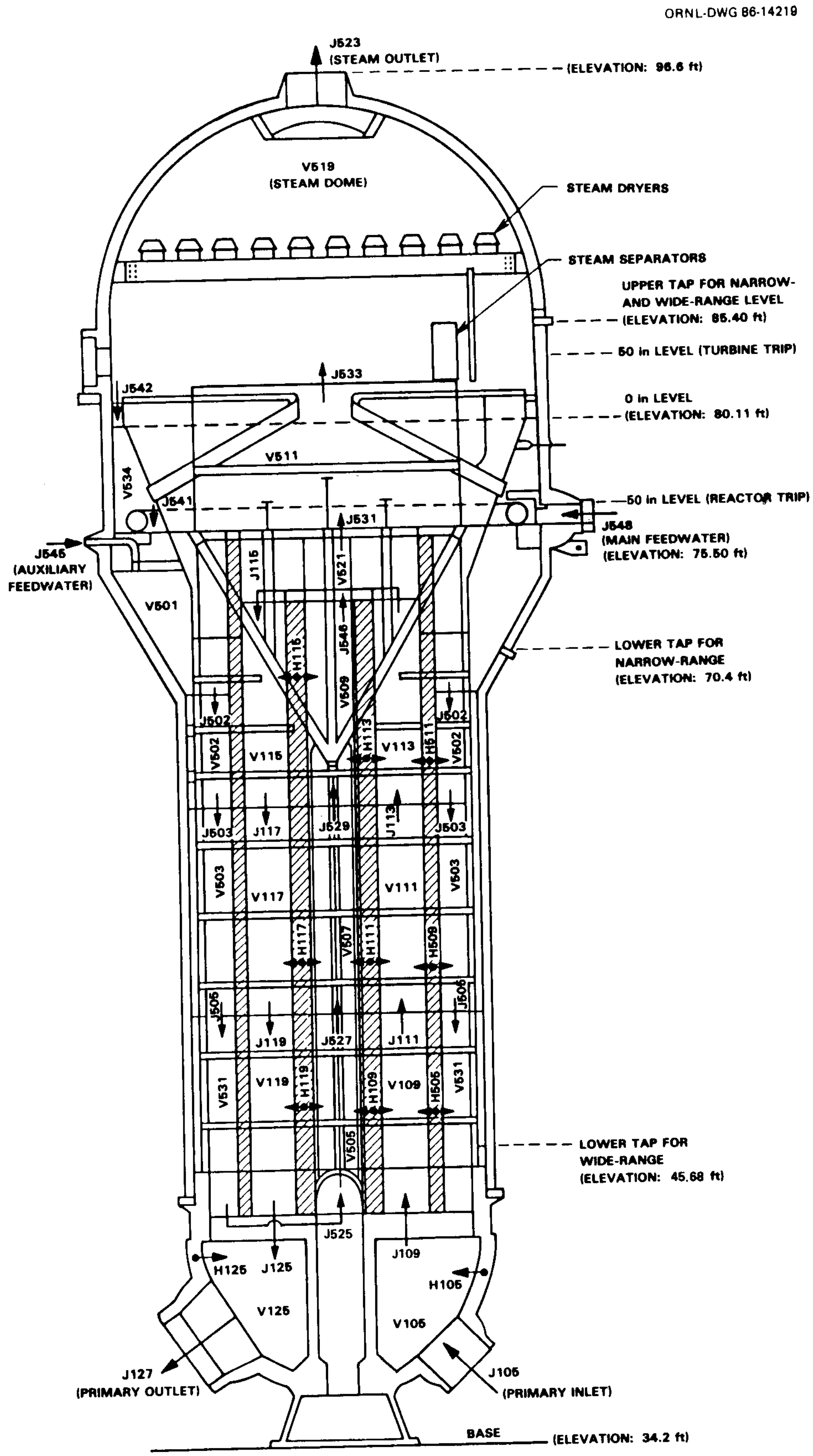

Fig. A.2.3. Nodal diagram of steam generator SG-11 with four riser nodes and four downcomer nodes.

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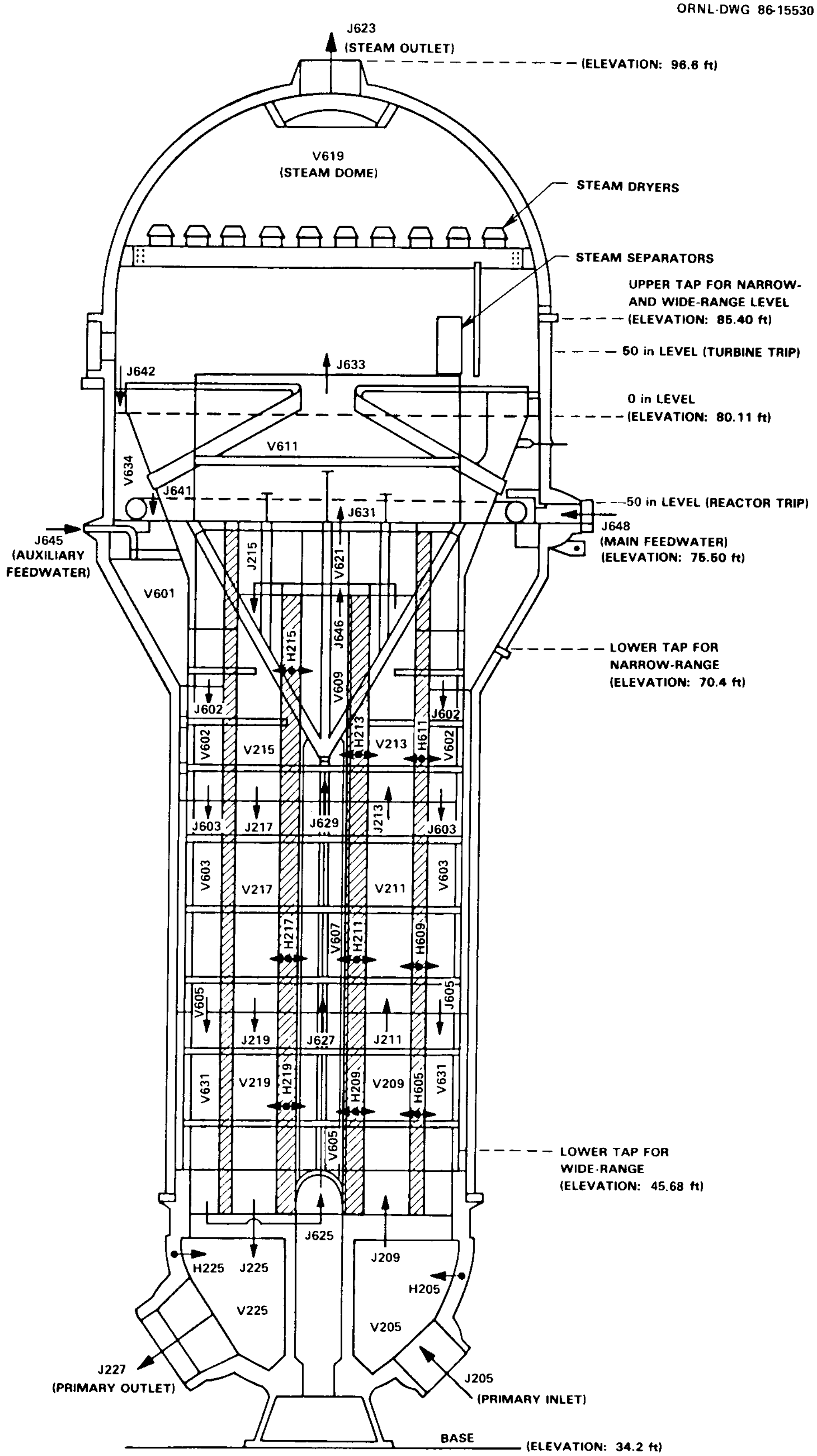

Fig. A.2.4. Nodal diagram of steam generator SG-12 with four riser nodes and four downcomer nodes.

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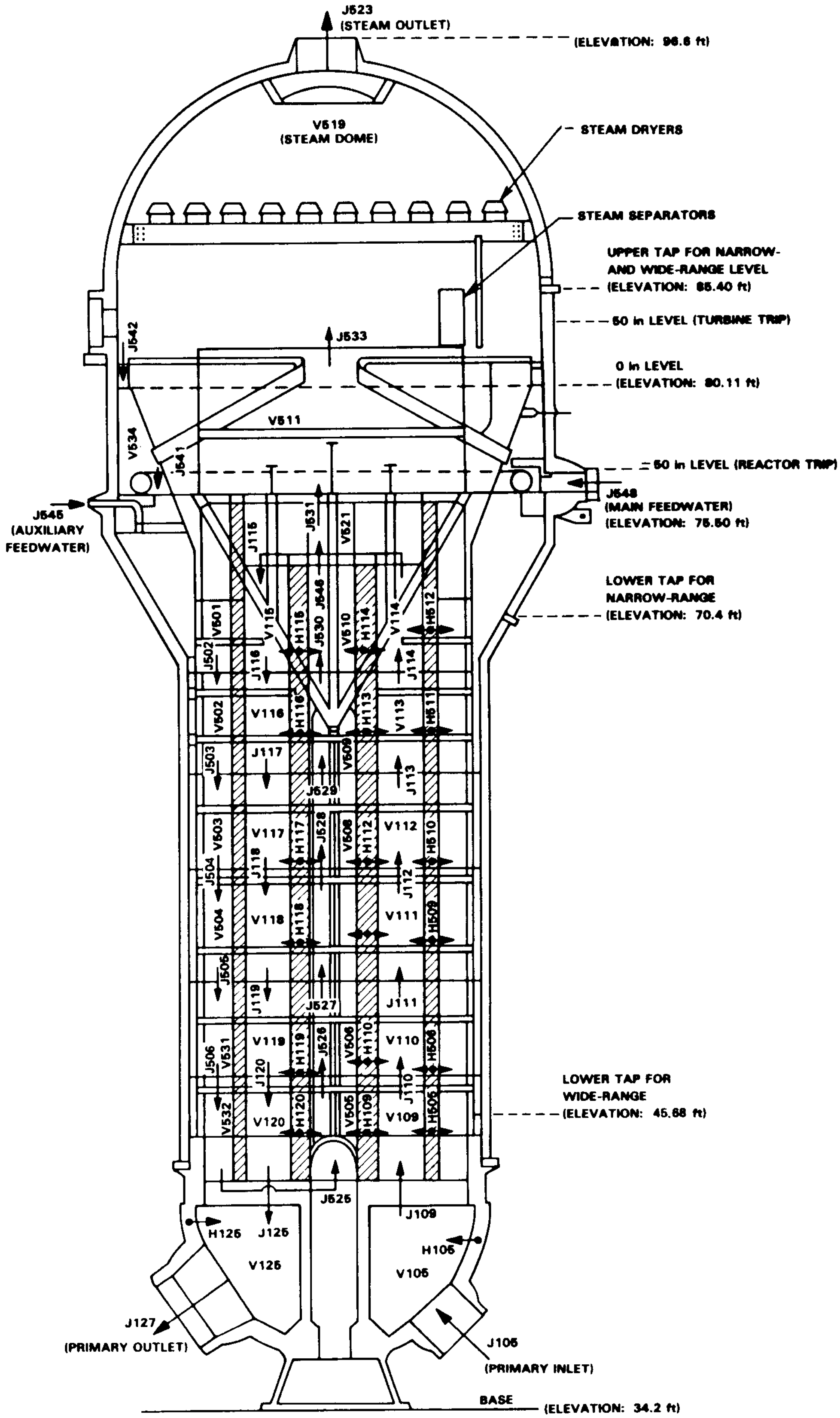

Fig. A.2.5. Nodal diagram of steam generator SG-11 with six riser nodes and six downcomer nodes.

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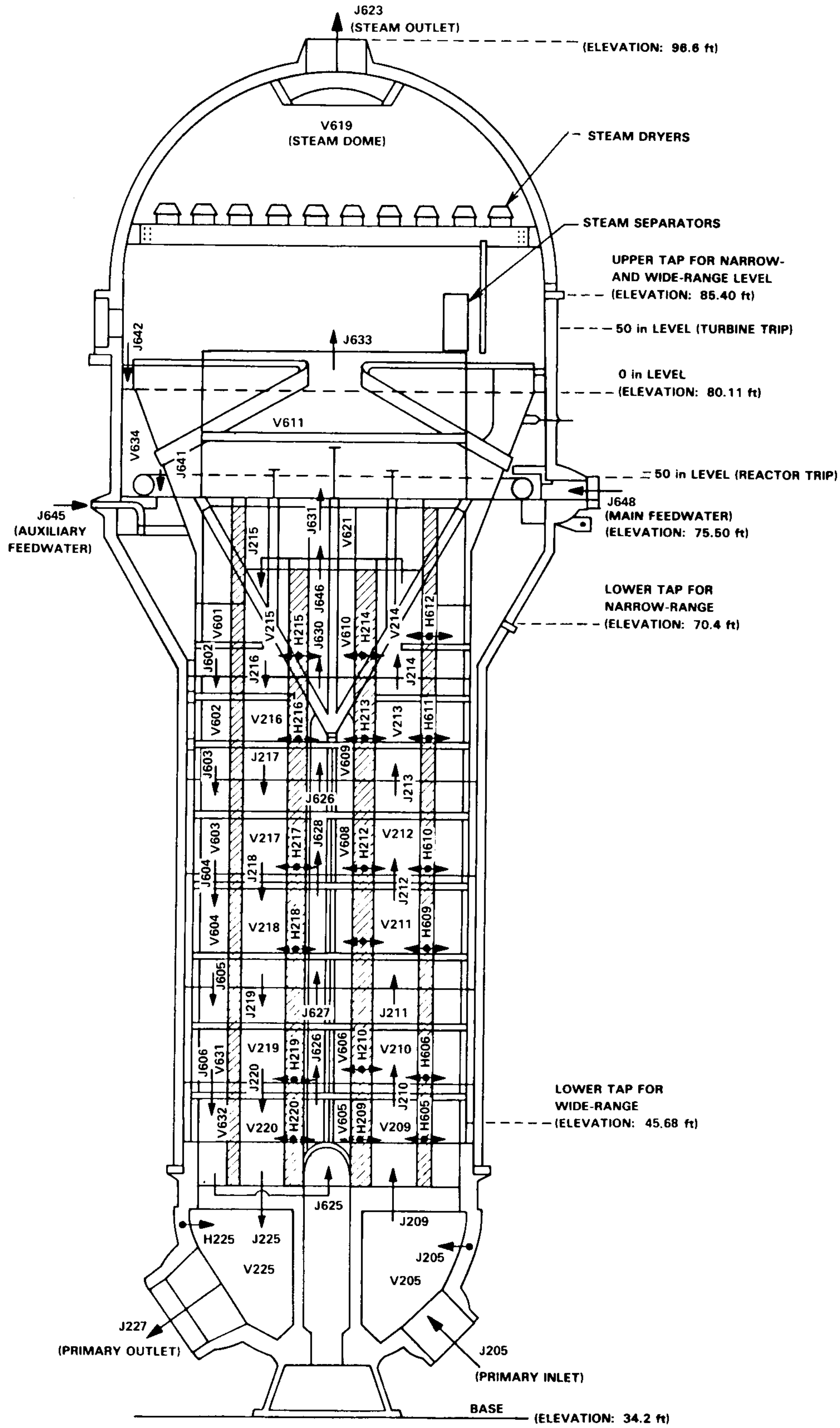

Fig. A.2.6. Nodal diagram of steam generator SG-12 with six riser nodes and six downcomer nodes.

The riser for SG-11 is represented by RETRAN volume nodes V505 (Fig. A.2.1); volume nodes V505, V507, V509, and V521 (Fig. A.2.3); and volume nodes V505, V506, V507, V508, V509, V510, and V521 (Fig. A.2.5). RETRAN volume node V605 (Fig. A.2.2); volume nodes V605, V607, V609, and V621 (Fig. A.2.4); and volume nodes V605, V606, V607, V608, V609, V610, and V621 (Fig. A.2.6) represent SG-12.

The water/steam mixture then enters 166 centrifugal steam separators at RETRAN junction J533-SG11/J633-SG12. The water is recirculated to the downcomer via RETRAN junction J542-SG11/ J642-SG12. Note that the recirculation ratio is dependent on the power level of the steam generator. At full power it has a value of approximately 4.

Steam leaving the steam separators is directed inside RETRAN volume nodes V519-SG11/V619-SG12 through 126 steam dryers, which are made of corrugated plates.

The bubble-rise model of RETRAN is used for the steam dome (RETRAN volume node V519-SG11/V619-SG12). The characteristics of the SG steam dome were modeled by using a variable value for the bubble-rise velocity of the RETRAN volume. The bubble-rise velocity has been made dependent on

1. The mixture level inside the steam dome, in order to take into account the change in separation efficiency when flooding of the steam dome occurs.

2. Steam velocity: At normal steam velocities, the bubble-rise velocity has been set to a high value in order to assure complete separation inside the steam separators. When steam velocities increase above the normal at-power values, the efficiency of the steam separators decreases and bubble-rise velocity is reduced accordingly.

The RETRAN control diagram that controls the bubble-rise velocity and gradient of steam-dome volume node V519 in steam generator SG-11 and volume node V619 in steam generator SG-12 is displayed in Fig. A.2.7.

Several level transmitters are tapped into the outer shell of the SGs. Pressure transmitters also come off certain level-transmitter lines.

In the RETRAN model, the level in each steam-generator is determined by the difference in pressure at taps located at different elevations in the steam generator, as is done in the actual power plant. The RETRAN model uses two different ways to determine the level in SG-11 and SG-12:

a. The narrow-range (NR) level is determined by the difference between pressure at a tap in steam-dome volume node V519-SG11/V619-SG12 located at elevation 85.40 ft, and at a tap in the downcomer located at elevation 70.4 ft (see Figs. A.2.1-A.2.6). The narrow-range level is used in

1. Controlling the opening area of MFW regulating valves MFRV-SG11 (RETRAN valve VA007 at junction J552 for SG-11) and MFRV-SG12 (RETRAN valve VA008 at junction J652 for SG-12). The MFW valve controllers are displayed in Figs. A.2.8 and A.2.9.

2. Tripping the reactor (reactor scram) when the narrow-range level drops below the -50 in. set point (see Figs. A.1.11, A.2.8, and A.2.9).

3. Closing the main steam stop valves (MSSV) (represented by RETRAN valve VA015 at junction J730) to the main steam high-pressure turbine when the narrow-range level exceeds the +50 in. set point (Figs. A.1.11, A.2.8, and A.2.9).

b. The wide-range (WR) level is determined by using the difference between pressure at a tap located in steam-dome volume node V519-SG11/V619-SG12 at elevation 85.40 ft, and at a tap located at the bottom of the downcomer at elevation 45.7 ft. The wide-range level is used in :

1. Startup of the auxiliary feedwater system, which pumps water into the SGs via RETRAN junction J545-SG11/J645-SG12 when the wide-range level drops below the -170 in. set point (see Fig. A.2.10).

2. Closure of MFW isolation valve MFIV-SG11 or MFIV-SG12 initiated by startup of the AFW system. In recent Calvert Cliffs-1 design changes, closure of the MFIV valves upon low-low level trip in the steam generators has been deactivated. In the RETRAN model, MFIV closure upon low-low level can be activated with a manual enable signal. Valve MFIV-SG11 is displayed in Fig. A.1.12 as valve VA005 at junction J550, and valve MFIV-SG12 is displayed as valve VA006 at junction J650. The RETRAN control diagrams for the MFW isolation valves are displayed in Fig. A.2.11.

Since the results of pressure calculations using the RETRAN code give a volume-averaged pressure in the volume nodes, and since the nodes are relatively tall, adjustments were calculated using the thermal-hydraulics properties of the RETRAN volume nodes and the exact elevations of the pressure taps. These adjustments were based on Bernouilli's equation and were used in several RETRAN control diagrams. (see Figs. A.2.8 through A.2.11).

Conversion of the narrow-range (NR) and wide-range (WR) pressure differences to the NR and the WR levels was done by using instrument calibrations on the steam generators of the power plant. The NR level was then fed into the RETRAN controllers (see Figs. A.2.8 and A.2.9) of the MFW regulating valves MFRV-SG11 (RETRAN valve VA007 at junction J552) and MFRV-SG12 (valve VA008 at junction J652).

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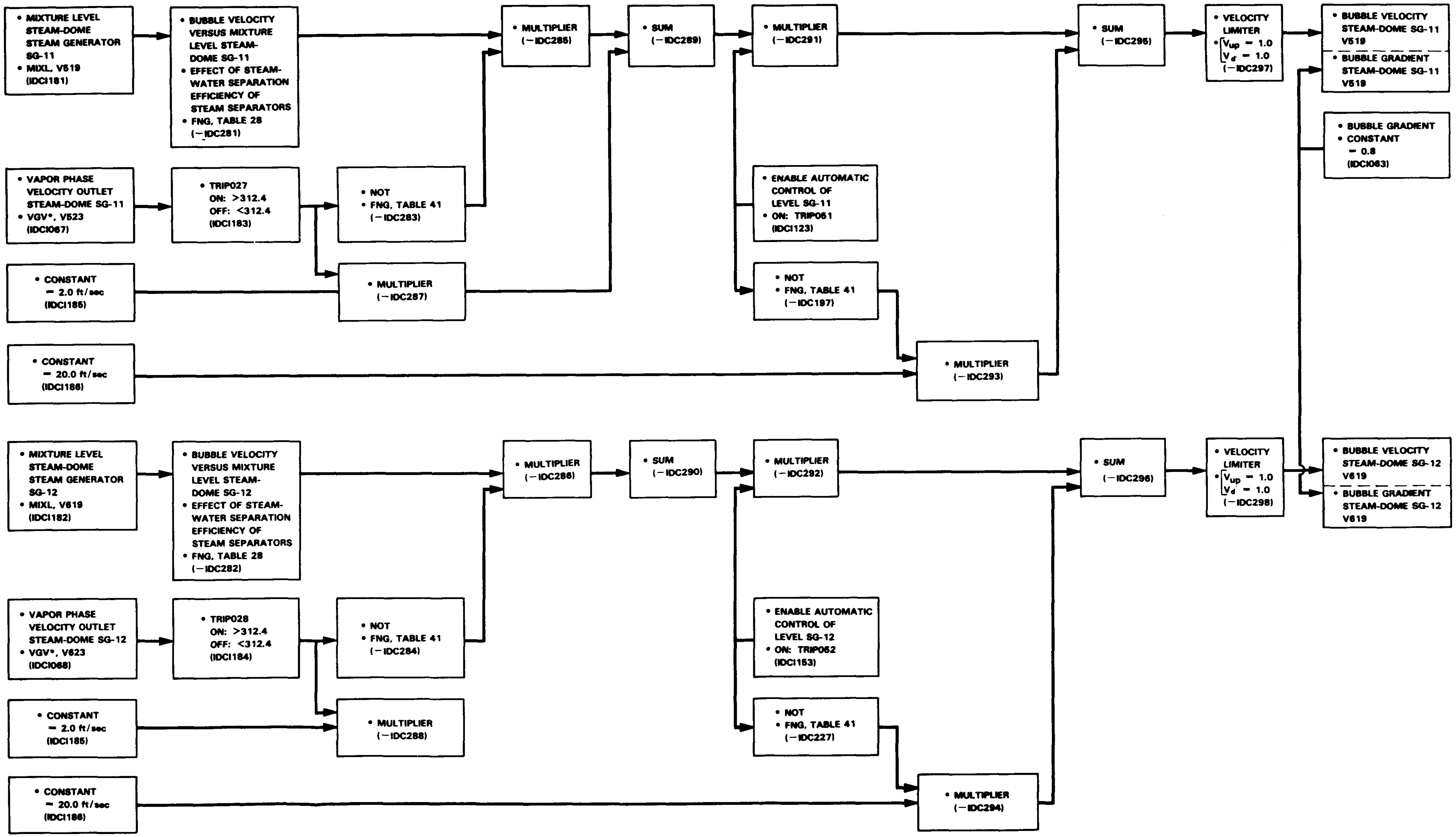

Fig. A.2.7. RETRAN controllers for bubble velocity and gradient in the steam dome of the steam generator.

ORNL-DWG 86-13668

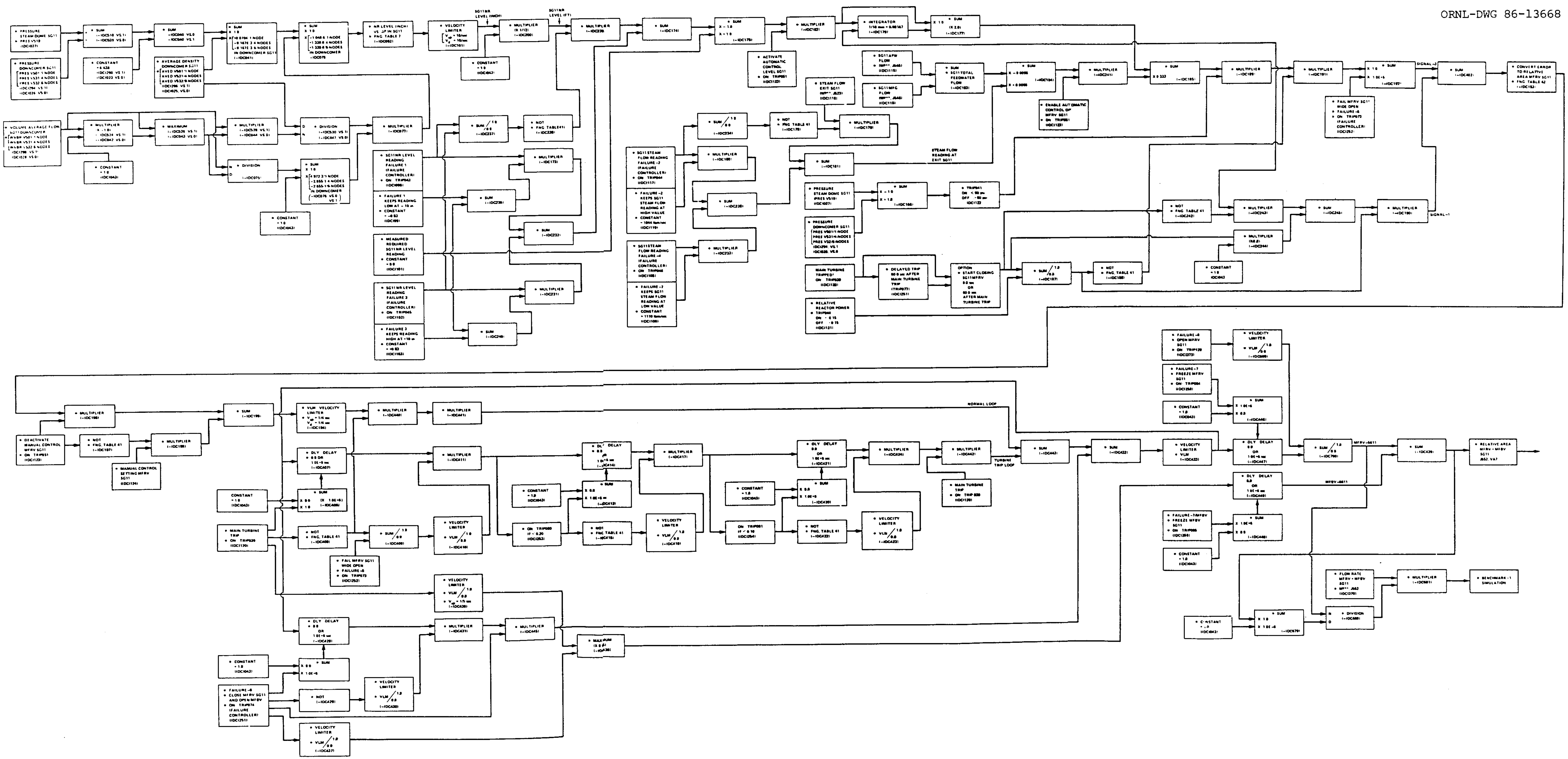

Fig. A.2.8. RETRAN controller for the main feedwater regulating valve and for the main feedwater bypass valve of steam generator SG-11.

ORNL-DWG 86-13668B

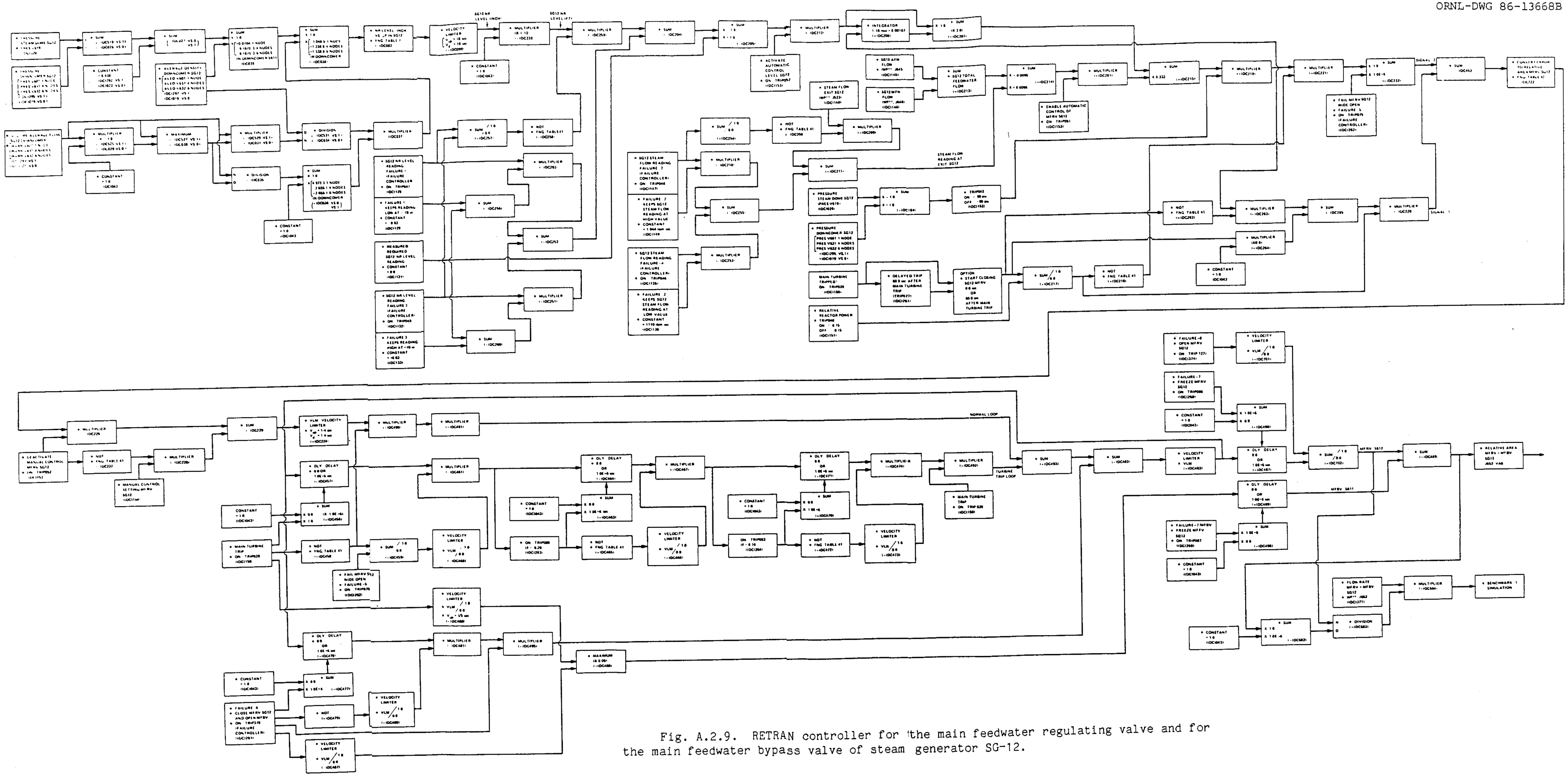

Fig. A.2.9. RETRAN controller for the main feedwater regulating valve and for the main feedwater bypass valve of steam generator SG-12.

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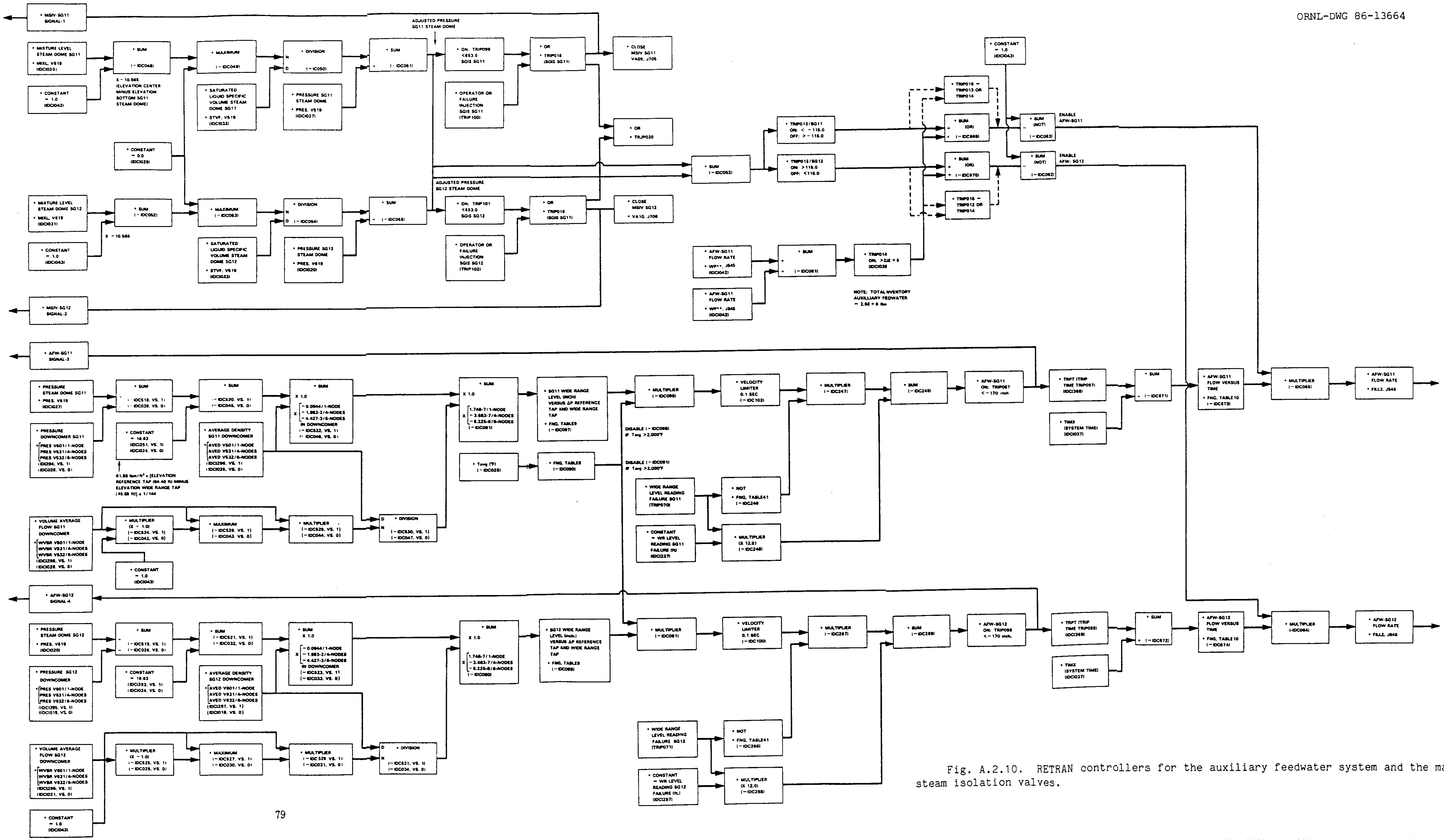

Fig. A.2.10. RETRAN controllers for the auxiliary feedwater system and the main steam isolation valves.

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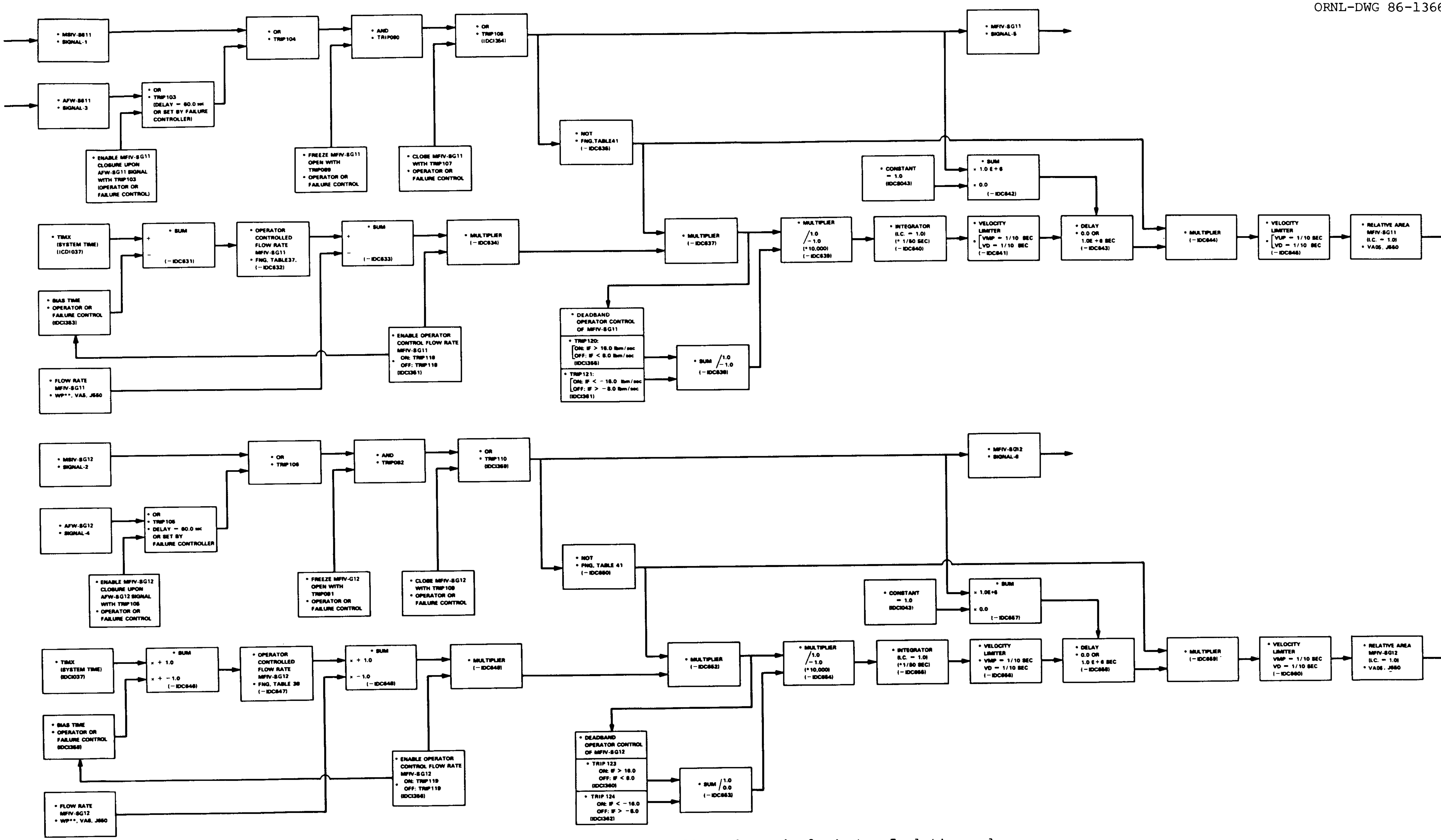

Fig. A.2.11. RETRAN controllers for main feedwater Isolation valves.

The WR level was fed into the RETRAN controllers that activate the auxiliary feedwater system using the RETRAN controller displayed in Fig. A.2.10. It was also previously used to control MFW isolation valves MFIV-SG11 (RETRAN valve VA005 at junction J550) and MFIV-SG12 (valve VA006 at junction J650) using the RETRAN controllers displayed in Fig. A.2.11.

A.3 SECONDARY SYSTEM

The secondary system (Fig. A.1.12) contains the following systems:

- main steam system
- main feedwater system
- auxiliary feedwater system
- secondary side of the steam generators

A.3.1 MAIN STEAM SYSTEM

The primary purpose of the main steam system is to transfer steam from the steam generators to the main steam turbines and to transform the heat contained in the steam into electrical power via the turbine generator unit.

The main steam system contains the following principal components:

- main steam lines
- two main steam isolation valves (MSIVs), which close upon a steam generator isolation signal (SGIS).
- two atmospheric dump valves.
- four main steam safety relief valves (SRV) on each main steam line.
- four main steam bypass valves (MSBV) and main steam bypass lines to the condenser hotwell unit.
- four main steam stop valves (MSSV).
- four main steam turbine regulating valves (MSRV).
- one turbine generator unit, containing a high-pressure turbine (HPT), two moisture separator reheater units, and three low-pressure turbines (LPTs). (The turbine generator unit for Calvert Cliffs-1 is a General Electric Co. design, and Calvert Cliffs-2 is a Westinghouse Corp. unit.)
- a three-shell, single-pass condenser-hotwell unit.
- two main-feedwater pumps.
- two main-feedwater-pump steam turbines (not included in the RETRAN model).

Exact pipe lengths, volumes, diameters, and elevations have been preserved as much as possible unless otherwise stated. Note that the pipe sections of the main steam lines from SG-11 and SG-12 are different lengths and elevations. Thus the main steam lines are asymmetrical. This was taken into account in the RETRAN model.

A.3.1.1 Main Steam Lines

A 34-in.-diam pipe section connects the outlet of each steam generator to the main steam isolation valve. In the RETRAN model each of these pipe sections was modeled with two RETRAN volume nodes, V523 and V514 for SG-11, and V623 and V524 for SG-12 (see Fig. A.1.2).

Each main steam line is equipped with an venturi type insert flow restrictor. In the RETRAN model, flow restrictors were modeled as controlled valves at RETRAN junction J523 for SG-11 and J623 for SG-12. Each restrictor is designed to limit the steam flow rate to 170% of normal flow rate (at 100% power) in the steam line in the event of a main steam line rupture downstream of the restrictors. Each main steam line section is equipped with an atmospheric dump valve (see RETRAN valve VA012 at junction J594 for SG-11 and VA013 at junction J694 for SG-12 in Fig. A.1.2) and four main steam line safety relief valves.

The emplacement of safety relief valves (SRVs) is displayed in Fig. A.1.2. For the steam line section that connects to SG-11 we have the following SRVs:

- SRV1: modeled as RETRAN FILL5 at junction J590, connected to volume node V524
- SRV2: modeled as FILL6 at junction J591, connected to volume node V524
- SRV3: modeled as FILL7 at junction J592, connected to volume node V524
- SRV4: modeled as FILL8 at junction J593, connected to volume node V524.

We have the following SRVs for the steam line section that connects to SG-12:

- SRV1: modeled as RETRAN FILL9 at junction J690, connected to volume node V624
- SRV2: modeled as FILL10 at junction J691, connected to volume node V624
- SRV3: modeled as FILL11 at junction J692, connected to volume node V624
- SRV4: modeled as FILL12 at junction J693, connected to volume node V624.

Downstream of each main steam isolation valve we have a 34-in.-diam pipe section (see volume node V712-SG11/V714-SG12 in Fig. A.1.2). The main steam bypass line (RETRAN volume node V719) is connected to the main steam line section represented by volume node V712. The flow through main steam line volume nodes V712 and V714 is discharged into a collector main steam line represented by RETRAN volume node V715. Four 24-in.-diam lines are connected to volume node V715. Through each of those lines, saturated steam from the steam generators is supplied to the main steam turbine throttle through four main steam stop valves (MSSVs) and four governing control (regulating) valves (MSRVs).

Note that the main steam turbines possess a trip system that closes the main steam stop valves and main steam regulating valves in the event of turbine overspeed or low vacuum in the condenser hotwell unit. The turbines also trip 0.1 s after a reactor scram signal.

A.3.1.2 Main Steam Isolation Valves

Upon depressurization of a steam generator, a steam generator isolation signal (SGIS) will close the main steam isolation valves (MSIV-SG11/MSIV-SG12) and the MFW isolation valves (MFIV-SG11/MFIV-SG12) associated with the depressurized steam generator.

The RETRAN control diagrams that control this closure are shown in Fig. A.2.10. The MSIV will close when the adjusted pressure in the SG dome drops below a given set point. Upon this SGIS, the MSIV will close, thus isolating the steam generator (see RETRAN control diagram in Fig. A.2.11). Note that in the model, MSIV-SG11 and MSIV-SG12 have been programmed to close completely in 3.5 s.

A.3.1.3 Atmospheric Dump Valves

An atmospheric dump valve (ADV) is connected to the main steam line of each SG. These valves are controlled by the average core coolant temperature T_{avg}. The ADVs are represented as RETRAN valves VA012 at junction J594 for SG-11 and VA013 at junction J694 for SG-12 (see Fig. A.1.2).

The RETRAN controllers simulating operation of the ADVs are shown in Fig. A.3.1. A hysteresis type of opening upon T_{avg} is used. The ADVs are each sized to release steam at a rate of 5% of the full-power steam flow through one main steam line. The RETRAN control diagram to calculate T_{avg} is shown in Fig. A.3.2.

A.3.1.4 Main Steam Safety Relief Valves

There are four SRVs in the main steam line of each steam generator. They are programmed to open at different pressure set points: SRV1 at 1000 psia, SRV2 at 1010 psia, SRV3 at 1030 psia, and SRV4 at 1050 psia. The RETRAN control diagrams that simulate operation of these four valves are shown in Fig. A.3.3.

A.3.1.5 Main Steam Bypass Lines

The main steam bypass line (RETRAN volume node V719 in Fig. A.1.2.) is a 24-in.-diam pipe connected to the main steam line of SG-11, downstream of MSIV-SG11.

Four separate 10-in.-diam pipe sections are connected to this bypass line, each containing a main steam bypass valve (MSBV). Steam passing through the MSBVs is dumped into one of the shells of the three-shell, single-pass condenser-hotwell unit. Each of the three shells is internally equipped to dump 20% of main steam capacity at full power. However, only two shells are connected to the bypass lines, thus yielding an equivalent dumping capacity of 40% of full-power steam, or an equivalent power of 1080 MW(th).

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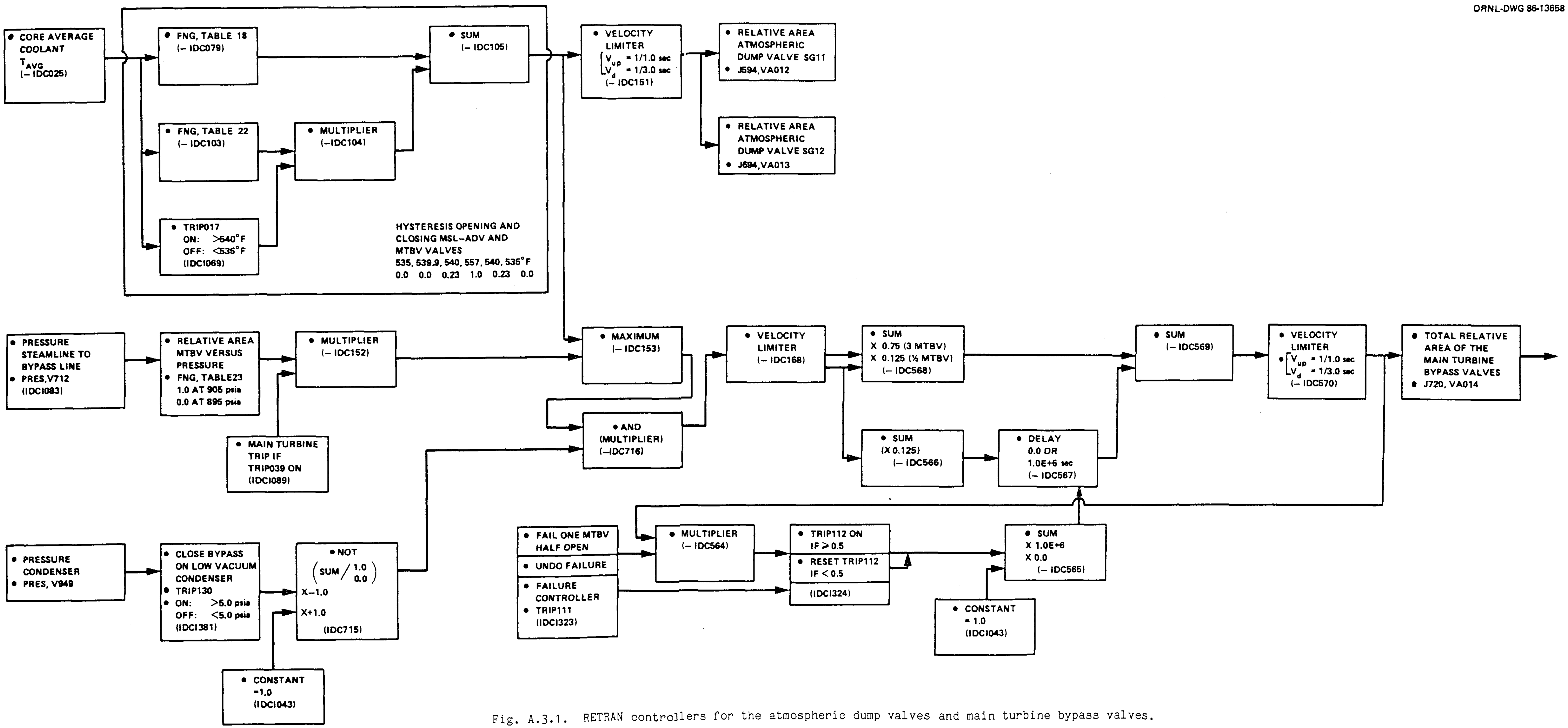

Fig. A.3.1. RETRAN controllers for the atmospheric dump valves and main turbine bypass valves.

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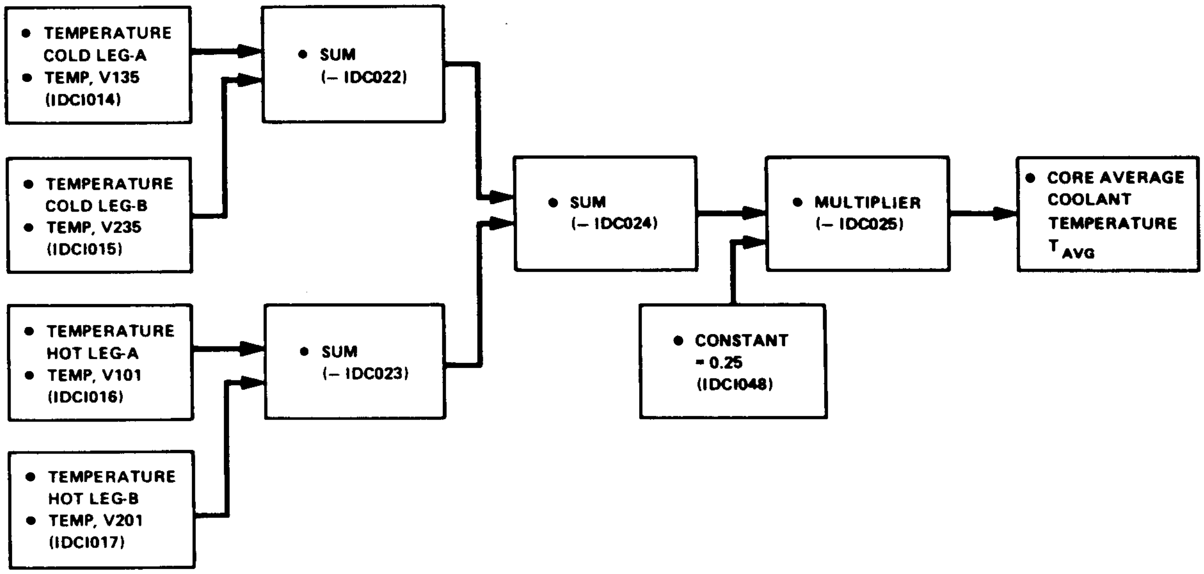

Fig. A.3.2. RETRAN controller for the average core coolant temperature.

The main steam bypass system is designed to provide a means of dissipating excess stored energy within the primary coolant system following a main steam turbine trip, thus minimizing an overshoot in secondary pressure and avoiding lifting the main steam line SRVs.

Steam flow through the main steam lines via the dump valves and the MSBVs is regulated by the RETRAN controller of the MSBVs in response to reactor core average coolant temperature (T_{avg}) and to the main steam line pressure (see RETRAN control diagrams in Fig. A.3.1 and A.3.2).

Note that at hot zero power (HZP), the main steam turbine stop valves (MSSVs) are closed and the MSBVs are open. The steam generated at HZP in the steam generators will therefore be dumped directly into the condenser hotwell unit via the bypass lines.

In the RETRAN model, the four 10-in. pipe sections were combined into one volume node V718 of equivalent volume, and the four MSBVs were combined into one valve, RETRAN valve VA014 at junction J720.

A.3.1.6 Main Steam Bypass Valves

The four main steam bypass valves were combined into one RETRAN valve, sized such that the maximum steam flow at normal conditions does not exceed 40% of the full-power steam flow through the main steam lines. The RETRAN control diagram, which controls the opening and closing of the MSBVs is shown in Fig. A.3.1. The bypass valves open under the following conditions:

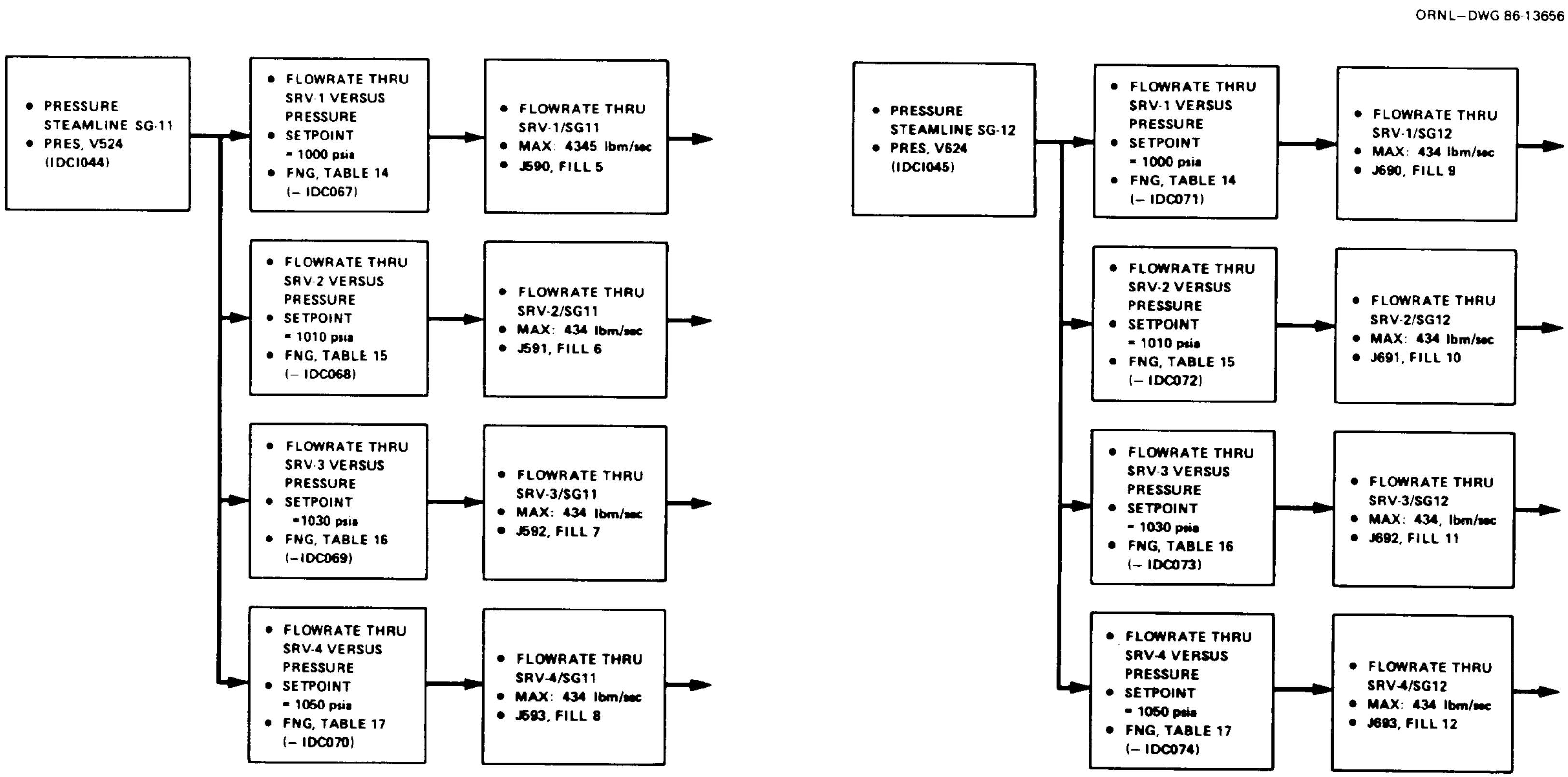

Fig. A.3.3. RETRAN controllers for the main steam safety relief valves.

1. Reactor core coolant average temperature (T_{avg}) exceeds a set point of ~535°F. Note that hysteresis behavior is incorporated into the controller to T_{avg}.
2. Pressure in the main steam line section of SG-11 downstream of MSIV-SG11 exceeds a set point of ~895 psia. The bypass valves are then gradually opened and are fully open at 905 psia.
3. Main steam turbine trip will close the MSSVs and open the MSBVs.

Note that the turbine bypass valves are interlocked closed on loss of condenser vacuum. Loss of on-site power will also cause the steam dump valves and MSBVs to fail closed and remain closed. This feature (loss of on-site power) was not implemented in the RETRAN model.

A.3.1.7 Main Steam Stop Valves and Main Steam Regulating Valves

In the RETRAN model, the main steam stop valves (MSSVs) and the main steam regulating valves (MSRVs) were combined into one valve, RETRAN VA015 at junction J730. The RETRAN control diagram that controls MSSVs and MSRVs is not shown as it contains proprietary information.

The MSRV is controlled by the main steam turbine control system, which depends on

- steam flow
- steam line pressure
- turbine speed (speed error)
- power load mismatch.

Note that the MSSVs will close upon main steam turbine trip (Fig. A.1.11). This trip occurs

- at 0.1 s after a reactor trip (scram)
- on turbine overspeed
- on low vacuum in the condenser hotwell unit.

A.3.1.8 Main Steam Turbine Generator and Moisture Separator Reheaters

The turbines are 1800-rpm tandem compound units. Saturated steam is supplied through the main steam stop valves (MSSVs) and the main steam regulating valves (MSRVs) to the header of a two-flow, high-pressure turbine (HPT). The exhaust of the HPT is then directed to two moisture separator reheater units. (Note that Calvert Cliffs-2 has four moisture separator reheater units). The steam from the reheaters is then directed to three double-flow, low-pressure turbines (LPTs) whose exhaust is directed to the condenser-hotwell unit. The high-pressure and low-pressure turbines share the same shaft.

In the RETRAN model, the HPT was represented by five RETRAN volume nodes: V730, V441, V442, V443, and V444. The three LPTs were combined into one turbine containing seven RETRAN volume nodes: V465, V466, V467, V468, V470, and V471. The two moisture separator reheaters were combined into one unit containing three modules: a RETRAN moisture separator, a first-stage reheater, and a second-stage reheater.

A.3.1.9 Main Condenser-Hotwell Unit

The outlet of the three low-pressure main steam turbines, the steam from the main steam bypass lines, the outlet of the MFW pump turbines, the drain from the feedwater drain coolers, the feedwater from the recirculation lines of the MFW pumps, the condensate booster pumps, and the condensate pumps are directed to a three-shell, single-pass condenser-hotwell unit. The condenser is designed to condense exhaust steam from vapor to liquid at an absolute pressure of ~1 psia (2 in. Hg) at 101°F, assuming a river-water inlet temperature of 70°F.

The condensation process is necessary because it is more efficient to pump a liquid than a vapor from the hotwell to the steam generators. The condensed steam is collected in the hotwell at the bottom of each shell of the condenser-hotwell unit. At normal operating conditions, each shell will contain in its hotwell ~25,600 gal of condensate.

In the RETRAN model the three condenser shells were combined into one volume node on the shell side (V949/V720), and the hotwells were combined into one hotwell (V988/V720). Circulating water from the river passes through the tubes in the condenser.

In the RETRAN model, the condenser hotwell condensation surface is ~1.36 Mft^2, with a total heat removal rate of 5.9E+9 Btu/h. Water flow through the tube side is ~320 lbm/s. Circulating water enters the tubes at 70°F through RETRAN fill F38 at junction J957 and fill F42 at junction J987.

Note again that the condenser hotwell unit has the capacity to absorb 40% of the full-power steam flow through the main steam bypass lines.

Due to changing load conditions, thermal-hydraulics properties in the primary and secondary systems will change, and the mixture level in the hotwell will vary. The mixture level in the hotwell, represented by RETRAN volume node V988, is maintained between two set points by injecting (on low level) or removing (on high level) fluid from the secondary system, using makeup/dump valves at the low and high hotwell set point levels. The valves allow liquid to flow from or to the condensate storage tank (CST).

A level transmitter in the hotwell transmits a signal corresponding to the hotwell level, to the condenser-makeup-and-dump controller. The controller opens the dump valve on high level, allowing condensate to flow from the discharge header of the condensate pumps (RETRAN volume node V937 in Fig. A.1.12) to the condensate storage tank. The controller opens the makeup valve on low level, allowing water to flow from the condensate storage tank to the hotwell (RETRAN volume node V988/V720 in Fig. A.1.12).

The RETRAN control diagram of the condenser makeup and dump controller is displayed in Fig. A.3.4). The function of the storage tank, makeup/dump valves and their associated control system were replaced by the following:

1. On low level (48 in.) in the hotwell, a makeup valve opens, injecting water into the hotwell using RETRAN fill F43 at junction J481, thus increasing the water inventory in the secondary system.

2. On high level (54 in.) in the hotwell, a dump valve opens in the discharge header of the condensate pumps, using RETRAN fill F44 at junction J482, allowing water to flow from the feedtrain to the condensate storage tank, thus reducing the water inventory in the secondary system.

A.3.2 AUXILIARY FEEDWATER SYSTEM

The auxiliary feedwater (AFW) system is designed to inject feedwater into the steam-generators to remove decay heat and to cool the coolant in the primary system when feedwater is not available from the main feedtrain.

Auxiliary feedwater is injected into SG-11 through RETRAN FILL3 at junction J545 (Figs. A.2.1, A.2.3, and A.2.5), and into SG-12 through FILL2 at junction J645 (Figs. A.2.2, A.2.4, and A.2.6).

The AFW system consists principally of a steam-turbine-driven pump and a motor-driven pump. The pumps start upon an AFW activation signal (AFAS). In automatic control mode, this signal occurs when

1. the wide-range (WR) level in one of the SGs drops below the -170 in. set point. However, AFW will not be injected if the difference in the adjusted pressures in the steam dome of the steam generators is greater than 95 psia.

2. upon equipment malfunction: failure of condensate pumps, condensate booster pumps, or MFW pumps.

3. malfunction of the controller of the MFW regulating valves causing all MFW valves to close.

4. loss of on-site power (not implemented).

In manual control mode, the operator

1. closes both of the MFW regulating valves, MFRV-SG11 and MFRV-SG12.

2. closes both of the MFW isolation valves, MFIV-SG11 and MFIV-SG12.

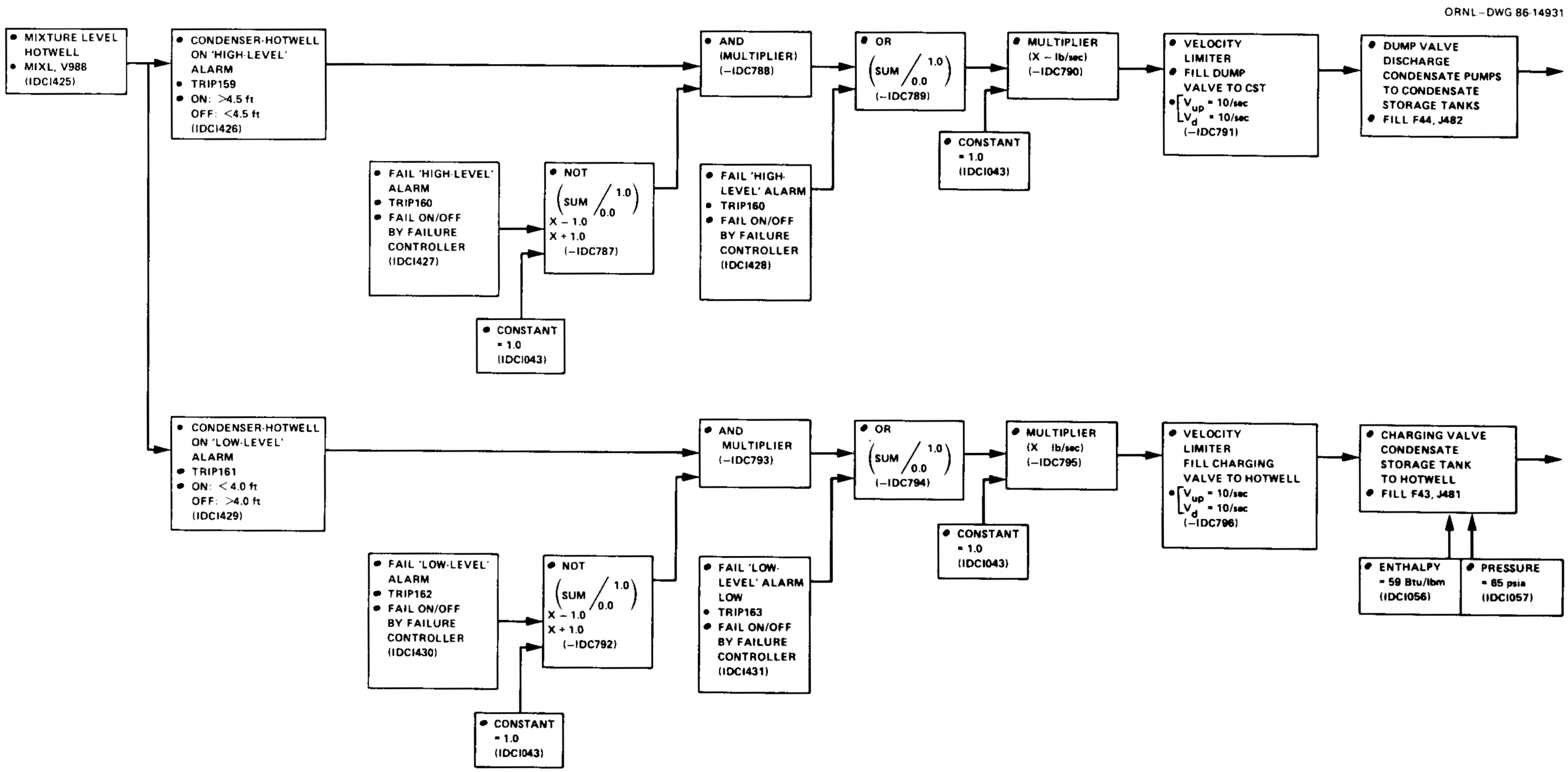

Fig. A.3.4. RETRAN controller for the condenser-hotwell unit makeup and dump valves.

The RETRAN control diagram to simulate the AFW system is displayed in Fig. A.2.10. Note that the suction of the auxiliary pumps comes directly from the condensate storage tank. Since the tank contains a finite amount of fluid, a limit was set on the total amount of fluid that can be injected through the auxiliary system.

A.3.3 MAIN FEEDWATER TRAIN

The primary purpose of the MFW system is to transfer the condensate of the condenser hotwell unit to the input of the steam generators, while raising the temperature and pressure of the condensate to the operating conditions required by the SGs. Another purpose of the feedtrain is to raise the thermal conversion efficiency of the power plant.

The steam coming from the exhaust of the three low-pressure steam turbines is converted from a vapor to a liquid at a constant temperature of 101°F and pressure of 2 in. Hg. The low temperature and pressure of the condensate means that considerable heat and compression must be added to convert it to SG conditions.

The feedtrain can be subdivided into three parts:

1. A high-pressure feedtrain containing FW heaters 16A and 16B, the MFW regulating valves (MFRV), the MFW bypass valves (MFBV), and the MFW isolation valves (MFIV-SG11 and MFIV-SG12).

2. Main-feedwater pumps MFWP-11 and MFWP-12.

3. A low-pressure feedtrain containing FW heaters 15A and 15B, 14A and 14B, 13A and 13B, 12A, 12B and 12C, 11A, 11B and 11C, two drain tanks, two drain tank pumps, three condensate booster pumps, three condensate pumps, and three drain coolers.

Following a main turbine trip, the bleeder valves in the steam extraction lines from the high-pressure turbine and the three low-pressure turbines to the FW heaters will close. In the RETRAN model, the extraction-line valves that will close upon a main turbine trip are as follows (see Fig. A.1.12):

- RETRAN valve VA031 at junction J461 and VA033 at junction J463, to high-pressure FW heaters 16A and 16B.

- RETRAN valve VA038 at junction J953 to low-pressure FW heaters 14A and 14B.

- RETRAN valve VA039 at junction J954 to low-pressure FW heaters 13A and 13B.

- RETRAN valve VA040 at junction J955 to low-pressure FW heaters 12A, 12B, and 12C.

- RETRAN valve VA041 at junction J956 to low-pressure FW heaters 11A, 11B, and 11C.

A.3.3.1 High-Pressure Feedtrain

In the high-pressure condensate system, FW flows from MFW pumps MFWP-11 and MFWP-12 through one set of high-pressure FW heat exchangers, prior to its entry into the MFW lines to the steam generators, via MFW regulating valves MFRV-SG11 and MFRV-SG12 and MFW isolation valves MFIV-SG11 and MFIV-SG12.

A.3.3.1.1 Main Feedwater Isolation Valves. Upon depressurization of one of the SGs, a steam generator isolation signal (SGIS) for that SG will close the main feedwater isolation valve (MFIV) associated with the depressurized SG.

The MFIV to SG-11 (MFIV-SG11) is located downstream of the main feedwater regulating valve (MFRV) to SG-11. In the RETRAN model, it is displayed (Fig. A.1.12) as valve VA005 at junction J550.

The MFIV to SG-12 (MFIV-SG12) is located downstream of the MFRV to SG-12. In the RETRAN model, it is displayed (Fig. A.1.12) as valve VA006 at junction J650.

The MFIV-SG11 will close when the adjusted pressure in the steam dome of SG-11 drops below a given set point. Note that MSIV-SG11, represented as RETRAN valve VA009 at junction J705 in Fig. A.1.2, will also close upon this steam-generator-isolation signal (SGIS-SG11).

Similarly, MFIV-SG12 will close when the adjusted pressure in the steam dome of SG-12 drops below a given set point. Note that the main-steam-isolation valve MSIV-SG12, represented as RETRAN valve VA010 at junction J706 in Fig. A.1.2 will also close upon this steam generator isolation signal (SGIS-SG12).

The RETRAN control diagrams that simulate the operation of the MFIV are shown in Fig. A.2.10 and A.2.11. The MFIV-SG11/MFIV-SG12 valves have been modeled to close in ~10 s upon a SGIS-SG11/SGIS-SG12 signal. Note that a SGIS produces a trip of both MFW pumps. This is displayed in Fig. A.3.5.

A.3.3.1.2 Main Feedwater Regulating Valves and Bypass Valves. The MFW regulating system maintains the measured SG level within acceptable limits by regulating the opening of MFRV-SG11 and MFRV-SG12. There is one regulating valve per SG, and it controls the FW to each SG. In parallel to each MFRV there is a MFW bypass valve (MFBV-SG11 and MFBV-SG12), which has a flow capacity of ~5% of the capacity of the MFRV valve.

The MFW regulating valve to SG-11 (MFRV-SG11) and the main feedwater bypass valve (MFBV-SG11), are shown in Fig. A.1.12 as RETRAN valve VA007 at junction J552. Similarly, MFRV-SG12 and MFBV-SG12 to SG-12 are shown as RETRAN valve VA008 at junction J652.

The two steam-generators, SG-11 and SG-12, are operated in parallel. The MFRVs of the SGs can be operated in two different modes, automatic or manual.

Manual control of the MFW regulating system is available at any power level. The operator then has control of

- the position of MFRV-SG11 and MFRV-SG12
- the position of MFBV-SG11 and MFBV-SG12
- the open or close position of MFIV-SG11 and MFIV-SG12
- the individual speed of each of MFW pumps MFWP-11 and MFWP-12.

Automatic control of the MFW regulating system operates in two different configurations:

1. At or above 15% of full power, a three-element control configuration is used on each SG in order to maintain the level in the SG within acceptable limits. The three-element controller is based on MFW flow, steam flow, and SG level.

   In this mode the total error signal is based on the sum of the following errors:

   - flow error between measured main steam flow and measured MFW flow and

   - level error between the measured narrow-range level in the SG and the desired level (normally at 0 in. relative level).

2. Below 15% of full-power, a one-element control configuration is used in each SG. The one-element controller is based on the error between the measured narrow-range level in the SG and the desired level. This mode can be used because below 15% of full power most likely there are no "shrink-and-swell" effects, which might give misleading values of the true SG level. Note that the one-element controller is also used after shutdown (after a turbine trip) and for startup.

Upon a main steam turbine trip, the MFW regulating valves are automatically closed using a complicated preprogrammed function of valve opening versus time (i.e., time relative to the time at which the turbine trip occurred). At the same time the MFW bypass valves automatically open to 5% of MFRV full flow. Note, however, that a trip override is available to manually control the opening of the MFW bypass valves.

Note that in the automatic control mode of the MFW valves, manual control of one or both of the MFW regulating valves is always possible.

The RETRAN control diagram to simulate operation of the MFRVs and MFBVs of SG-11 is shown in Fig. A.2.8, and the diagram for SG-12 is shown in Fig. A.2.9. Note that the control diagrams also display the determination of the measured SG narrow-range level, which is used in the automatic three-element and one-element control mode and in the manual control mode.

In the RETRAN model, the MFRVs and MFBVs for SG-11 were combined into one RETRAN valve, VA007 at junction J552, and for SG-12 they were combined into RETRAN valve VA008 at junction J652 (Fig. A.1.12). Note, however, that the distinct features and differences in the operation of the MFRVs and MFBVs were specifically modeled in the RETRAN controllers.

The outputs of the two controllers are used to provide analog signals to set the position of the MFRVs. A proportional integrator was used in the RETRAN controller so that, for a zero value of the error, the controller will have an output and will hold the MFRV opening to its position.

At full power, the steady-state opening of the MFW regulating valves was determined by the model to be ~90% of the maximum valve opening.

A.3.3.1.3 High Pressure Feedwater Heaters 16A and 16B. Feedwater flows from the discharge of the MFW pumps MFWP-11 and MFWP-12 into two high-pressure FW heaters, 16A and 16B. The MFW leaving the high-pressure heaters then enters SG-11 and SG-12 via MFRV-SG11/MFRV-SG12 and MFIV-SG11/MFIV-SG12.

Main feedwater heaters 16A and 16B possess a 'U-tube' design, and the shell-tube heat transfer area is ~23,400 ft^2 per heater. In the RETRAN model, the high-pressure FW heaters were modeled as RETRAN heater FW01 using volume node V950 tube-side and V904 shell-side for heater 16A, and RETRAN heater FW07 using volume node V951 tube-side and V905 shell-side for heater 16B (Fig. A.1.12). Extraction steam from the high-pressure turbine, together with steam from the second stage of the moisture separator reheater units, is used to raise the MFW temperature in the tube side of high-pressure FW heaters 16A and 16B.

A.3.3.2 Main Feedwater Pumps

The main feedwater pumps MFWP-11 and MFWP-12 [also called steam generator feedpumps (SGFP)] are used in the FW system to connect the low-pressure feedtrain to the high-pressure feedtrain. In the plant the MFW pumps are driven by small turbines. At power the steam comes from the main steam lines between the moisture separator reheater units and the low-pressure turbines. At shutdown, the steam comes from the main steam lines. The speed of the small turbines is controlled by steam-regulating valves.

In the RETRAN model, the small MFW pump turbines are not modeled, and the speed of the MFW pumps is directly controlled with the MFW pump control system displayed in Fig. A.3.5.

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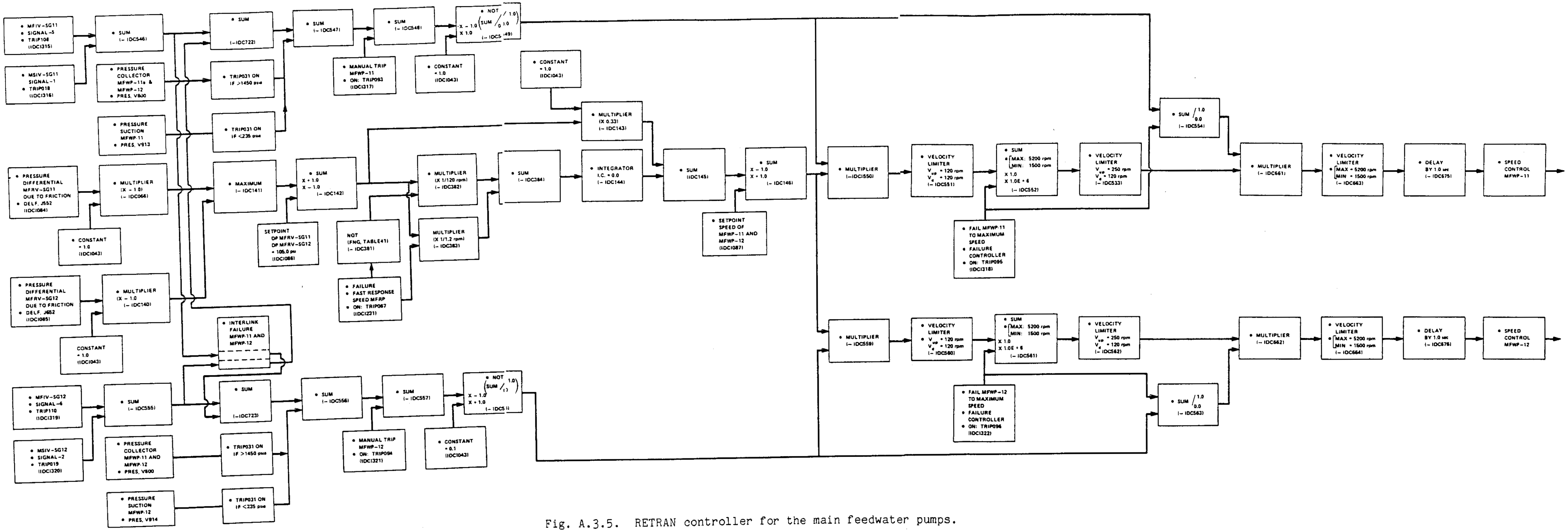

Fig. A.3.5. RETRAN controller for the main feedwater pumps.

Main feedwater pumps MFWP-11 and MFWP-12 are represented respectively in the RETRAN model as pump P30 using volume node V911 (V803), and pump P40 using volume node V912 (V804) (Fig. A.1.12). Each pump has a rated flow of 15,000 gpm and a rated speed of 5,130 rpm. The head, power, and torque versus flow-rate curves of the pumps were provided by the vendor and converted into RETRAN-compatible homologous pump curves.

In automatic control mode, the MFW pump-speed controller operates by using pressure transmitters sensing the differential pressure across valves MFRV-SG11 and MFRV-SG12. The MFW pump-speed controller is set to maintain a fixed differential pressure of ~105 psi across each of the the MFRVs. The larger of the differential pressures is then used to generate an error signal, which is injected into a proportional integrator whose output then controls the steam admission valve to each of the MFW-pump steam turbines in order to change the pump speed.

Note that in the controller implemented in the RETRAN model, the output of the proportional integrator is used to directly control the speed of the MFW pumps because the small MFWP steam turbines were not modeled. The proportional gain was set at 1/3, and the gain of the integrator was set at 1/120 rpm. Conversion of the differential pressure ΔP to Δrpm was made by using a ΔP scale of 1:150 psi, corresponding to a pump rpm scale of 3070 to 5200 rpm. The lower end of the rpm scale is the minimum speed at which (under normal operating pressures) the MFW pumps will have a positive net flow.

Note that there is a direct relationship between SG level, MFRV opening, and MFW pump speed. A level error in one of the SGs will cause the MFRV controller to that SG to change the opening of the MFRV. This change will cause the differential pressure across the valve to deviate from the set point of 105 psi. The MFW pump controller will minimize the error by changing the speed of the MFW pump based on the higher ΔP value of the MFRVs.

The steady-state solution to the RETRAN model, followed by a null-transient at hot-full-power, gave a settled value of ~4642 rpm for the speed of the MFW pumps based on a FW flow rate of 1637 lbm/s/pump.

Each of the two MFW pumps requires a minimum flow-through of 498 lbm/s to prevent pump damage. A flow detector in the suction line of each pump will open a valve in the recirculation line of each respective pump when its flow drops below 498 lbm/s. The recirculation valve controllers will close the valve when the flow reaches 600 lbm/s. The RETRAN control diagrams for the recirculation valves of the MFW pumps are displayed in Fig. A.3.6, and the recirculation valves are displayed in Fig. A.1.12 as RETRAN valve VA018 at junction J806 for MFWP-11 and VA019 at junction J807 for MFWP-12.

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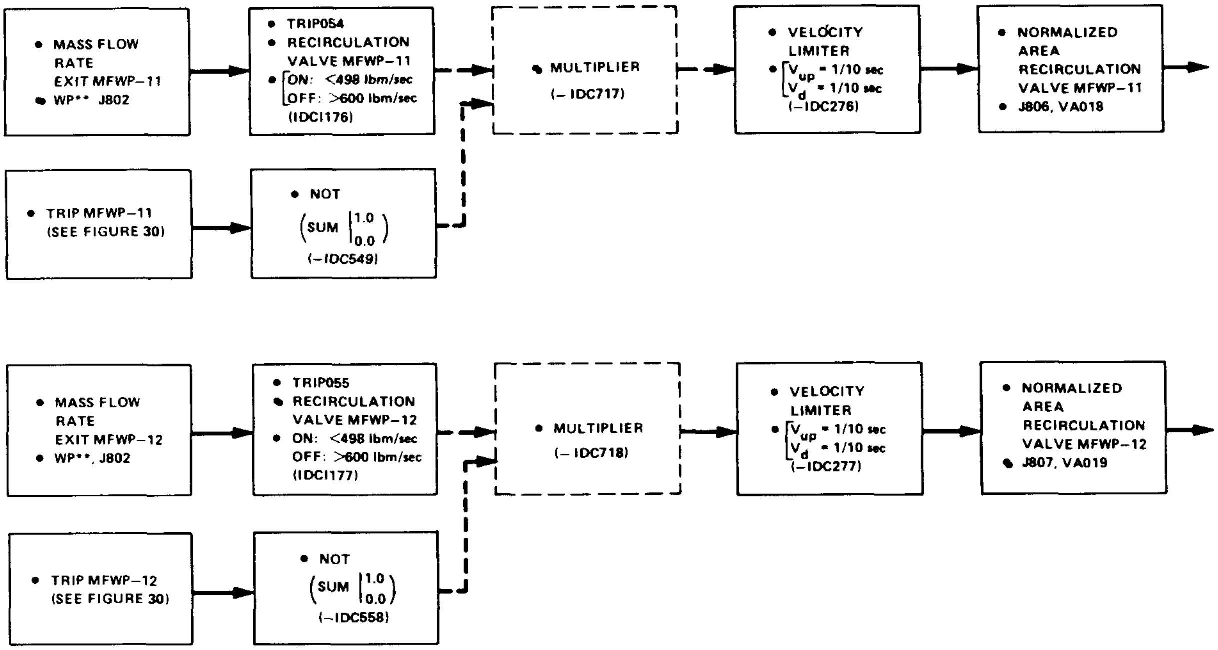

Fig. A.3.6. RETRAN controllers for the recirculation valves of main feedwater pumps MFWP-11 and MFWP-12.

The following MFW pump trips were used in the RETRAN model:

- Feed-pump discharge pressure exceeds 1450 psia (high-pressure discharge trip).
- Feed-pump suction pressure drops below 235 psia (low-pressure suction trip).
- Closing of MFIV-SG11 or MFIV-SG12.

A.3.3.3 Low-Pressure Feedtrain

In the condensate water system, the MFW flows through five sets of low-pressure FW heat exchangers prior to its entry into the suction of the MFW pumps. The condensate pumps and the condensate booster pumps increase the pressure of the MFW to provide adequate suction pressure for the MFW pumps.

A.3.3.3.1 Condensate Pumps. The condensate from the condenser-hotwell unit goes through three parallel condensate pumps prior to its entry into three drain-coolers.

Condensate pumps CP-11, CP-12 and CP-13 are represented respectively in the RETRAN model as RETRAN pump P61 using volume node V941, P62 using volume node V942, and P63 using volume node V943. The condensate pumps are centrifugal pumps, each having a rated flow of 8250 gpm at a rated speed of 1180 RPM. Operating discharge pressure is ~215 psia. The head, power, and torque versus flow-rate curves of the condensate pumps were converted into RETRAN-compatible homologous pump curves.

The number of operating condensate pumps depends on the power level of the plant and the discharge header pressure of the pumps. The following sequence was used:

- 0 to 50% of full power: CP-11 operating (RETRAN pump P61).
- 50 to 80% of full power: CP-11 and CP-12 operating (RETRAN pumps P61 and P62).
- above 80% of full power: CP-11, CP-12, and CP-13 operating (RETRAN pumps P61, P62, and P63).
- when the discharge pressure drops below 180 psia, the next non-operating condensate pump will start.

The RETRAN control diagrams that implement this sequence in the model are displayed in Fig. A.3.7.

The three condensate pumps require a minimum flow of 4400 gpm each when in operation, to prevent pump damage on low flow or when operating against shut-off head. A flow detector in the suction head of each pump sends a signal to the condensate pump minimum-flow controller. The minimum-flow RETRAN control diagram is displayed in Fig. A.3.7. When the flow drops below the minimum flow set point, the controller will open a valve in the recirculation line back to the condenser-hotwell unit. If the flow is greater than the minimum required flow, the minimum-flow controller of each condensate pump will close the recirculation valve associated with that particular pump. Note that in the RETRAN controller, the minimum-flow controller of a condensate pump is deactivated if the pump is tripped.

The recirculation valves from the condensate pumps are represented in Fig. A.1.12 as RETRAN VA046 at junction J991 for condensate pump CP-11, VA047 at junction J992 for condensate pump CP-12, and VA048 at junction J993 for condensate pump CP-13. In order to avoid reverse flow in the condensate pumps, RETRAN check valves were placed at junctions J937, J938, and J939.

A.3.3.3.2 Drain Coolers. The flow from the discharge of the condensate pumps is directed to three parallel drain coolers. In the RETRAN model drain coolers DC-11, DC-12, and DC-13 were combined into one unit, RETRAN volume nodes V936 tube-side and V957 shell-side. The drain coolers receive and condense the drain from low-pressure FW heaters 11A, 11B, and 11C below the saturation temperature. The drain coolers have a heat transfer area of ~2800 ft^2.

Note that in the RETRAN model the demineralizers were not modeled.

A.3.3.3.3 Low Pressure Feedwater Heaters 11 and 12. Prior to entering the suction of the condensate booster pumps, the condensate water flows through three parallel loops, each containing a drain cooler, a low-pressure FW heater 11, and a FW heater 12.

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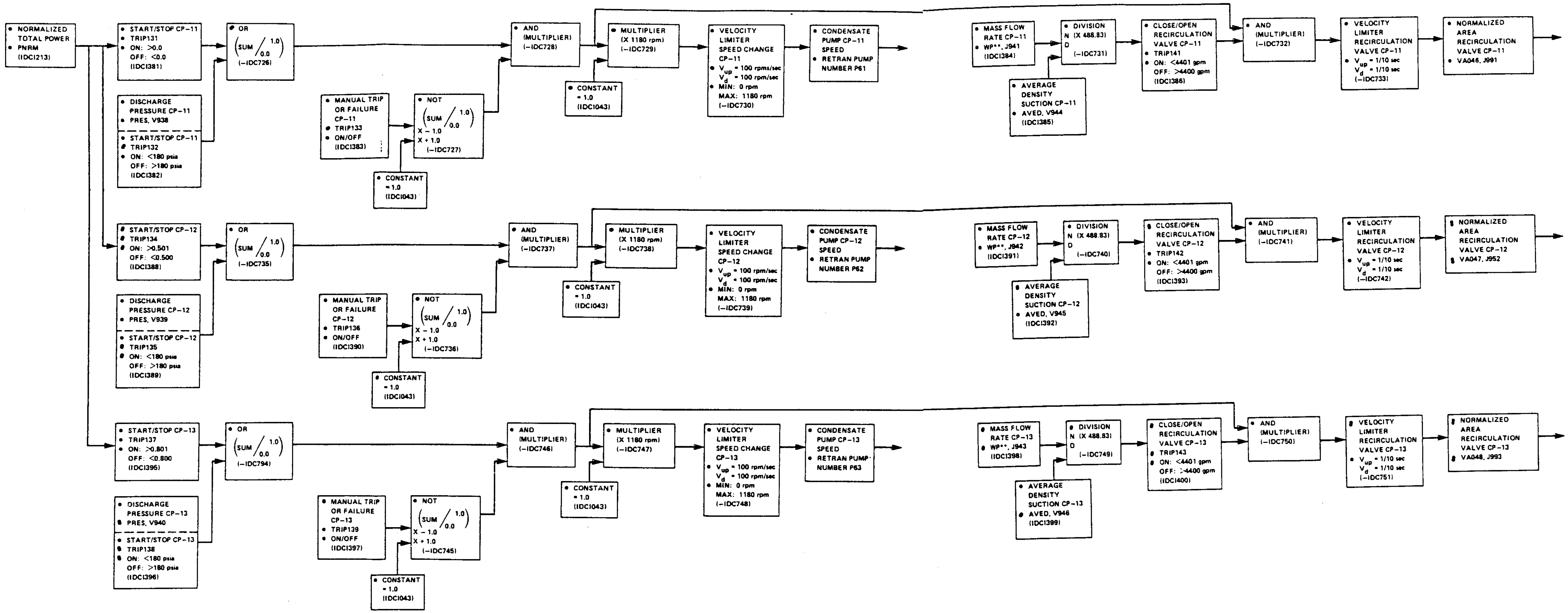

Fig. A.3.7. RETRAN controllers for the pump speed and recirculation valves of the condensate pumps.

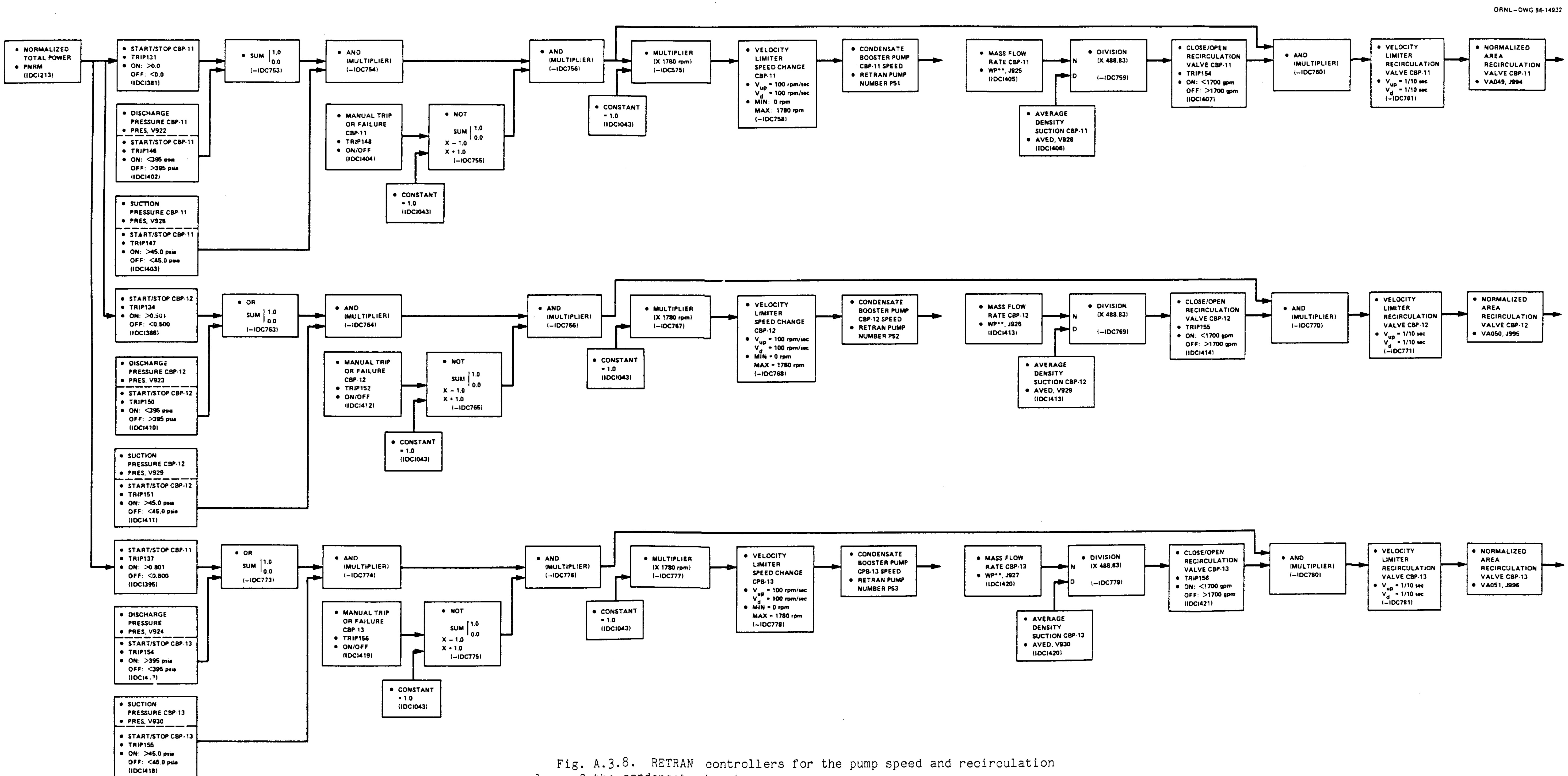

Fig. A.3.8. RETRAN controllers for the pump speed and recirculation valves of the condensate booster pumps.

Extraction steam from the 12th stage of the low-pressure steam turbines is used to raise the condensate temperatures in heaters 11A, 11B, and 11C. Extraction steam from the 10th stage of the low-pressure turbines and the drain from FW heaters 13A and 13B are used in heaters 12A, 12B, and 12C.

In the RETRAN model FW heaters 11A, 11B, and 11C were combined into one heater, RETRAN heater FW02, composed of volume nodes V934 tube-side and V956 shell-side. Feedwater heaters 12A, 12B, and 12C were combined into one heater, RETRAN heater FW03, using volume nodes V932 tube-side and V955-shell-side.

A.3.3.3.4 Condensate Booster Pumps. The condensate water from FW heaters 12 enter the suction of the condensate booster pumps. The booster pumps CBP-11, CBP-12, and CBP-13 provide the required pressure increase for the suction of the MFW pumps.

As shown in Fig. A.1.12, the booster pumps were represented in the RETRAN model as follows: RETRAN pump P51 using volume node V925 for condensate booster pump CBP-11, P52 using volume node V926 for CBP-12, and P53 using volume node V927 for CBP-13.

The condensate booster pumps are centrifugal pumps, each having a rated flow of 8540 gpm at a rated speed of 1780 rpm. The head, power, and torque versus flow-rate curves of the condenser booster pumps were converted into RETRAN compatible homologous curves. The number of operating condensate booster pumps depends on the power level of the power plant.

The following operating sequence was used:

- 0 to 50% of full power: CBP-11 operating (RETRAN pump P51).
- 50 to 80% of full power: CBP-11 and CBP-12 operating (RETRAN pumps P51 and P52).
- above 80% of full power: CBP-11, CBP-12, and CBP-13 operating (RETRAN pumps P51, P52, and P53).
- when the discharge pressure in the discharge header of the condensate booster pumps drops below 395 psia, the standby pump will be started automatically.

If suction pressure decreases below 45 psia, the pumps will trip (low pressure suction trip).

The RETRAN control diagrams that start and stop the condensate booster pumps following the above sequence and trips are displayed in Fig. A.3.8.

The three condensate booster pumps require a minimum flow of 1700 gpm each to prevent pump damage on low flow or when operating against shut-off head. When the flow drops below the minimum-flow set point a flow detector in the suction head of each pump sends a signal to the condensate booster pump miniflow controllers to open a recirculation valve downstream of that pump. When the flow is greater than this set point, the RETRAN controller will close the recirculation valve. The RETRAN control diagrams for the recirculation mini flow valves are displayed in Fig. A.3.8. The recirculation valves of the condensate booster pumps are represented in the RETRAN model (Fig. A.1.12) as RETRAN VA049 at junction J944 for condensate booster pump CBP-11, VA050 at junction J945 for pump CBP-12, and VA051 at junction J946 for pump CBP-13.

A.3.3.3.5 Low-Pressure Feedwater Heaters 13, 14, and 15. Prior to entering the suction of the MFW pumps MFWP-11 and MFWP-12, the condensate flows through two parallel loops composed of low-pressure FW heaters 13A-14A-15A and 13B-14B-15B (see RETRAN nodal diagram in Fig. A.1.12).

Feedwater heaters 13, 14, and 15 are of U-tube design. The shell-tube heat transfer areas of the heaters are approximately

- 16,900 ft^2 each for heaters 13A and 13B
- 11,800 ft^2 each for heaters 14A and 14B
- 22,200 ft^2 each for heaters 15A and 15B.

Extraction steam from the 8th stage of the three low-pressure steam turbines is used to raise the condensate temperature in FW heaters 13A and 13B, and extraction steam from the 7th stage is used in FW heaters 14A and 14B. Extraction fluid from the first stage of the moisture separator reheater units, together with the drain of high-pressure FW heaters 16A and 16B, is used to raise the condensate temperatures in the tube side of FW heaters 15A and 15B.

In the RETRAN model, FW heaters 13A and 13B were combined into one heater, RETRAN number FW04, using volume nodes V920 tube-side and V954 shell-side; FW heaters 14A and 14B were combined into one heater, RETRAN number FW05, using volume nodes V918 tube-side and V953 shell-side; and FW heaters 15A and 15B were combined into one heater, RETRAN FW06, using volume nodes V916 tube-side and V952 shell-side.

A.3.3.3.6 Heater Drain Tanks. Two heater drain tanks receive the following flows:

1. Drain from FW heaters 14A, 14B, 15A, and 15B; and
2. Drain from the moisture separator reheater units.

The fluid is subsequently injected back through two pumps into the low-pressure feedtrain via the MFW pipes located between low-pressure FW heaters 14 and 15. In the RETRAN model, the two heater drain tanks were combined into one volume node, V963 (see RETRAN nodal diagram in Fig. A.1.12).

Following a main turbine trip, the bleeder valves in the steam extraction lines from the high-pressure steam turbine to high-pressure FW heaters 16A and 16B, and from the low-pressure turbines to the low-pressure FW heaters, will close. The drain from the FW heaters to the heater-drain tanks (RETRAN volume node V963) will continue to flow until the liquid level in the drain tank trips on a low-level signal. The low-level signal will then close the valves in the drain lines to the heater drain tank and will also trip the heater drain tank pumps (RETRAN P70 using volume node V965).

The RETRAN valves that will close in the drain lines to the drain tanks are:

- RETRAN VA053 at junction J964, drain from low-pressure FW heaters 15A and 15B.
- RETRAN VA052 at J966, drain from low-pressure FW heaters 14A and 14B.
- RETRAN VA037 at J460, drain from the moisture separator reheater units.

The diagram of the RETRAN controller to close the valves and trip the drain tanks is shown in Fig. A.3.9.

A.3.3.3.7 Heater Drain Tank Pumps. The two heater drain tank pumps take their suction from the heater drain tanks, and they discharge their flow into the condensate water piping between low-pressure FW heaters 14 and 15. In the RETRAN model, the two heater drain tank pumps were combined into one pump, RETRAN P70, using volume node V965 (see RETRAN nodal diagram in Fig. A.1.12).

The drain-tank pumps are centrifugal pumps, each given a rated flow of 4290 gpm. These pumps will trip when the mixture level in the drain tanks falls below the low-level set point (see RETRAN control diagram in Fig. A.3.9).

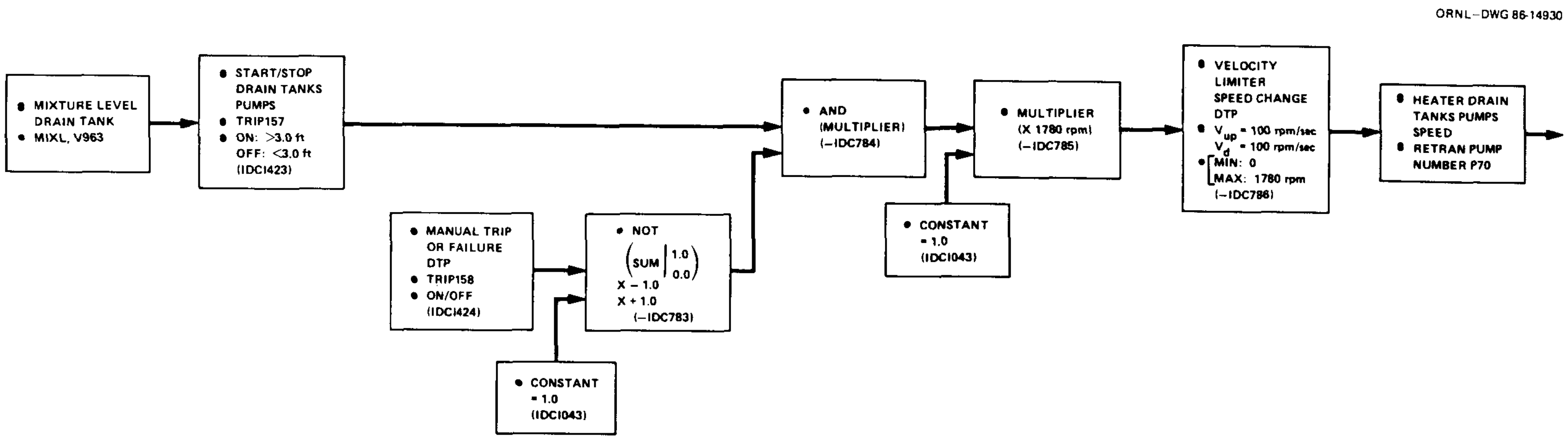

Fig. A.3.9. RETRAN controller for the heater drain tank pumps.

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