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A PRESSURIZED THERMAL SHOCK EVALUATION OF THE H. B. ROBINSON UNIT 2 NUCLEAR POWER PLANT

Chapter 3. Development of Overcooling Sequences for H. B. Robinson Unit 2 Nuclear Power Plant

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Date of Draft: November 21, 1984

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*Research sponsored by U.S. Nuclear Regulatory Commission under Contract No. DE-AC05-84OR21400 with the Martin Marietta Energy Systems, Inc. with U.S. Department of Energy.

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3. DEVELOPMENT OF OVERCOOLING SEQUENCES FOR H. B. ROBINSON UNIT 2 NUCLEAR POWER PLANT

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3.0. DEVELOPMENT OF OVERCOOLING SEQUENCES FOR H. B. ROBINSON UNIT 2 NUCLEAR POWER PLANT

3.1. Introduction

The development of overcooling sequences that potentially could result in pressurized thermal shock (PTS) to a reactor vessel is difficult due to the complex interactions of the many systems comprising a nuclear power plant. The first step in the development of these sequences for H. B. Robinson Unit 2 was the analysis of plant systems to determine possible system operating states, including failed states, which could affect an overcooling transient. The system state trees resulting from this analysis are presented in Section 3.2. The second step was the identification of specific initiating events which could lead to overcooling transients, followed by a review of the events to evaluate whether they need be considered with respect to PTS. A summary of the initiators determined to be applicable to the H. B. Robinson Unit 2 PTS analysis is presented in Section 3.3.

The third step in the development of the overcooling sequences was an examination of the system operating states with respect to the initiating events and the development of initiator-specific transient sequences in an event tree format. In each case the event tree includes pertinent operator actions associated with each initiator that were determined from a review of plant operating procedures. The resulting event trees are presented in Section 3.4.

Finally, as described in Section 3.5, the expected frequency of each event tree transient was calculated based on data from H. B. Robinson Unit 2 and generic failure data. The calculated frequencies and engineering judgement were then used to group the event tree sequences to develop a final list of sequences to be considered in subsequent thermal-hydraulics and fracture-mechanics analyses.

3.2. System State Trees

Each of the systems discussed in Chapter 2.0 was examined to identify those system and subsystem functions which could have a significant effect on the temperature or pressure in the reactor vessel downcomer region, and system state trees were then developed for the pertinent systems. The headings and the possible branches associated with these trees are described in this section, but for brevity the system state trees themselves are not included.

System state trees represent possible system operating states in response to an unspecified initiating transient. Since the systems were analyzed on a functional basis, the branching on the state trees may be more complex than simple binary success and failure branches. This will be noted by qualifying conditions specified for some of the branches.

Thermal-hydraulic "conditioning events" are also included on the functional system state trees. These events serve a dual purpose: (1) they limit the number of potential end states for a given system state tree that must be considered, and (2) they permit the coupling between the various functional system state trees (due to the thermal-hydraulic interactions). The term "conditioning events" is used since subsequent system responses are

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considered conditional on the thermal-hydraulic parameters which typically comprise the event description.

3.2.1. Reactor Vessel and Its Internals

The components of the first system examined consist of the pressure vessel and its internals, or, more specifically, the reactor core and its support structure. Since a reactor trip is assumed to occur following any initiating transient considered in the PTS analysis, the only "action" expected of the reactor core is that it achieve subcriticality following the trip. The power generated by the core following the trip is a known function of time and past operation (i.e., it is not a function of an initiating event or the system failure), and thus no system state tree was developed for the pressure vessel and its internals.

3.2.2. Reactor Coolant System

As described in Chapter 2.0, the function of the reactor coolant system (RCS) is to remove heat from the reactor core and transfer it to the secondary system. This primary function is accomplished by two subfunctions: (1) maintaining reactor coolant loop flow from the core to the steam generators and (2) controlling the reactor coolant loop pressure to maintain the reactor coolant in a subcooled liquid state. Thus, there is a potential need for two system state trees to describe this system. [Another subfunction, control of reactor coolant inventory, is discussed in the subsequent sections on the safety injection system (SIS) and the chemical and volume control system (CVCS).]

A review of reactor coolant system components revealed that the reactor coolant pumps (RCPs) comprise the only set of active components required to maintain forced circulation of reactor coolant. For an overcooling event of any consequence, the RCPs are expected to be manually tripped by the operator,[*] an act that increases the potential for loop flow stagnation, which, in turn, could lead to reduced downcomer temperatures.[†] Hence, failure to trip the pumps would improve the situation from the PTS point of view; however, as the procedures are presently written, this would constitute a failure of the operator to comply with procedures. Since credit should not be taken for a failure which could reduce the severity of a transient, the assumption was made that the RCPs would always be tripped within 30 seconds following a safety injection actuation signal (SIAS).[‡] Thus, the operation of the pumps was not considered in the system state tree.

As discussed in Section 2.3.4, the reactor coolant loop pressure is controlled by the pressurizer heaters, the pressurizer spray valves, two pressurizer power-operated relief valves (PZR PORVs), and three pressurizer safety valves (PZR SVs).

The operating mode of the pressurizer heaters has little effect on cooling sequences and was not included in the system state tree. For any overcooling event of significance, the pressurizer will drain and the heaters will automatically turn off. This assumed proper operation of the heaters need not be addressed in the system state tree. Even if the heaters failed to turn off with low pressurizer level, their continued operation would not affect the RCS pressure (although heater damage could be expected).

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[*] An overcooling event of any significance will cause primary system coolant contraction, resulting in the reactor coolant system pressure being lowered to the extent that it triggers the safety injection actuation signal. According to procedures, the operators are required to trip the RCPs when this signal is generated.

[†] Loop flow stagnation is discussed in detail in Chapter 4 of this report.

[‡] It should be noted that the procedures may be changed in the near future. This change would cause the pump trip to be based on subcooling criteria. This could result in the pumps remaining on during certain secondary side events, such as steam-line breaks. Under these conditions the analysis presented in this report would appear to be an overprediction of the risk. Some calculations made to quantify this condition are discussed later in this report.

Restoration of pressurizer water level would permit the heaters to turn back on and function as required. The additional effect of the heaters is considered to be small, and, in any case, the assumption that they will operate as designed accounts for their effect.

The pressurizer spray valve operation was also eliminated from the system state tree, since tripping the reactor coolant pumps stops the normal spray flow regardless of spray valve position. This leaves only the auxiliary spray from the CVCS. Even though the auxiliary pressurizer spray can have a significant effect on repressurization, it can be initiated only manually, which makes it an operator action that is addressed on an event-specific basis on the event trees and not on the system state trees.

Thus, the system state tree for the RCS is limited to the control of the coolant loop pressure, which, in turn, is limited to the potential states of the PZR PORVs and the PZR SVs. The system state tree headings and the potential branches for each heading are described in Table 3.1.

3.2.3. Main Steam System

The main steam system was described in Section 2.3 as consisting of eight major subsystems: (1) the steam generators (SGs), (2) the main turbine stop valves and governor valves, (3) the steam dump valves (SDVs), (4) the steam power-operated relief valves (STM PORVs), (5) the main steam-line isolation valves (MSIVs), (6) the main steam-line safety valves (SSVs), (7) the steam-line flow restrictors, and (8) the main steam check valves.

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Table 3.1. Description of state tree headings and potential branches for reactor coolant system pressure control*

System State Tree Heading	Heading Description and Discussion	Descriptions of Conditional Branches
Max RCS pressure < lift pressure for PZR PORVs.	This thermal-hydraulic parameter identifies the need for components in this system to function. If the pressure < lift set point, no components in this system are required to change state. If the pressure > lift set point, some components will be required to change state. Thus, two branches are required under this heading.	The two branches required are: **(1) Pressure < PZR PORV lift set point.** **(2) Pressure ≥ PZR PORV lift set point.**
PZR PORVs open on demand.	Given that the PZR PORVs are required to open, the potential exists for one or both to fail to open. A failure for a PZR PORV to open could lead to the opening of a PZR SV, which is not isolatable. The number of branches required depends on the initial thermal-hydraulic branching.	If the RCS pressure < PZR PORV lift set point, no branches are required under this heading. If the RCS pressure ≥ PZR PORV lift set point, three branches are required: **(1) Both PZR PORVs open.** **(2) One PZR PORV fails to open.** **(3) Both PZR PORVs fail to open.**
Max RCS pressure < lift pressure for PZR SVs.	This thermal-hydraulic parameter identifies the demand for PZR SVs. The number of branches required depends on the initial thermal-hydraulic branching.	If the RCS pressure < PZR PORV lift set point, it will be < PZR SV lift set point, and no branches are required. If the RCS pressure > PZR PORV lift set point, two branches are required: **(1) PZR SV demand exists.** **(2) PZR SV demand does not exist.**
PZR SVs open on demand.	Given that the PZR SVs are required to open, the potential exists for one, two or all three to fail to open.	Four branches are required: **(1) All three PZR SVs open.** **(2) One PZR SV fails to open.** **(3) Two PZR SVs fail to open.** **(4) All three PZR SVs fail to open.**
PZR SVs close on low pressure.	For those branches involving the opening of the PZR SVs, the failure of the valves to close on low pressure must be considered. The number of branches required is determined by the number of PZR SVs that opened.	If only one PZR SV has opened, two branches are required: **(1) PZR SV closes.** **(2) PZR SV fails to close.** If only two PZR SVs have opened, three branches are required: **(1) Both PZR SVs close.** **(2) One PZR SV fails to close.** **(3) Both PZR SVs fail to close.** If all three PZR SVs have opened, four branches are required: **(1) All three PZR SVs close.** **(2) One PZR SV fails to close.** **(3) Two PZR SVs fail to close.** **(4) All three PZR SVs fail to close.**

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Table 3.1. (Continued)

System State Tree Heading	Heading Description and Discussion	Descriptions of Conditional Branches
PZR PORVs close on demand.	For those branches involving the opening of the PZR PORVs, the failure of the valves to close on demand must be considered. The number of branches required is determined by the number of PZR PORVs that opened.	If only one PZR PORV has opened, two branches are required: **(1) PZR PORV closes.** **(2) PZR PORV fails to close.** If both PZR PORVs have opened, three branches are required: **(1) Both PZR PORVs close.** **(2) One PZR PORV fails to close.** **(3) Both PZR PORVs fail to close.**
Block valves close.	A block valve is provided to isolate each PZR PORV if it fails to close automatically. The number of branches is determined by the number of valves demanded.	If only one block valve is demanded, two branches are required: **(1) Block valve closes.** **(2) Block valve fails to close.** If both block valves are demanded, three branches are required: **(1) Both block valves close.** **(2) One block valve fails to close.** **(3) Both block valves fail to close.**

*Acronyms used in this table are: RCS = reactor coolant system, PZR PORV = pressurizer power-operated relief valve, and PZR SV = pressurizer safety valve.

Of the eight subsystems, the steam generators and the flow restrictors have passive functions and are not included on the system state tree. The system state tree headings used to define the condition of each of the remaining subsystems, together with descriptions of the possible branches for each heading, are presented in Table 3.2.

3.2.4 Feedwater and Condensate System

In Section 2.4 of this report the seven major subsystems of the feedwater and condensate system were identified as: (1) the condensate storage tank, (2) the condenser, (3) the condensate pumps, (4) the feedwater heaters, (5) the main feedwater (MFW) pumps, (6) the MFW control valves and bypass valves, and (7) the MFW isolation valves.

The condensate storage tank, the condenser, and the feedwater heaters have passive functions and thus are not considered in the system state tree. The active functions of the condensate pumps, the MFW pumps, and the MFW control and isolation valves provide feedwater flow in their operating (open) condition while stopping flow in their tripped (closed) condition. These component functions have been grouped under the heading of "main feedwater flow isolated on demand."

Following any reactor trip, the MFW regulating valves are required to close and the bypass valves are opened (manually) to about 5% flow. This action is referred to as "main feedwater runback." The question of whether runback occurs must be addressed in the system state tree.

Table 3.2. Description of state tree headings and potential branches for the main steam system*

System State Tree Heading	Heading Description and Discussion	Descriptions of Conditional Branches
Turbine stop valves and governor valves close.	This step identifies whether the turbine trips on demand. Closure of the turbine stop valves or turbine governor valves is the function considered. Thus, two branches are required under this heading.	The two branches required are: **(1) All stop valves or governor valves close.** **(2) One or more stop valve(s) and one or more governor valve(s) fail to close.**
SDVs open.	High T_{ave} or high steam pressure thermal-hydraulic condition could cause the SDVs to the condenser to open.	Six branches are required: **(1) All five SDVs open.** **(2) One SDV fails to open.** **(3) Two SDVs fail to open.** **(4) Three SDVs fail to open.** **(5) Four SDVs fail to open.** **(6) All five SDVs fail to open.**
STM PORVs open.	High T_{ave} or high steam pressure thermal-hydraulic condition could result in the steam PORVs opening.	Four branches are required: **(1) All three STM PORVs open.** **(2) One STM PORV fails to open.** **(3) Two STM PORVs fail to open.** **(4) All three STM PORVs fail to open.**
Steam pressure < SRV lift set point.	This thermal-hydraulic function opens the 12 SRVs (four on each of three lines), which lift in pairs at various pressures. It is assumed that even if some SRVs fail to open, one or more SRV(s) will eventually open on each line if the steam pressure > SSV lift pressure.	Only one branch is required: **(1) SRVs open.**
SRVs close on demand.	Given that one or more pairs of SRVs open, the question of whether or not they close on demand must be examined. Since both a single valve failure and multiple valve failures are considered to be small steam-line breaks, they need not be treated individually.	Four branches are required: **(1) All twelve SRVs close.** **(2) One or more SRVs fail to close on one line.** **(3) One or more SRVs fail to close on two lines.** **(4) One or more SRVs fail to close on all three lines.**
STM PORVs close on demand.	Failure of a STM PORV to close is equivalent to a small steam-line break upstream of the MSIVs.	Four branches are required: **(1) All three STM PORVs close.** **(2) One STM PORV fails to close.** **(3) Two STM PORVs fail to close.** **(4) All three STM PORVs fail to close.**
SDVs close on demand.	Failure of the SDVs to close is equivalent to a steam-line break downstream of the MSIVs.	Six branches are required: **(1) All five SDVs close.** **(2) One SDV fails to close.** **(3) Two SDVs fail to close.** **(4) Three SDVs fail to close.** **(5) Four SDVs fail to close.** **(6) All five SDVs fail to close.**
MSIVs close on demand.	Closure of the MSIVs on demand can isolate failed-open SDVs.	Four branches are required: **(1) All three MSIVs close.** **(2) One MSIV fails to close.** **(3) Two MSIVs fail to close.** **(4) All three MSIVs fail to close.**

*Acronyms used in this table are: SDV = steam dump valve, STM PORV = steam power-operated relief valve, SRV = safety relief valve, and MSIV = main steam isolation valve.

The coupling of components on a functional basis produces the system state tree headings and possible branches identified and explained in Table 3.3.

3.2.5 Auxiliary Feedwater System

As described in Section 2.5, the principal active components of the auxiliary feedwater (AFW) system are: (1) the AFW pumps, (2) the AFW control valves, and (3) the AFW block valves.

The control signals and functions of these components are used to construct the system state tree headings and branches described in Table 3.4. It should be noted that the AFW system state tree is constructed to consider three flow conditions to the steam generators: maximum flow, normal flow, and no flow.

3.2.6 Safety Injection System

The safety injection (SI) system consists of three types of coolant injection processes: (1) high-pressure injection, (2) coolant injection from the accumulators, and (3) low-pressure injection. [As noted in Chapter 2, two low-pressure injection (LPI) pumps also serve as residual heat removal (RHR) pumps.]

On a first evaluation it appeared that failure of any of the injection processes would be more of an undercooling concern that an overcooling problem, and, therefore, the conservative perspective would be to assume that all components would work when required and no system state tree would

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Table 3.3. Description of state tree headings and potential branches for main condensate and feedwater system*

System State Tree Heading	Heading Description and Discussion	Descriptions of Conditional Branches
MFW regulating valves close.	Following a reactor trip, the MFW system is required to run back to prevent a steam generator overfeed. The MFW regulating valves will throttle to control the steam generator level. In addition, a reactor trip and low T_{ave} will close the control valves. Rather than identify several branches to cover the various levels of runback possible, the branches under this heading bound the potential conditions by assuming that complete runback occurs (i.e., valves close) or that no runback occurs (i.e., valves fail to close).	Four branches are required: **(1) All three MFW regulating valves close.** **(2) One MFW regulating valve fails to close.** **(3) Two MFW regulating valves fail to close.** **(4) All three MFW regulating valves fail to close.**
MFW pumps trip.	Upon occurrence of an SI signal or a high SG level signal, the MFW pumps (two) trip. This is a redundant mechanism to prevent steam generator overfeed.	Three branches are required: **(1) Both MFW pumps trip.** **(2) Only one MFW pump trips.** **(3) Both MFW pumps fail to trip.**
MFW isolated on demand.	Upon occurrence of an SI signal, the MFIVs close, stopping all flow in the MFW lines.	Four branches are required: **(1) All three MFW lines are isolated.** **(2) Two MFW lines are isolated.** **(3) One MFW line is isolated.** **(4) No MFW lines are isolated.**
SI signal generated on demand.	The SI signal trips the MFW pumps, closes the MFIVs and the MFW regulating valves, and prevents the bypass valves from opening.	Two branches are required: **(1) SI signal is generated.** **(2) SI signal is not generated.**

*Acronyms used in this table are: MFW = main feedwater, SI = safety injection, SG = steam generator, and MFIV = main feedwater isolation valve.

Table 3.4. Description of state tree headings and potential branches for auxiliary feedwater system*

System State Tree Heading	Heading Description and Discussion	Descriptions of Conditional Branches
AFW pump breakers open.	This signal will start the two motor-driven AFW pumps. Two branches are required to describe this system state.	The two branches required are: **(1) AFW pump breakers open.** **(2) AFW pump breakers fail to open.**
Two of three SGs give low-level signal.	A low-level signal of < 15% volume from any two of the three steam generators will start the steam-driven AFW pump.	Two branches are required: **(1) Signals from two SGs occur.** **(2) Signals from two SGs do not occur.**
One of three SGs gives low-level signal.	A low-level signal of < 15% volume from any one of the three steam generators will start the motor-driven AFW pumps.	Two branches are required: **(1) Signal from one SG occurs.** **(2) Signal from one SG does not occur.**
Motor-driven AFW pumps operate.	Given that the MFW pump breakers open or that a low-level signal from one SG occurs, the two motor-driven pumps should start and deliver water to the steam generators. The potential for failure of the pumps to start must be considered.	Three branches are required: **(1) Both motor-driven AFW pumps start.** **(2) One motor-driven AFW pump fails to start.** **(3) Both motor-driven AFW pumps fail to start.**
Steam-driven AFW pump operates.	Given that low-level signals from two SGs occur, the steam-driven AFW pump should start and deliver water to the steam generators. The potential for failure of the pump to start must be considered.	Two branches are required: **(1) Steam-driven AFW pump starts.** **(2) Steam-driven AFW pump fails to start.**
Nominal AFW flow occurs.	For those sequences in which flow occurs, the level of flow must be considered. The flow is controlled at each pump, rather than to each steam generator. Nominal flow rate and overfeed are the only options considered. (A low flow can be considered as no flow and treated with the case in which AFW flow does not occur; i.e., pumps do not start.)	Two branches are required: **(1) Nominal flow occurs.** **(2) Overfeed occurs.**

*Acronyms used in this table are: AFW = auxiliary feedwater, and SG = steam generator.

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be necessary. However, further evaluation of an SI failure revealed two potential overcooling factors. First, an initial SI failure with recovery at some later time could affect the loop flow characteristics and the cooldown rate. Second, an SI failure during a loss-of-coolant accident (LOCA) could result in low-pressure injection and accumulator tank flow at a considerably earlier time. This, coupled with a potential repressurization from the charging pumps and thermal expansion, could have PTS consequences. Thus, an SI failure is considered on the system state tree. Although failure of accumulators and low-pressure injection would most likely be of greater concern for undercooling sequences than for overcooling sequences, failure of these functions is retained in the system state tree for completeness. This results in the tree headings described in Table 3.5.

3.2.7. Chemical and Volume Control System

Four system functions were considered for the chemical and volume control system (CVCS) state tree: (1) letdown isolation, (2) letdown flow control, (3) charging flow heating, and (4) charging flow.

Letdown isolation and letdown flow control can be coupled together as one function: letdown flow. A letdown isolation signal occurs whenever a low pressurizer level signal is generated and thus is expected to occur for any overcooling transient. When letdown isolation occurs, letdown flow is stopped. Failure of both isolation valves to close or the failure of the signal will cause failure of letdown isolation. In this case the flow control valves must be examined to identify the flow state. A low pressurizer level will cause the flow control valves to stop the flow. Failure of

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Table 3.5. Description of state tree headings and potential sequence branches for the safety injection system*

System State Tree Heading	Heading Description and Discussion	Descriptions of Conditional Branches
RCS pressure > HPI pump discharge pressure of 1500 psig.	This is a thermal-hydraulic test that determines whether or not HPI can physically occur. Two branches are used to examine this system state.	The two branches required are: **(1) RCS pressure > 1500 psig.** **(2) RCS pressure ⩽ 1500 psig.**
HPI occurs on demand.	For those sequences in which reactor coolant pressure ⩽ 1500 psig, the question as to whether or not HPI is activated must be addressed.	Two branches are required: **(1) HPI occurs.** **(2) HPI fails to occur.**
RCS pressure > accumulator pressure of 600 psig.	This is a thermal-hydraulic test that determines whether the accumulator water can discharge into the RCS.	Two branches are required: **(1) RCS pressure > 600 psig.** **(2) RCS pressure ⩽ 600 psig.**
Accumulators discharge.	For those sequences in which RCS pressure ⩽ 600 psig, the question as to whether the accumulators will actually discharge must be addressed.	Two branches are required: **(1) Accumulators discharge.** **(2) Accumulators fail to discharge.**
RCS pressure > LPI pump discharge pressure of 175 psia.	This is a thermal-hydraulic test that determines whether or not LPI water can enter the RCS.	Two branches are required: **(1) RCS pressure > 175 psia.** **(2) RCS pressure ⩽ 175 psia.**
LPI occurs on demand.	For sequences in which the RCS pressure falls below the LPI pump discharge pressure, the question as to whether or not coolant is injected must be addressed.	Two branches are required: **(1) LPI occurs.** **(2) LPI fails to occur.**

*Acronyms used in this table are: RCS = reactor coolant system, HPI = high-pressure injection, and LPI = low-pressure injection.

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these valves to run back will result in the normal letdown flow continuing. Any intermediate flow rate is considered to be small both in size and in consequence. Thus letdown flow is not considered for system state description.

Heating of the charging flow is performed by the regenerative heat exchanger. The heat source for this heat exchanger is letdown coolant downstream of the letdown stop valves. Thus, when letdown isolation occurs, this heat source is automatically lost. The regenerative heat exchanger is a passive component in either mode and is not considered on the system state tree.

The low pressurizer level signal which isolates letdown also causes all operating charging pumps to accelerate to full speed. Anything less than full flow will result in less cold water entering the primary coolant system and a slower repressurization rate. Thus, failure of the charging pumps to start is not considered. However, runback of the charging flow late in the transient is very important since failure to run back would result in higher RCS pressures. Therefore, runback of charging pump flow must be considered. But since this was the only heading to be addressed under the CVCS system, no system state tree was generated for the CVCS. Instead, the following two assumptions were made which define the system for overcooling events:

(1) Letdown isolation will occur whenever a pressurizer low-level signal is generated.

(2) All operating charging pumps will accelerate to full speed and provide full flow whenever a pressurizer low-level signal is generated.

Charging flow will be automatically controlled to maintain pressurizer level when it is recovered. Failure of this control function is addressed, as appropriate, in the initiator-specific event trees.

3.3. Potential Initiating Events

In the preceding section a set of system state trees was identified to describe potential system responses to overcooling event initiators. In this section, specific initiating events considered to have a potential for causing significant cooling of the reactor vessel are identified and discussed.

The first step in identifying potential initiating events was the examination of the RCS to determine what events would reduce the temperature in the reactor vessel downcomer region. In general, the temperature in the downcomer region can be reduced by the injection of cold water into the vessel inlet lines; by a net removal of energy from the RCS via the steam generators; or by a breach in the primary system, resulting in significant RCS depressurization [a loss-of-coolant accident (LOCA)]. The initiating events identified as potentially leading to one of these cooling mechanisms

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fall into eight classes as follows:

(1) Events causing a decrease in the charging water enthalpy.

(2) Events causing an excess steam flow from the steam generators.

(3) Events causing a decrease in the feedwater enthalpy.

(4) Events causing feedwater overfeed.

(5) Inadvertent safety injection (SI) events.

(6) Loss-of-coolant accidents (LOCAs).

(7) Events consisting of pressurizer pressure control failures.

(8) Events leading to steam generator tube ruptures.

These classes of events were examined and initiator events specific to H. B. Robinson Unit 2 were identified as described below.

3.3.1. Events Causing a Decrease in the Charging Flow Enthalpy

The charging flow enthalpy can be reduced by: (1) stopping the heat source to the regenerative heat exchanger (that is, stopping the letdown flow), (2) increasing the charging flow in excess of the letdown flow, or (3) both isolating the letdown flow and actuating (manually) the three charging pumps.

The maximum enthalpy decrease would be caused by isolation of letdown and manual actuation of the three charging pumps, but since this event is addressed separately in Section 3.3.5, it will not be discussed here.

With the normal charging flow of 45 gpm, a loss of the regenerative heat exchanger would result in a decrease of 363°F or more in the charging flow temperature.[*] If it is assumed that perfect loop flow mixing (see Section 4.4) and a simple mass-energy balance exist, which is the normal assumption, the loop flow temperature would be reduced by ~1°F. This is clearly not an overcooling event and thus loss of the heat exchanger is not considered to be an initiating event.

An increase in the charging flow from nominal to maximum would increase the flow rate from 45 gpm to 105 gpm. The resulting water temperature would be at 279°F rather than at the nominal temperature of 493°F. Again, if perfect loop flow mixing and a simple mass-energy balance are assumed, the loop flow temperature would drop by only ~1°F, which is not an overcooling event. Thus increasing the charging flow is not considered to be an initiating event.

In summary, events decreasing the charging flow enthalpy will not lead to overcooling transients in H. B. Robinson Unit 2.

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[*] 363°F is the normal increase in charging flow temperature across the regenerative heat exchanger. Direct injection of water from unheated tanks (e.g., Radwaste Storage Tank) would decrease the charging flow temperature further. For this discussion, the energy stored in the heat exchanger, charging piping, etc. is neglected.

3.3.2. Events Causing an Excess Steam Flow from the Steam Generators

Events causing an abnormally high steam flow from the steam generators result in the depressurization of the steam generator(s) and an increased energy removal rate from the primary system. This class of potential initiating events includes the following: (1) a large steam-line break, (2) a small steam-line break, (3) the STM PORVs or SDVs opening and failing to close, and (4) one or more main steam-line SVs opening and failing to close. In addition, after a reactor trip has occurred, the failure of some pieces of equipment could also result in an excess steam flow. Thus, an additional initiating event is (5) a reactor trip followed by the opening of the STM PORVs or SDVs as required, but with one or more of the STM PORVs or SDVs failing to close.

3.3.2.1. Large Steam-Line Break

Potential large steam-line break events are characterized by two variables: the location of the pipe break and the core decay heat level, which is the primary heat source following the reactor trip accompanying all steam-line pipe breaks.

The extent and duration of the steam blowdown depend on whether the break is upstream or downstream of the main steam check valves and the main steam-line isolation valves (MSIVs).* Because these valves are very close together, the probability of a break between them is considered to be small compared to the likelihood of a break in the remainder of the steam piping. Thus when reference is made in this report to upstream or downstream of the MSIV, we are actually referring to upstream or downstream of both the MSIV and the check valve on a line.

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*A break upstream of the flow restrictor could result in a somewhat faster RCS temperature drop than would accompany a full pipe break downstream of the flow restrictor. However, the potential for a pipe break in this small section of piping was considered to be very small and thus was not analyzed.

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The check valves are downstream of the MSIVs and are intended to prevent the backflow steam from the unbroken steam lines to a steam-line break inside the containment. A break upstream of the MSIV, however, is not isolatable and one steam generator will blow down completely. The MSIVs are designed to prevent blowdown of more than one steam generator and to isolate the steam generators from breaks downstream of the valves.

Examination of the pipe configuration showed that pipe welds, pipe elbows, extraction lines, etc. were about equally distributed upstream and downstream of the MSIVs. Since these are considered to be the most probable pipe break locations, it was assumed that a pipe break was equally likely to be upstream or downstream of the MSIV.[*]

The core decay heat source following the reactor trip can impact the downcomer temperature in two ways:

(1) It can promote natural loop circulation and mixing of the SI and loop flows.

(2) It can increase the downcomer temperature. [Whenever loop flow exists, the reactor coolant heated in the core will be transported to the downcomer (vessel inlet) region.]

The magnitude of the core decay heat source over the two-hour analysis period used in this study[†] was determined by applying the ANS decay heat curve shown in Figure 3.1.[‡] The curve shows that immediately following a reactor trip, the decay heat power would be ~7% of the preshutdown power, decreasing to ~1.2% after two hours (7200 seconds). If it is assumed that the plant has been operating at full power (2300 MWt), then 161 MWt would be generated as decay heat immediately following a reactor trip and ~19 MWt would be generated two hours after the trip (7200 seconds). Based on a review of the operating history of H. B. Robinson Unit 2 during 1980, 1981, and 1982, this decay heat production would apply to 98.1% of the opera-

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[*] It should be noted that the grade of piping used upstream of the MSIVs would imply a lower failure potential than that used downstream of the MSIVs. However, since the steam-line pipe failure mechanisms are not fully understood, the effect of the different grades of piping can not be realistically quantified. Therefore, the same failure probability is used for both upstream and downstream of the MSIVs.

[†] The analysis period is defined as two hours for reasons discussed in Chapter 4.

[‡] The curve shown in Figure 3.1 assumes infinite core operation time prior to shutdown. The effect of using this curve rather than an operation-specific curve is included in the uncertainty of the temperature as applied in Chapter 7.

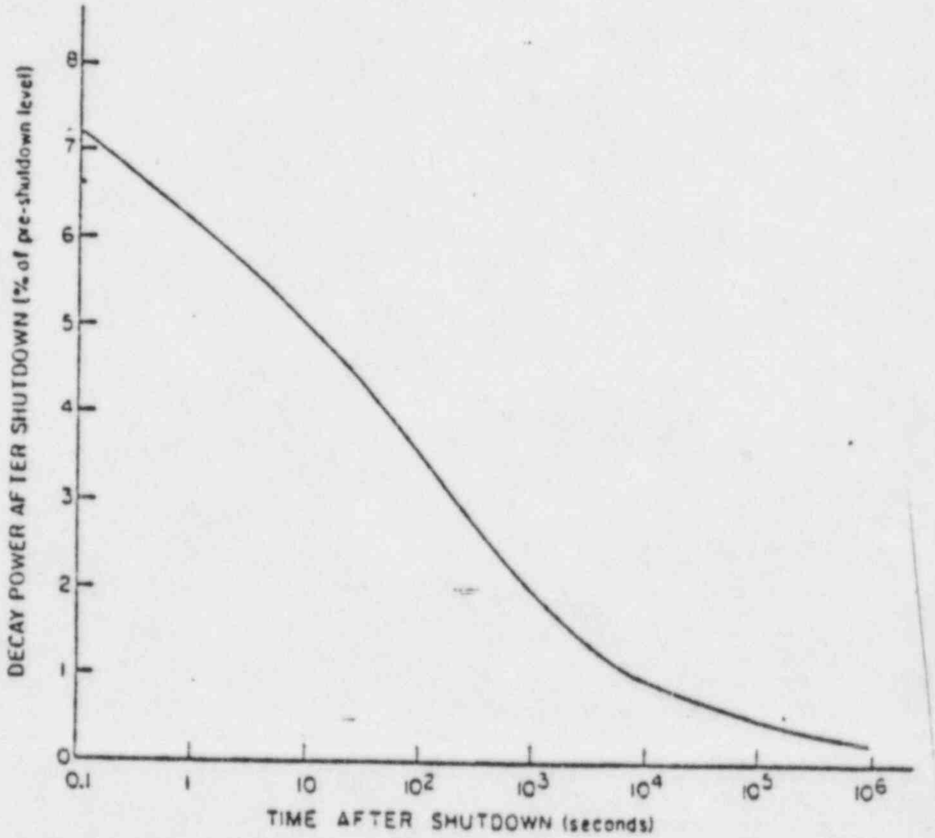

Figure 3.1. Thermal power after reactor shutdown.

tional time of the plant (i.e., 98.1% of the time excluding cold shutdown). Thus this condition was deemed one for which the effects of a large steam-line break should be considered.

For the remaining 1.9% of its operational time, H. B. Robinson Unit 2 is in a hot 0% power or startup condition. Decay heat associated with a hot 0% power condition depends upon the length of time since the previous reactor shutdown.* A review of the plant's history revealed that in most cases (~80% of the time) plant startups occur within four days (~100 hours) after a reactor trip has occurred. Figure 3.1 shows that at 100 hours the decay heat production would be ~8.3 MWt over a two-hour transient period.† This was considered to be a second decay heat condition for which the effects of a large steam-line break should be considered.

Finally, there are scheduled outages and major incidents for which the time between shutdown and startup would be as much as 100 days or more. The decay heat for this condition would be less than 1 MWt. Rather than perform an analysis for a third decay heat condition, it was decided to examine the sensitivity of the downcomer temperature to changes in decay heat for the hot 0% power decay heat condition at 100 hours after shutdown. The effects of potentially lower decay heat events would then be reflected as part of the uncertainty.

On the basis of the above, two large steam-line break initiating events were selected for examination for their potential importance:

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[*] Since H. B. Robinson Unit 2 is already in operation and since full core replacement is extremely unusual, the initial startup with a full fresh fuel core is not considered.

[†] It is assumed that the plant was operating at full power prior to the reactor trip or shutdown.

- A large steam-line break at full power with decay heat production followed during the two-hour analysis period.

- A large steam-line break at hot 0% power with the decay heat production based on the heat generated approximately 100 hours after shutdown.

3.3.2.2. Small Steam-Line Break

As for the case of a large steam-line break, potential small steam-line break events resulting in excess steam flow are characterized by two variables: the location of the break and the core decay heat level. Many of the same considerations for the large break also apply to the small break.

The most probable small break locations are in the small steam extraction lines that come off of the main steam lines. At H. B. Robinson Unit 2, almost all of the steam extraction lines are in the 4- to 6-inch range. The lines to the STM PORVs are 6 inches, as are those for the 12 SRVs. Breaks upstream and downstream of the MSIVs are assumed to be equally likely.

For the same reasons discussed above for the large break, two decay heat levels are important for small breaks. Thus the small steam-line break initiating events to be examined also fall in two categories:

- A small steam-line break at full power with decay heat production followed during the two-hour analysis period.

- A small steam-line break at hot 0% power with the decay heat production based on the heat generated approximately 100 hours after shutdown.

3.3.2.3. Failed-Open STM PORVs or SDVs

STM PORVs and SDVs which open and fail to close are equivalent to small steam-line breaks. Since their locations are already known, only the decay heat level must be determined. For these events, the two decay heat levels defined above were again assumed, that is, the decay heat level following full-power operation and at hot 0% power.

If during operation the reactor is tripped, the turbine is also tripped, and this causes the SDVs and, possibly, the STM PORVs to automatically open for a brief period of time. Failure of one or more of these valves to subsequently close has the same effect as a valve or valves spuriously opening at power, since the reactor is expected to trip soon after the valves open.* Thus those events involving STM PORVs or SDVs which spuriously open and in which a reactor trip occurs have been grouped together with STM PORV and SDV failures to close following a reactor trip. These events are discussed in Section 3.3.2.5 below.

At hot 0% power, there is no requirement for the STM PORVs to operate (to open). However, they will open periodically to control pressure and

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*The reactor trip may be either an automatic trip or a manual trip. For single STM PORV spurious openings, the reactor trip may not occur.

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potentially could fail open. This event was treated as a small steam-line break initiator and was not analyzed separately.

3.3.2.4. Main Steam-Line Safety Valves Open and Fail to Close

A steam-line safety valve (SSV) that fails to close cannot be isolated. Thus, SSV failures of this type will behave the same as the small steam-line breaks upstream of the MSIV discussed in Section 3.3.2.2. As a result, SSV failures of this type were grouped into the small steam-line break category and were not examined separately. (Note: If multiple breaks occur, they may be grouped into the large steam-line break category.)

3.3.2.5. Reactor Trip

Although as noted in Section 3.3.2.3, a reactor trip is not an overcooling initiating event by itself, a reactor trip causes a turbine trip, which, in turn causes the SDVs to open and may possibly cause the STM PORVs also to open. Failure of the valves to close would result in excess steam flow. Thus, an additional potential initiating event selected for examination is:

- A reactor trip from full power.

Failure of the main turbine to trip following a reactor trip (open path to the condenser) is a special case of the reactor-trip-induced excess steam

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flow event. Owing to functional similarity of this event to a large steam-line break occurring downstream of the MSIV at full power, the turbine trip failure was grouped with the large steam-line pipe break cases and was not examined separately.

3.3.3. Events Causing a Decrease in the Feedwater Enthalpy

Two initiating events can cause a decrease in the feedwater enthalpy: (1) a loss of feedwater heaters, and (2) the initiation of auxiliary feedwater flow to the steam generators.

A loss of feedwater heaters does not appear to result in an overcooling event, since sufficient energy is stored in the feedwater heaters and piping to prevent a rapid decrease in main feedwater temperature following a reactor trip. This is exemplified by the fact that the steam supply to the feedwater heaters is isolated following every turbine trip and the resulting feedwater temperature change observed is small. Thus, the loss of feedwater heaters is not considered to be an important initiating event. However, the effects of the loss of steam supply to the feedwater heaters which accompany other overcooling initiator events will be considered along with those initiator events.

Similarly, the effects of auxiliary feedwater flow will be minimal. While the auxiliary feedwater temperature is lower than the main feedwater temperature and thus feedwater enthalpy will decrease whenever auxiliary feedwater flow is initiated, the auxiliary feedwater flow is small with respect to main feedwater flow or steam generator (liquid) volume. The effects of auxiliary feedwater flow on the coolant temperature become more important when main feedwater flow is lost and auxiliary feedwater flow is actuated. Thus, another specific potential initiating event to be considered is:

- Loss of main feedwater flow.

3.3.4. Events Causing Feedwater Overfeed

Two types of feedwater overfeed events are of interest as potential overcooling initiating events: (1) main feedwater overfeed, and (2) auxiliary feedwater overfeed.

A main feedwater overfeed is not considered a significant overcooling event prior to a reactor trip; thus, only those main feedwater overfeed events that follow a reactor trip need be considered. This type of event can be characterized by an overfeed resulting from a failure of the feedwater system to run back following a reactor trip. The initiating event is a reactor trip and the failure associated with the initiating event is a failure of feedwater to run back on one or more lines.

The relatively low temperature of the auxiliary feedwater makes an overfeed of auxiliary feedwater potentially significant even though the maximum flow rate is small compared to the main feedwater flow rate. Spurious auxiliary feedwater actuation is not considered as an initiating event. With a spurious actuation, the high main feedwater flow rate with its relatively high temperature and the large volume of water in the steam generator would minimize the overcooling effects. Only those auxiliary feedwater overfeeds following a required actuation of auxiliary feedwater (isolation of main feedwater) will be considered.* In these cases, the steam generator level will be low and the overfeed will have the potential to cause a higher cooldown rate.

The auxiliary feedwater overfeed condition can be reached only if some initiating event which leads to auxiliary feedwater actuation has occurred. The appropriate initiating events are a reactor trip and large and small steam-line breaks, which in themselves are overcooling events but which also result in auxiliary feedwater actuation.

3.3.5. Inadvertent Safety Injection (SI) Events

With a maximum high-pressure safety injection (HPI) pump discharge pressure of 1500 psia, an inadvertent safety injection (SI) actuation will not result in SI flow while the RCS is pressurized. The spurious signal will cause a reactor trip and consequential reduction in pressurizer level. In response to the reduced pressurizer level, the charging pump speed increases and the letdown line is isolated. The resulting pressure is expected to remain above the HPI flow pressure and thus the event will not result in a significant decrease in the reactor coolant temperature (see Section 3.3.1). Therefore, the inadvertent SI signal is not considered an overcooling initiator.

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*This is also the most probable occurrence of an auxiliary feedwater overfeed.

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3.3.6. Loss-of-Coolant Accidents (LOCAs)

The categories of potential loss-of-coolant accidents (LOCAs) which lead to overcooling are the most difficult to define due to the potential for repressurization and the importance of loop flow stagnation. A review of potential LOCA sizes was therefore considered in defining LOCA categories.

The first category was composed of those breaks for which HPI could fully compensate and thus the pressure would stabilize at some level slightly below the HPI shutoff head. In terms of size, this corresponds with breaks that are less than ~$0.016\ ft^2$. It should be noted that single PZR PORV or SRV failures and reactor coolant pump seal failures[*] are also included in this category of "small-break LOCAs."

The second category of LOCA sizes includes those for which HPI can not keep up with the flow out the break but for which the pressure decrease is gradual owing to a partial compensation from the HPI flow. Identified as "medium-break LOCAs," these break sizes run from ~$0.016\ ft^2$ to ~$0.05\ ft^2$,[*] the most probable size appearing to be a break of one of the many 2-inch lines which come off of the primary piping.[*] This corresponds to a break size of ~$0.02\ ft^2$. However, based on analyses performed by Westinghouse, it appeared that a 2.5-inch break would result in early loop flow stagnation. Since this condition was considered to be potentially important, the

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[*] The largest break flows observed for pump seal failures have been about 400 gal/min or ~160,000 lb/hr. Thus the pump seal failures would be in the first LOCA category.

[†] The 0.05-ft^2 limit was chosen in the following manner. From a review of generic parametric studies of PTS, it was felt that a flow out the break equivalent to twice the HPI flow would substantially reduce the PTS risk owing to the rapid pressure reduction. For conservatism, breaks as large as three times the HPI flow, ~$0.05\ ft^2$, were included in this second category.

[‡] It appears that breaks in this small size range will occur most often as small-line breaks in extraction or supply lines rather than as a small hole forming in a large pipe.

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break size was also considered in the analysis of this group.[*]

The third category of LOCA sizes includes all breaks larger than 0.05 ft^2. Without isolation of the break, a rapid depressurization will severely limit the potential for a vessel failure. Thus the only concern for breaks of this size is whether or not there is a break larger than 0.05 ft^2 which at some later time can be isolated. A review of the H. B. Robinson Unit 2 system revealed several 4- and 12-inch lines, but no potential break locations that could be isolated[+] were identified. Thus no LOCAs in this size category were considered as PTS initiators.

In summary, it was determined that two LOCA sizes should be considered as initiating events, and, as is the case for steam-line breaks, they each must be considered for two power conditions. Thus, four LOCA initiating events must be addressed as follows:

- Small-break LOCA at full power.
- Medium-break LOCA at full power.
- Small-break LOCA at hot 0% power.
- Medium-break LOCA at hot 0% power.

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[*] As discussed in Chapter 4, thermal hydraulic analysis of this event did produce relatively cold temperatures. However, the accompanying pressure was so low that the probability of the generation of a through-the-wall crack in the pressure vessel was very small. There was some concern that the 2-inch break might also produce relatively cold temperatures, but at a somewhat higher pressure. As a result, late in the analysis two additional LOCA calculations were performed, each of which incorporated the 2-inch break. Stagnation was predicted with somewhat higher pressure. However, the pressure increase was not high enough to greatly increase the failure probabilities associated with the medium-break LOCA.

[+] Several of these lines can be isolated. However, the isolation valves are upstream of multiple check valves.

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3.3.7. Events Consisting of Pressurizer Pressure Control Failures

The PZR PORV control signal failures and PZR SV failures have already been identified. An additional pressure control failure of interest could be the spurious actuation of the pressurizer sprays, which would decrease the pressure and could eventually result in SI actuation and the tripping of the reactor coolant pumps. A loss of pressurizer spray flow would follow and the depressurization would be terminated. Thus, even though safety injection actuation occurred, the actual SI flow would not be significant. As a result, this is not considered a potential PTS event initiator.

3.3.8. Events Leading to Steam Generator Tube Rupture

A rupture of a steam generator tube has many of the characteristics of a small-break LOCA that cannot be isolated. With normal operator action, or even without operator action, the effects of the rupture appear to be less severe than those of the LOCAs that were analyzed and the consequences associated with a steam generator tube rupture should be bounded by LOCA sequences. Nevertheless it was decided to address this event specifically and the following was included as a potential initiating event to be analyzed:

- A steam generator tube rupture.

3.3.9. Summary

In the preceding sections, 11 potential initiating events for overcooling have been identified:

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(1) A large steam-line break at hot 0% power.

(2) A small steam-line break at hot 0% power.

(3) A large steam-line break at full power.

(4) A small steam-line break at full power.

(5) A reactor trip from full power.

(6) Loss of main feedwater.

(7) A small-break LOCA at full power.

(8) A medium-break LOCA at full power.

(9) A small-break LOCA at hot 0% power.

(10) A medium-break LOCA at hot 0% power.

(11) Steam generator tube rupture.

3.4. Initiator-Specific Event Trees

Event trees have been developed for each of the initiating events identified in Section 3.3. This development involved the identification of applicable system functional conditions and potential operator actions.

The system state trees described in Section 3.2 were used to identify those systems or components that are required to function and whose failure will have a potentially adverse effect on overcooling transients. It should be noted, as discussed earlier, that since these trees are developed on a functional basis, the branching on the trees associated with system or component actions may be more complex than binary success and failure branches.

Operator actions were identified from a review of procedures associated with each specific initiating event. These operator actions were grouped into two categories:*

(1) Actions involving recovery of a failed system function. (Example: SI signal fails and the operator manually starts HPI injection.)

(2) Actions required by procedure following identification of an initiating event. (Example: Operator isolates AFW from the low-pressure SG following a steam-line break.)

Category 1 actions were examined on the basis of the time available for recovery and the effects of recovery. The results of this analysis were then used to adjust branch probabilities. For example, if a PZR PORV failure was isolated before SI actuation, the event would be very similar to a reactor trip event and would be created as such.

Category 2 actions were treated directly on the event tree. These operator

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*It should be noted, as stated in Chapter 1, that operator actions which are not part of the normal procedures but which could either lead to or add to the overcooling effects are not addressed by this study. It is recognized that by making this decision one category of potential overcooling events, i.e., those which are operator initiated or operator enhanced, have been eliminated.

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actions were defined as being performed during some time frame following the procedural cues to perform the action.

3.4.1. Steam-Line Break at Hot 0% Power

Although the frequencies of the small and large steam-line break events at hot 0% power are different, the event tree structures as shown in Figure 3.2 are the same.

The first heading of the event tree is "SI signal generated on demand," the direct "demand" being an initiating event that is either high steam-line differential pressure or high steam flow coincident with either low steam pressure or low T_{ave}. The high steam flow signal will close the MSIVs, while the high differential pressure signal will not. If the steam-line break is upstream of the MSIVs, the only function of the MSIVs is to isolate the break from the other steam lines. It is more likely, however, that the check valve on the ruptured steam line will perform this function. It should be noted that neither an STM PORV failure nor an SDV failure was considered for this initiating event. With the low steam-line pressures accompanying the event, these valves would not be required to function.

The next heading on the event tree, "MFW isolated on demand," comes from the main feedwater and condensate system state tree and is concerned with stopping the main feedwater flow. Among other things, the SI signal will send a signal to trip the main feedwater pumps, run back the MFW control valves,* close the MFW pump discharge valves, and prevent the MFW bypass

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*It should be noted that for hot 0% power conditions, the feedwater runback operation does not apply.

Figure 3.2. Event tree headings for steam-line breaks at hot 0% power.

1	2	3	4	5	6	7	8	9	10
SI Signal Generated on Demand	MFW Isolated on Demand	SGs Blow Down	AFW Actuates on Demand	AFW Flow Automatically Controlled	OA: AFW Isolated to Low-Pressure SG	HPI Occurs on Demand	Charging Flow Runs Back on Demand	OA: AFW Throttled	PZR PORV Reseats on Demand
2 Branches: (1) Signal is generated. (2) Signal is not generated.	4 Branches: (1) No line overfeeds. (2) One line overfeeds. (3) Two lines overfeed. (4) All three lines overfeed.	4 Branches: (1) No SGs blow down. (2) One SG blows down. (3) Two SGs blow down. (4) All three SGs. blow down.	2 Branches: (1) AFW actuates. (2) AFW does not actuate.	2 Branches: (1) Flow controlled at nominal rate. (2) Overfeed occurs.	2 Branches: (1) Isolation occurs. (2) Isolation fails to occur.	2 Branches: (1) HPI occurs. (2) HPI fails to occur.	2 Branches: (1) Runs back as required. (2) Fails to run back.	2 Branches: (1) Operator throttles AFW flow. (2) Operator fails to throttle AFW.	2 Branches: (1) PORV reseats. (2) PORV fails to reseat.

valves from opening. A second important signal is high water level in any steam generator, which will do all of the above except close the MFW pump discharge valves. The final signal is reactor trip coincident with low T_{ave}, which only closes the MFW control valves.

The next heading, "SGs blow down," addresses the action of the main steam check valve on the ruptured line and the possible closing of the MSIVs. This branch considers whether an MSIV closure signal would be generated owing to the break and whether the MSIVs would close if the signal is given. The net system response to the break and MSIV closures is presented in terms of the number of steam generators "blowing down."

The next three headings are associated with defining auxiliary feedwater flow conditions. The first, "AFW actuates on demand," defines whether the auxiliary feedwater system is initiated. Once initiated, two potential conditions are considered under the heading "AFW flow automatically controlled": (1) flow controlled at a nominal flow rate or (2) a failure to automatically control, resulting in abnormally high flow rates (overfeed). The third heading, "AFW isolated to low-pressure SG," identifies whether auxiliary feedwater flow is isolated from the depressurized steam generator. It should be noted that this requires an operator action and is very important in minimizing the RCS overcooling.

The next branching, "HPI occurs on demand," addresses the initiation of SI flow as a result of an SI signal or an operator action.

Under the next heading, "Charging flow runs back on demand," control of

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repressurization via charging pump flow runback is addressed. Charging flow is run back automatically when the pressurizer water level is restored. Failure to run back automatically would result in challenging the PZR PORVs. Because the charging flow is controlled on pressurizer level rather than on pressure, it is conceivable that overpressurization could occur with resultant opening of the PZR PORVs. At this point, the operator can shut off the charging flow and monitor the repressurization caused by the thermal expansion of the primary system water, but because this sequence is extremely unlikely, no operator action was considered.

The second operator action of importance, included under the heading "AFW throttled," is controlling auxiliary feedwater to maintain the steam generator level. Once the broken steam line is isolated, the initial cooldown will be limited to the blowdown of the steam generator inventory. When steam generator dryout occurs, the cooldown will then be dominated by the conditions in the intact steam generators and steam lines. If the operator manually controls the auxiliary feedwater flow to maintain level, the primary system temperature will begin to increase. If, on the other hand, flow is not controlled, auxiliary feedwater overfeed will occur, which could further reduce the primary system temperature.

The two operator actions, auxiliary feedwater isolation to a depressurized steam generator and auxiliary feedwater throttling, are related. This coupling between the two actions is addressed in the event trees. If the operator fails to isolate the AFW when required, it is assumed that he will also fail to control the AFW flow.

The final tree heading, "PZR PORV reseats on demand," is required because if the repressurization is not controlled (charging flow does not run back), the high pressure is assumed to lead to a PORV lift. Thus, the potential for a PORV failure to close must be examined. This failure to close includes mechanical failures to close and the failure of the operator to block the PORVs in a short period of time.*

3.4.2. Steam-Line Break at Full Power

As shown in Figure 3.3, the event tree headings for the steam-line break at full power are the same as those for hot 0% power except that one branch has been added for the full-power steam-line break and one has been modified. The additional branch comes from the main steam system state tree and addresses the potential for a SDV failure to close following a small break in which a momentary T_{ave} increase occurs. The SDVs are not considered to be of importance for large breaks because no increase in T_{ave} will occur prior to MSIV closure.

The modified branch deals with the feedwater system runback and is taken from the main feedwater system state tree. (Runback was not considered for the hot 0% power case, because the valves are already closed.) All four potential branches as identified in Table 3.3 are considered as potential states.

The STM PORVs are not expected to open during the initial phases of either a large or small steam-line break. Following break isolation and steam generator blowdown (if applicable), T_{ave} may increase to the normal

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*The time for early isolation was assumed to be 15 minutes. If the PZR PORV is isolated within this time, the thermal-hydraulic analysis shows that the risk associated with the initial steam-line break will not be increased. In fact, failure to isolate for a few minutes may actually decrease the PTS risk associated with the initial steam-line break since the initial effect of the PZR PORV failure will be a substantial reduction of pressure.

Figure 3.3. Event tree headings for steam-line breaks at full power.

1	2	3	4	5	6	7	8	9	10	11
SDVs Close on Demand	SI Signal Generated on Demand	MFW Run Back and Isolates on Demand	SGs Blow Down	AFW Actuates on Demand	AFW Flow Automatically Controlled	OA: AFW Isolated to Low-Pressure SG	HPI Occurs on Demand	Charging Flow Runs Back on Demand	OA: AFW Throttled	PZR PORV Reseats on Demand
4 Branches: (1) All five close. (2) One fails to close. (3) Two fail to close. (4) Three or more fail to close.	2 Branches: (1) Signal is generated. (2) Signal is not generated.	4 Branches: (1) All lines run back and MFW is isolated. (2) One line overfeeds. (3) Two lines overfeed. (4) Three lines overfeed.	4 Branches: (1) No SGs blow down. (2) One SG blows down. (3) Two SGs blow down. (4) All three SGs blow down.	2 Branches: (1) AFW actuates. (2) AFW does not actuate.	2 Branches: (1) Flow controlled at nominal rate. (2) Overfeed occurs.	2 Branches: (1) Isolation occurs. (2) Isolation fails to occur.	2 Branches: (1) HPI occurs. (2) HPI fails to occur.	2 Branches: (1) Runs back as required. (2) Fails to run back.	2 Branches: (1) Operator throttles AFW flow. (2) Operator fails to throttle AFW.	2 Branches: (1) PORV reseats. (2) PORV fails to reseat.

Note: The event tree headings for a reactor trip are the same as these except (1) the heading "STM PORVs close on demand" should precede heading 1, and heading 3 should be divided into two headings that treat MFW runback and MFW isolation separately.

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hot 0% power level unless plant cooldown is initiated. In this case, the STM PORVs will be required to modulate to remove decay heat. STM PORV failures in this situation have not been considered.

3.4.3. Reactor Trip

The event tree for a reactor trip initiator has the same basic structure as the event tree for a steam-line break at full power (see Figure 3.3); however, since there is no initial steam-line break, the closure of the STM PORVs, in addition to the SDVs, must be considered.

In addition, whereas MFW runback and isolation are combined in a single heading in Figure 3.3, they are treated as separate branchings in the event tree for a reactor trip because the isolation signal will not necessarily occur. Also, many of the implicit branchings used for the steam-line break will be used only in conjunction with additional failures. For example, the MSIVs will not be commanded to close following a reactor trip unless there is an additional failure, such as SDVs failing to reseat, which may eventually require closure of the MSIVs.

3.4.4. Small-Break LOCA at Full Power

Since any overcooling event of significance will involve a reactor trip, it is assumed that a LOCA event will be followed by a reactor trip. In this case, the reactor trip event tree headings apply for the LOCA event tree with appropriate additions as shown in Figure 3.4. The additions are: turbine trip, accumulator discharge and low-pressure injection, PZR PORV

6.2.

Figure 3.4. Event tree headings for small-break LOCAs at full power.

1	2	3	4	5	6	7	8
Turbine Trips on Demand	STM PORVs Close on Demand	SDVs Close on Demand	SI Signal Generated on Demand	MFW Runs Back and Isolates on Demand	HPI Occurs on Demand	SGs Blow Down	AFW Actuates on Demand
2 Branches: (1) Trips on demand. (2) Fails to trip.	4 Branches: (1) All three close. (2) One fails to close. (3) Two fail to close. (4) All fail to close.	4 Branches: (1) All close. (2) One fails to close. (3) Two fail to close. (4) Three or more fail to close.	2 Branches: (1) Signal is generated. (2) Signal is not generated.	4 Branches: (1) All lines run back and MFW is isolated. (2) One line overfeeds. (3) Two lines overfeed. (4) Three lines overfeed.	2 Branches: (1) HPI occurs. (2) HPI fails to occur.	4 Branches: (1) No SGs blow down. (2) One SG blow-down. (3) Two SGs blow down (4) All three SGs blow down.	2 Branches: (1) AFW actuates. (2) AFW does not actuate.

Figure 3.4. (Continued)

9	10	11	12	13	14	15
AFW Flow Automatically Controlled	OA: AFW Isolated to Low-Pressure SG	Accumulators Discharge	OA: Break Not Isolated	Charging Flow Runs Back on Demand	OA: AFW Throttled	LPI Occurs on Demand
2 Branches: (1) Flow controlled at nominal rate. (2) Overfeed occurs.	2 Branches: (1) Isolation occurs. (2) Isolation fails to occur.	2 Branches: (1) Accumulators discharge when required. (2) Accumulators fail to discharge.	2 Branches: (1) Operator fails to isolate break. (2) Operator isolates break.	2 Branches: (1) Runs back as required. 2) Fails to run back.	2 Branches: (1) Operator throttles AFW flow. (2) Operator fails to throttle AFW flow.	2 Branches: (1) LPI occurs as required. (2) LPI fails to occur.

Note: The event tree headings for other LOCAs are similar to these except for the following: (1) For medium-break LOCA at full power, delete headings 12 and 13. (2) For small-break LOCA at hot 0% power, delete headings 1, 2, 3, and 10 and modify heading 5 to read "MFW isolated on demand." (3) For medium-break LOCA at hot 0% power, delete headings 1, 2, 3, 10, 12, and 14 and modify heading 5 to read "MFW isolated on demand."

reseat and LOCA isolation. In addition, main feedwater runback and main feedwater isolation have been combined into a single branch.

An SI failure condition was considered for the LOCA event tree. However, this condition can be considered as an overcooling situation only if loop flow stagnation and subsequent recovery of SI flow occur.

3.4.5. Medium-Break LOCAs at Full Power

The event tree for a medium-break LOCA at full power is identical to that for the small-break LOCA at full power except that the branches "Break not isolated" (No. 12) and "Charging flow runs back on demand" (No. 13) are deleted. Because the break cannot be isolated, control of charging flow is irrelevant.

3.4.6. Small-Break LOCA at Hot 0% Power

The event tree for a small-break LOCA at hot 0% power was constructed from the event tree for a small-break LOCA at full power by deleting the headings "Turbine trips on demand" (No. 1), "STM PORVs close on demand" (No. 2), "SDVs close on demand" (No. 3), "SGs blow down" (No. 7), and "AFW isolated to low-presure SG" (No. 10). In addition heading No. 5 should be modified to read "MFW isolated on demand." (MFW runback does not apply at hot 0% power, but MFW isolation is considered.)

3.4.7. Medium-Break LOCA at Hot 0% Power

The event tree for a medium-break LOCA at hot 0% power was obtained by deleting two branches from the tree for a small-break LOCA at hot 0% power: "Break not isolated" and "Charging flow runs back on demand" (Nos. 12 and 14 in Figure 3.4). The resulting event tree headings are summarized in the Section 3.5.

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3.4.8. Tube Rupture

The tube rupture event tree was developed based on a review of tube rupture procedures. It is composed of five branches:

(1) Steam Dumps Close on Demand - This branch is required to examine the potential combination of a tube rupture and a small-pipe steam-line break.

(2) OA: Number of Pressurizer PORV Lifts Performed - The Emergency Operating Procedures require the operator to use the pressurizer PORV to lower the primary system pressure. This adds an additional cooling effect to the system. The question arises as to whether the initial PORV lift is enough to keep the pressure at a lower level. There is at least some argument that a second manual opening of the PORV would be performed at some delayed time following the initial opening. This branch identifies whether one or two PORV openings are performed.

(3) PORV Reseat - Each time a PORV is opened, the potential for failure of the PORV to close must be examined. This branch determines whether closure is effected.

(4) OA: Close Block Valve - Each time a PORV fails to close, the potential for operator isolation of the valve via the block valve must be examined. This branch determines whether the operator

performs the action.

(5) OA: Terminate SI - This final branch addresses whether or not the operator terminates SI. Failure to terminate SI will lead to a continuous feed and bleed situation where HPI feeds cold water into the system and warmer water flows from the primary to the secondary system.

3.4.9. Loss of Main Feedwater

The loss of main feedwater event was also considered to be a potential overcooling initiating event because auxiliary feedwater flow will occur. The effects of auxiliary flow and potential overfeed associated with other events such as steam-line breaks, LOCAs, etc. are addressed by the event trees defined in the previous sections. However, the loss of main feedwater followed by auxiliary feedwater flow and potential auxiliary feedwater overfeed has not been addressed. Since there are only a limited number of these cases, no event tree was developed for the case of main feedwater loss. Instead, each sequence is simply defined and quantified.

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3.5. Event Tree Quantification and Collapse

In this section probabilities are assigned to each of the branches of the event trees identified in Section 3.4 and the probabilities are then combined with the frequencies of the corresponding initiating events identified in Section 3.3 to determine the frequency of each possible sequence on each event tree. The resulting frequencies are then screened and collapsed to determine which event tree sequences are important enough to undergo subsequent thermal-hydraulic and fracture-mechanics analyses. In addition, the importance of support system failures with respect to PTS events are examined and sequences initiated by such failures are selected for further analysis.

In determining the branch probabilities, the complete Licensee Event Report (LER) data base for H. B. Robinson Unit 2 was reviewed for initiating events and system failures, as well as for a general overview of the performance of plant systems of interest. Although the H. B. Robinson data base did reflect some failures and unavailability of components, it did not reflect a significant number of failures on demand for the systems of interest. Therefore, in lieu of relying solely on H. B. Robinson information, Westinghouse-specific and PWR-specific operational information was employed for the target event when available and when the H. B. Robinson operational experience did not provide an adequate data base for that event. Additional information was obtained from the national Reliability Evaluation Program Generic Data Base, the Nuclear Power Plant Operating Experience Summaries, and, when practical, from other sources. With the constraints imposed by programmatic needs and the availability of

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operational data, only simplified approaches to frequency and probability estimation were permitted, but these estimates were considered to be acceptable for use as screening estimates. The estimates developed, the rationale used, relevant information, and information sources are presented in Appendix B.

A somewhat simplified approach was used to quantify the failure rates for expected operator actions. The basis for this approach was a hierarchical structure of performance shaping factors that was developed as part of the current program and has since been labeled the STAHR approach* (see Appendix C). The structure used in the STAHR approach allowed the human error rate for a particular target event to be calculated from a network of related assessments by individuals who had some operational experience or had been involved in human reliability analyses on nuclear power plant transient analyses. Some error rates were conditional probabilities, while others reflected the weight of evidence concerning influences operating at this particular nuclear power station. Generally, influencing events were organized to reflect the potential effects of the operator's physical and social environment, as well as personal factors. Interactions among these factors were also modeled. Once operator failure rates were quantified, dependence or coupling factors taken from NUREG/CR-1278 were used to adjust the operator action failure probabilities. These final probabilities were then applied to the event tree branchings as necessary. The development of these probabilities is discussed in Appendix D.

After the frequencies for all the sequences for each initiating event were obtained, a frequency of 10^{-7}/yr or greater was used as a screening

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*This type of methodology was used due to a lack of resources, including the lack of task analysis information. Although the approach appears to have been successful for this application, the use of this methodology cannot be condoned for a more generic usage at this time. Even though the basic structure of the approach has merit, a more basic scientific analysis is necessary to perfect a usable methodology.

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criterion to identify those sequences which should undergo thermal-hydraulic and fracture-mechanics analyses on an individual basis. The remaining sequences were combined into a set of "residual" groups. These groups were then further examined to identify sequences that were similar enough to sequences above the 10^{-7} screening level that their consequences were bounded by the respective higher frequency sequences. Sequences falling into this category were removed from the residual group and their frequencies added in with those of the appropriate bounding sequences. The residual groups were also examined for additional sequences that should be specifically evaluated because the combination of their frequency and potential consequences identified them as being potentially important. These were removed from the residual group and treated separately.

The basis for bounding residual consequences by other existing sequences is tied to thermal-hydraulic and system state considerations. In general, sequences were bounded under the following conditions. Sequences which involved the failure of the AFW to actuate and with no subsequent recovery were considered bounded by sequences involving successful operation of AFW. Sequences involving failure of the SI signal to generate were considered bounded by failure of the HPI to occur on demand, since HPI would not occur without an SI signal. For LOCA initiators at power, all sequences involving failure of the SI signal or HPI were grouped with the top sequence involving failure of HPI to occur on demand, regardless of the events occurring on the secondary side, since the RCS could not be repressurized without HPI. For steam-line break initiators, sequences with HPI failure were considered of less consequence from a repressurization and overcooling standpoint than their counterpart sequences with HPI success and were

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therefore bounded. Likewise, failure of LPI is of less consequence to PTS than successful LPI. On the reactor trip tree, sequences with MFW isolation failure but with runback success were considered to be similar to sequences with AFW overfeed. Likewise, sequences with SI signal failure were considered to be similar to AFW overfeed sequences because MFW isolation would not occur immediately without an SI signal. AFW overfeed sequences were also considered to be similar to sequences with one MFW line failing to run back.

For each event tree discussed below, three items are presented: a table summarizing the branch headings and describing the branch probabilities used; the event tree; and a table describing the sequences identified for thermal-hydraulic and fracture-mechanics analyses. Sequence numbers and associated sequences provided in the tables are consistent with those included in the INEL analysis* and not necessarily consistent with the order of presentation of the tables. Sequences that have been combined with other sequences are indicated on the far right side of the event trees.

It will be noted that event trees per se are not included for tube rupture events or loss-of-feedwater (LOFW) events. However, potentially important sequences for these events are identified and quantified. In addition, as noted earlier, sequences from the support system failures that were identified as potential PTS sequence initiators are quantified.

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*C. D. Fletcher, et al. Thermal Hydraulic Analysis of Overcooling Sequences for the H. B. Robinson Unit 2 Pressurized Thermal Shock Study (Draft), Idaho National Engineering Laboratory, August 1984.

3.5.1. Reactor Trip

The frequency for a reactor trip as an initiating event is 8.7/yr (see development of initiating frequencies in Appendix B). This frequency combined with the branch tree probabilities given in Table 3.6 resulted in a total of 9773 sequences. Of this number, 112 had a frequency of 10^{-7}/yr or higher. The remaining 9661 residual sequences had a combined frequency of 3.63×10^{-6}/yr. The 112 sequences and the residual sequences are all shown in Figure 3.5.

T. 3.6

F 3.5

The 112 sequences with a frequency of 10^{-7} or higher were investigated to determine whether selected sequences could be combined. Where it was found that the thermal-hydraulic RCS response of a sequence was similiar to and bounded by that of another, the sequences were combined. The frequency of the bounding sequence was calculated as the sum of the constituent sequences. This process reduced the number of specific reactor trip sequences from 112 to 95.

At about this time it was realized that a very important operator action was missing from the analysis. It had initially been assumed that when SDVs failed, the MSIVs would automatically close, thereby isolating the SDV failures (except, of course, in the case where the MSIVs malfunction and fail to close). However, the initial thermal-hydraulic analysis revealed that conditions necessary for automatic MSIV closure would not exist. Thus, as stated in the procedures, the operator would be required to close the MSIVs. Some delay is anticipated since it was felt that once diagnosed there would be some attempt at closing the SDVs manually before isolating the system by closing the MSIVs. Thus the time of closure was chosen to be 30 minutes after reactor trip. This led to two sequences for each case

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Table 3.6. Branch probabilities for a reactor trip[a]

Tree Heading	Branch	Branch Probability
STM PORVs close on demand.	(1) All three STM PORVs close.	0.97981
	(2) One STM PORV fails to close.	1.8×10^{-2}
	(3) Two STM PORVs fail to close.	1.7×10^{-3}
	(4) All three STM PORVs fail to close.	4.9×10^{-4}
SDVs close on demand.	(1) All five SDVs close.	0.99768
	(2) One SDV fails to close.	1.6×10^{-3}
	(3) Two SDVs fail to close.	3.0×10^{-4}
	(4) Three or more SDVs fail to close.	4.2×10^{-4}
MFW runs back.	(1) All three lines run back.	0.9999940
	(2) One line fails to run back.[b]	5.3×10^{-6}
	(3) Two lines fail to run back.[b]	5.0×10^{-7}
	(4) All three lines fail to run back.[b]	1.4×10^{-7}
SI signal generated on demand.	(1) SI signal is generated.	0.99997
	(2) SI signal is not generated.	3×10^{-5}
MFW isolated on demand.	If all lines run back,	
	(1) no line overfeeds.	1.0
	If one line fails to run back,	
	(1) No line overfeeds.	0.99
	(2) One line overfeeds.	1×10^{-2}
	If two lines fail to run back,	
	(1) No line overfeeds.	0.97906
	(2) One line overfeeds.	2.0×10^{-2}
	(3) Two lines overfeed.	9.4×10^{-4}
	If three lines fail to run back,	
	(1) No line overfeeds.	0.96639
	(2) One line overfeeds.	3.0×10^{-2}
	(3) Two lines overfeed.	2.8×10^{-3}
	(4) All three lines overfeed.	8.1×10^{-4}
SGs blow down.	If one or two SDVs fail,	
	(1) All three SGs blow down.	1.0[c]
	If three or more SDVs fail,	
	(1) No SGs blow down.	0.99087[d]
	(2) One SG blows down.	6.6×10^{-3}[d]
	(3) Two SGs blow down.	2.0×10^{-3}[d]
	(4) All three SGs blow down.	5.3×10^{-4}[d]
	If one, two, or three STM PORVs fail, then, respectively,	
	(1) One SG blows down.	1.0
	(2) Two SGs blow down.	1.0
	(3) Three SGs blow down.	1.0
	If MSIV closure signal is not generated,	
	(1) All three SGs blow down.	1.0
AFW actuates on demand.	(1) AFW actuates.	0.999
	(2) AFW does not actuate.	1×10^{-3}
AFW flow automatically controlled.	(1) AFW flow is automatically controlled at nominal rate.	0.9925
	(2) Flow control failure leads to abnormally high AFW flow rate (overfeeds).	7.5×10^{-3}
OA: AFW isolated to low-pressure SG	(1) AFW isolation occurs.	0.9983
	(2) AFW isolation fails to occur.	1.7×10^{-3}
HPI occurs on demand.	If SI signal is generated,	
	(1) HPI occurs.	0.99939
	(2) HPI fails to occur.	6.1×10^{-4}
	If SI signal is not generated,	
	(1) Operator manually starts HPI.	0.99
	(2) Operator fails to start HPI.	1×10^{-2}

Table 3.6. Branch probabilities for a reactor trip[a] (cont.)

Tree Heading	Branch	Branch Probability
Charging flow runs back on demand.	(1) Charging flow runs back, as required (repressurization limited).	0.99
	(2) Charging flow fails to run back (repressurization not limited).	1×10^{-2}
OA: AFW throttled.	If operator isolates AFW,	
	(1) Operator throttles AFW flow.	0.99
	(2) Operator fails to throttle AFW flow.	1×10^{-2}
	If operator fails to isolate AFW,	
	(1) Operator fails to throttle AFW flow.	1.0
	(2) Operator throttles AFW flow.	0.0
PZR PORV reseats on on demand.	(1) PZR PORV reseats if charging flow fails to run back.	0.9988
	(2) PZR PORV fails to reseat if charging flow fails to run back.	1.2×10^{-3}

[a] The acronyms used in this table (in the order of their appearance) are: STM PORV = steam power-operated relief valve, SDV = steam dump valve, MFW = main feedwater, SI = safety injection, SG = steam generator, MSIV = main steam isolation valve, AFW = auxiliary feedwater, OA = operator action, HPI = high-pressure injection, and PZR PORV = pressurizer power-operated relief valve.

[b] Includes failure of MFW regulating valves to run back and failure of one or both MFW pumps to trip to high level in any steam generator.

[c] Only one branch is carried for either one or two SDVs. In the case of the failure of one SDV, it was felt that the operator would be very reluctant to close the MSIVs for this amount of excess steam flow and probably would allow the system to cool down as the transient defines. Thus all three SGs would blow down slowly. For two SDV failures, it is assumed that the operator still would be reluctant to isolate the SGs, but more than likely he would close the MSIVs within 30 minutes. But, since the operator action failure probability used for this case (1×10^{-2}) is higher than the valve for failure of the MSIVs to close on demand, the MSIV failure branches are not considered. Thus, with respect to the event trees, two SDV failures are presented as all three SGs blow down since closure of the MSIVs by the operator is considered separate from the event tree.

[d] The probabilities presented here represent blowdown due to MISV failure to close. It is anticipated that there will be times when a steam-line valve or pipe failure would not produce enough steam flow to cause automatic closure of the MSIVs. In this case, the operator would be required to manually close these valves. Failure to close the valves would result in the blowdown of all three steam generators. When applicable, "A" and "B" sequences are identified to designate whether or not the operator closes the valves. Probabilities associated with failure of the operator to close the valves vary with the circumstances and are discussed in Appendix D.

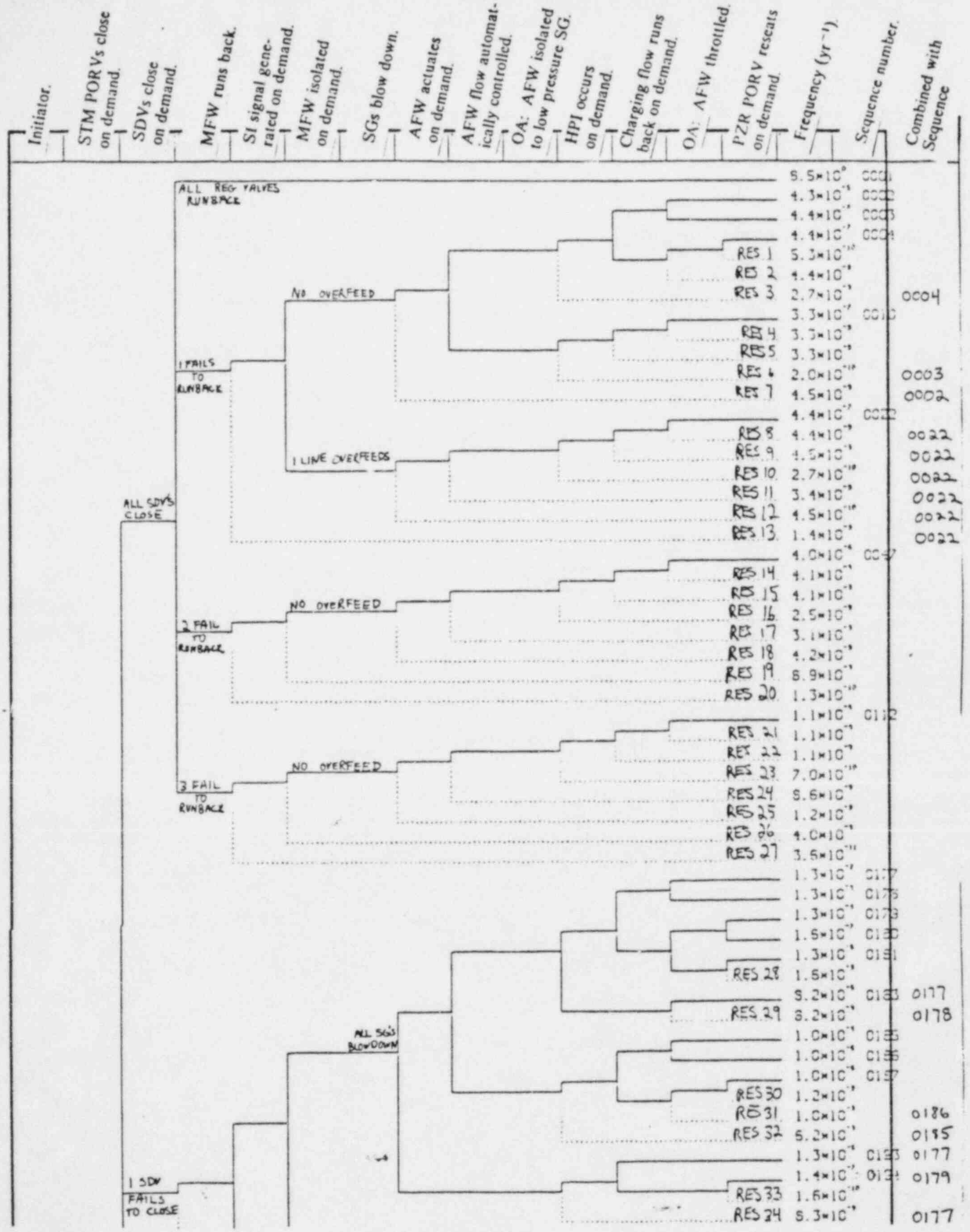

Figure 3.5. Event tree for a reactor trip.

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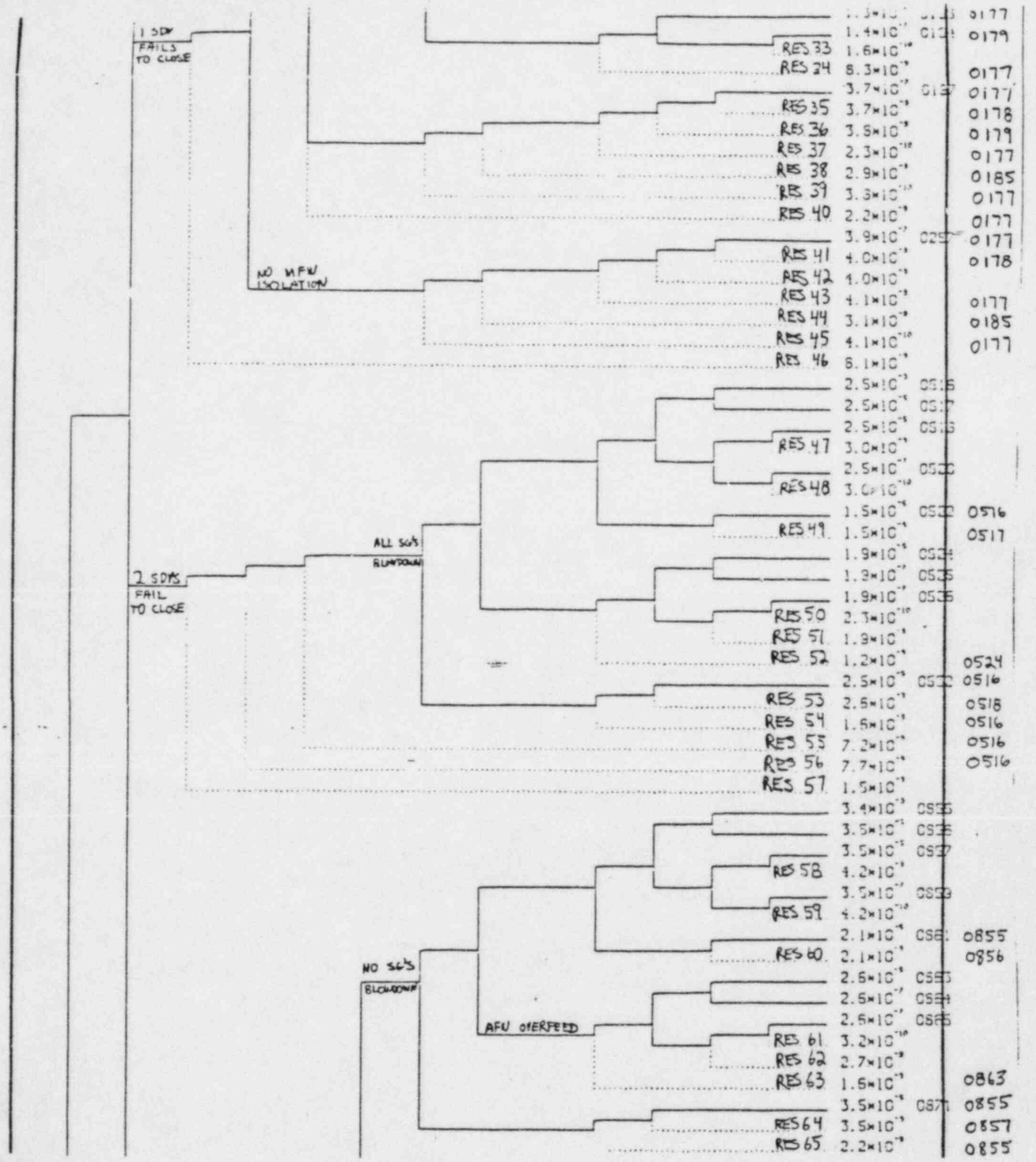

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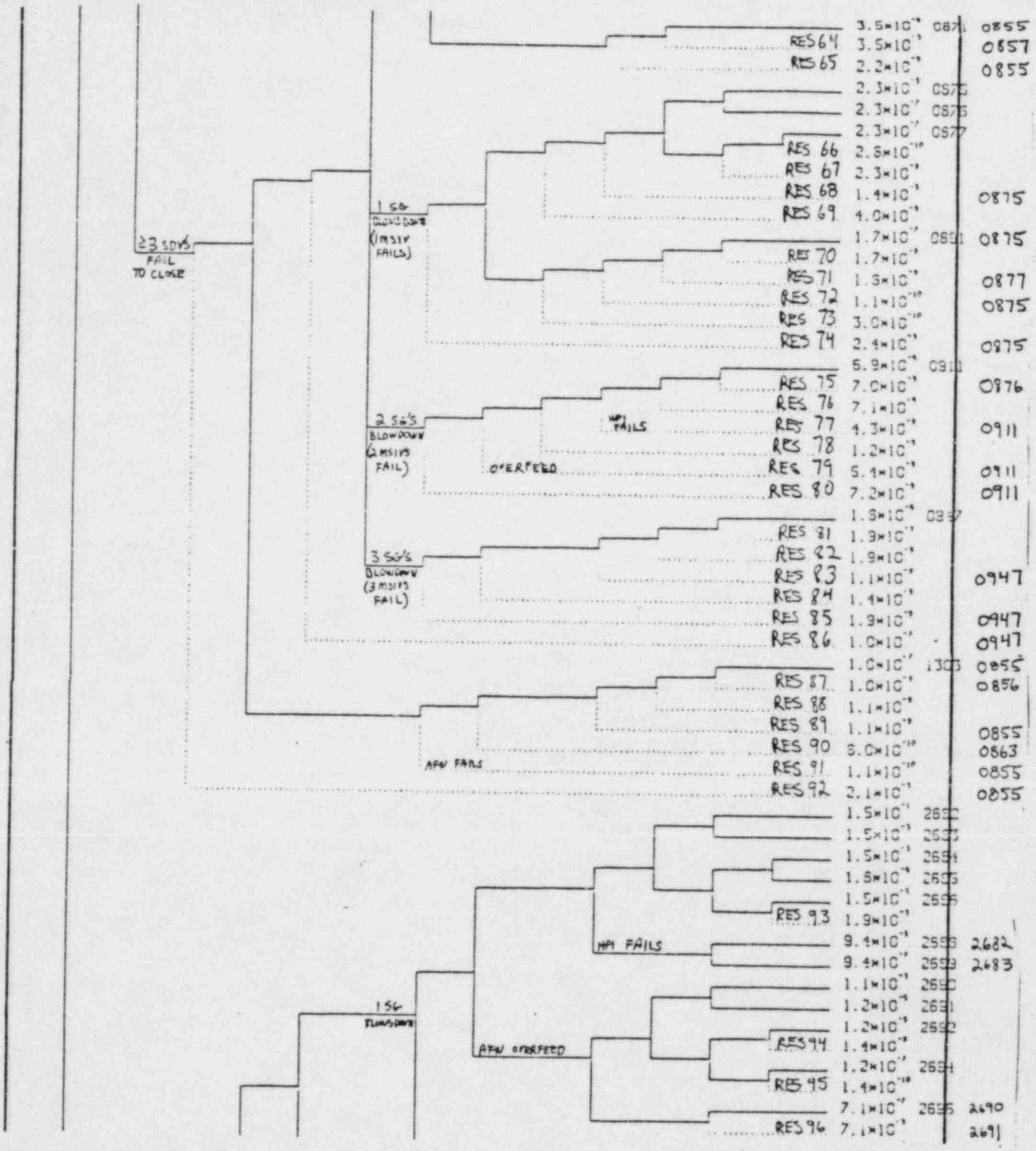

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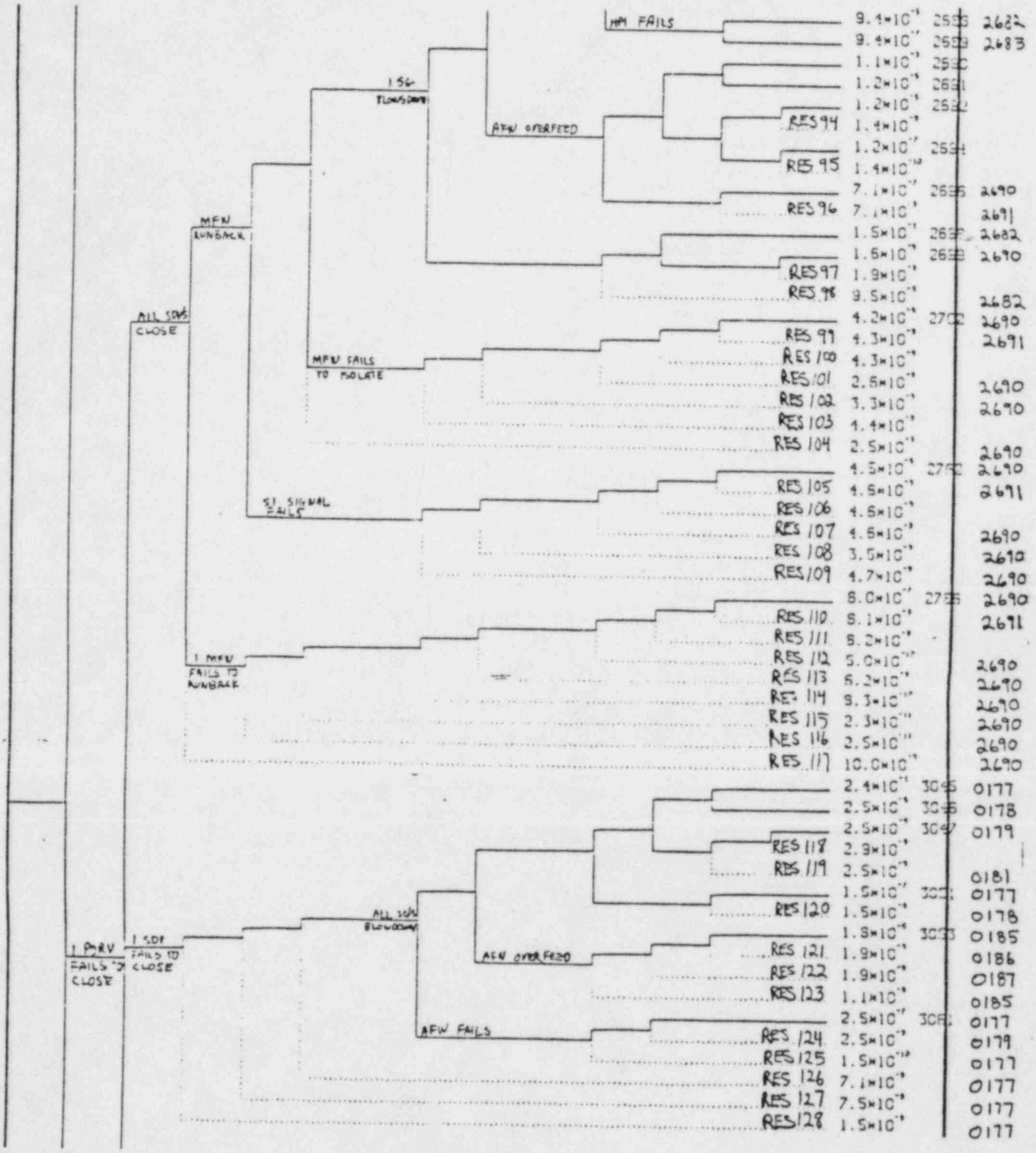

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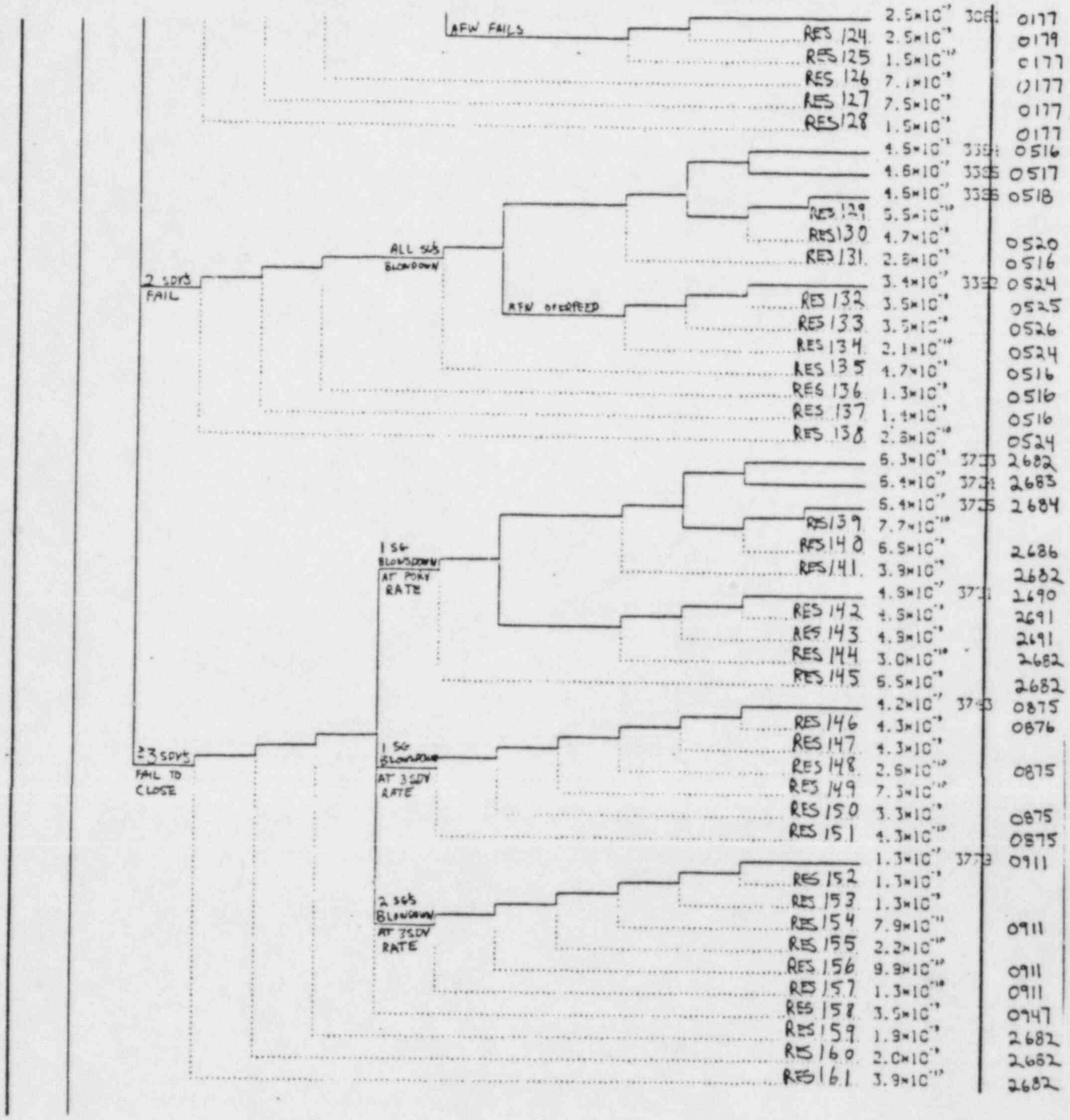

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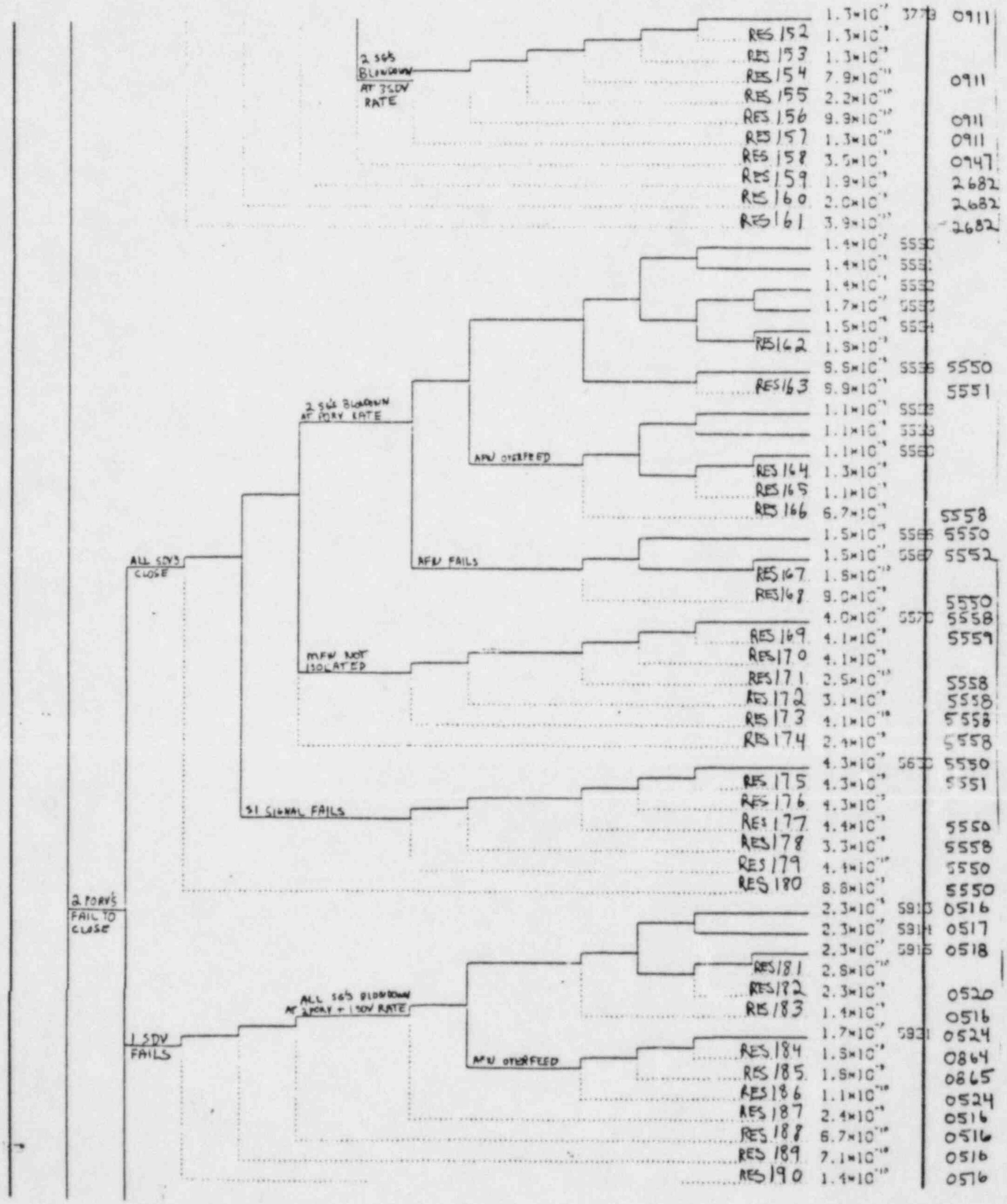

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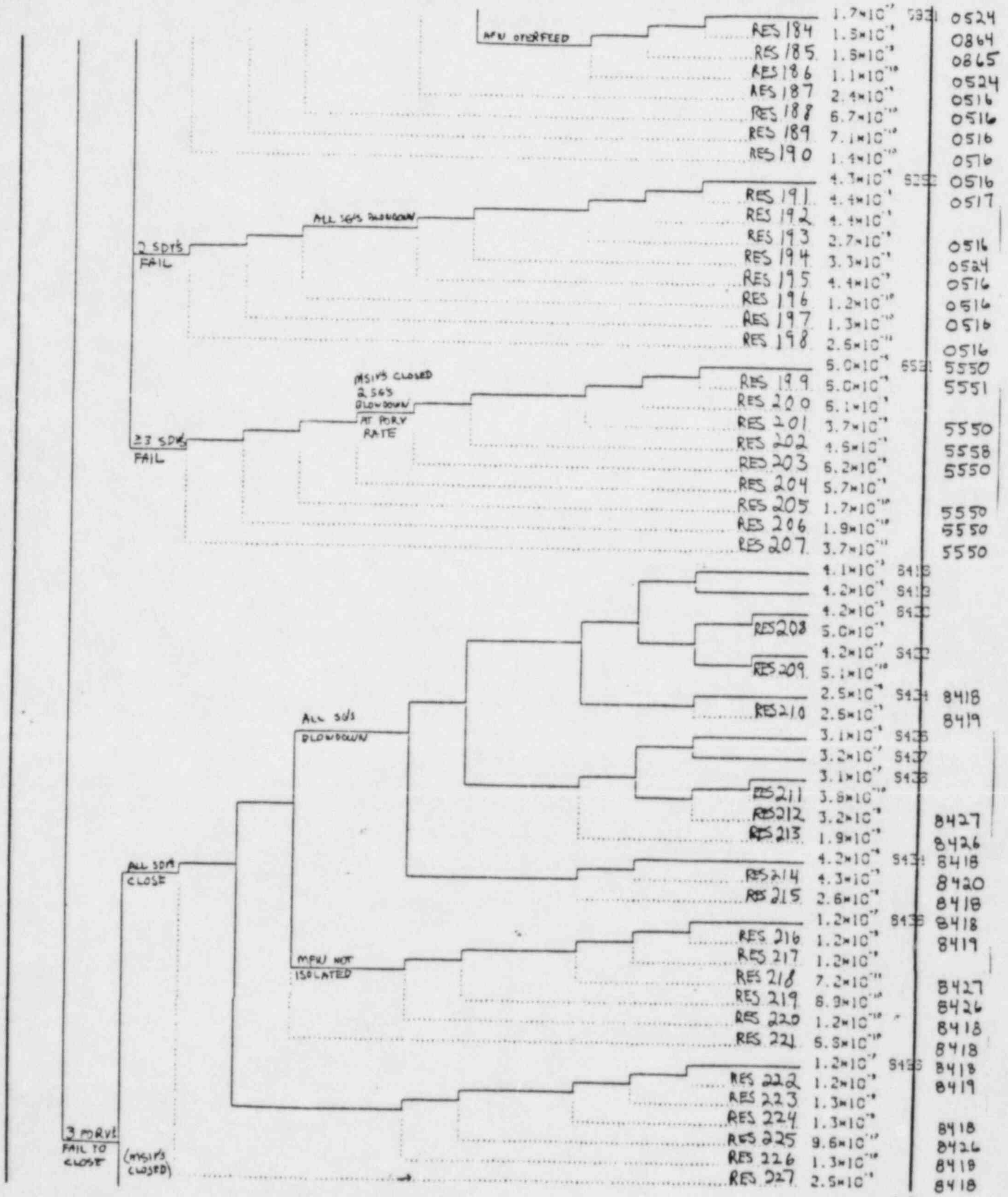

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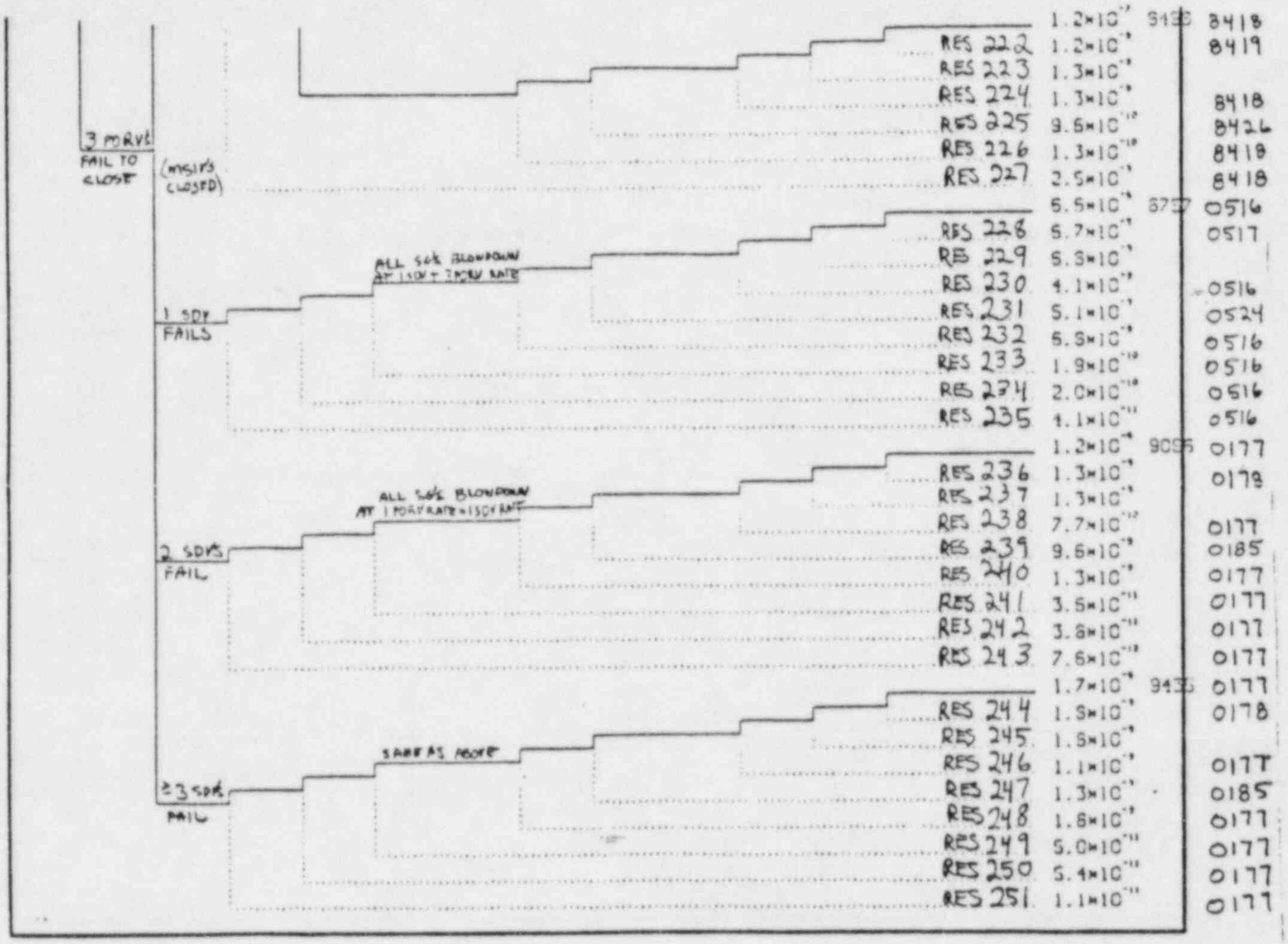

Figure 3.5. (Continued)

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involving a failure of SDV(s) to close: (1) SDV(s) fail and operator closes MSIV(s) at 30 minutes, and (2) SDV(s) fail and operator fails to close MSIV(s) in the two-hour time frame. The success and failure probabilities associated with this operator action were perceived to vary with conditions. (These probabilities are discussed in Appendix D.) The two sequences are designated "A" and "B" respectively.

The use of the "A" and "B" designation increased the number of reactor trip sequences to be analyzed from 95 to 110 (see Table 3.7). The bounding process performed on the residual sequences reduced the total frequency of the residual group to 2.7 x 10^{-6}/yr. The remaining residual sequences were very diverse with respect to consequences; therefore, they were divided into four different groups based on the nature of the event. The four residual classes can be characterized as:

(1) Equivalent to small-break LOCA (PZR PORV failed open).

(2) Equivalent to a small-break LOCA coupled with a small-pipe steam-line break (PZR PORV and SDV or STM PORV failed open).

(3) Equivalent to a small steam-line break with unisolated main or auxiliary feedwater flow.

(4) Equivalent to a small steam-line break with full RCS repressurization (unthrottled charging flow).

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Table 3.7. Sequences to be analyzed for reactor trip at full power[a]

Sequence No.[b]	STM PORVs Close on Demand	SDVs Close on Demand	MFW Runs Back	MFW Isolates on Demand	SGs Blow Down	AFW Flow Automatically Controlled	OA: AFW Isolated to LP SG	Charging Flow Runs Back	OA: AFW Throttled	Frequency (yr^{-1})
9.1 (0001)	All close	All close	All lines run back	NA	NA	NA	NA	NA	NA	8.5
9.2 (0177)	All close	One fails to close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	1.3E−2
9.3 (0178)	All close	One fails to close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Fails to throttle	1.3E−4
9.4 (0179)	All close	One fails to close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	1.4E−4
9.5 (0181)	All close	One fails to close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Fails to run back	Fails to throttle	1.3E−6
9.6 (0185)	All close	One fails to close	All lines run back	No line overfeeds	All SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG alarm	1.0E−4
9.7 (0186)	All close	One fails to close	All lines run back	No line overfeeds	All SGs blow down	Overfeeds	NA	Runs back run back	Fails to throttle	1.0E−6
9.8 (0187)	All close	One fails to close	All lines run back	No line overfeeds	All SGs blow down	Overfeeds	NA	Fails to run back	Throttles prior to SG high-level alarm	1.0E−6
9.9A (0516)	All close	Two fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	2.7E−3
9.9B (0516)	All close	Two fail to close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	2.7E−5
9.10A (0517)	All close	Two fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Automatically controlled	NA	Runs back as required	Fails to throttle	2.8E−5
9.10B (0517)	All close	Two fail to close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Fails to throttle	4.2E−6
9.11A (0518)	All close	Two fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	2.8E−5

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Table 3.7 (Cont'd)

Sequence No.[b]	STM PORVs Close on Demand	SDVs Close on Demand	MFW Runs Back	MFW Isolates on Demand	SGs Blow Down	AFW Flow Automatically Controlled	OA: AFW Isolated to LP SG	Charging Flow Runs Back	OA: AFW Throttled	Frequency (yr^{-1})
9.11B (0518)	All close	Two fail to close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	2.8E−7
9.12A (0520)	All close	Two fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Automatically controlled	NA	Fails to run back	Fails to throttle	2.9E−7
9.12B (0520)	All close	Two fail to close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Fails to run back	Fails to throttle	4.4E−8
9.13A (0524)	All close	Two fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	2.0E−5
9.13B (0524)	All close	Two fail to close	All lines run back	No line overfeeds	All SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	2.0E−7
9.14A (0855)	(Included in Sequence 9.19A)									
9.14B (0855)	(Included in Sequence 9.19B)									
9.15A (0856)	(Included in Sequence 9.20A)									
9.15B (0856)	(Included in Sequence 9.20B)									
9.16A (0857)	(Included in Sequence 9.21A)									
9.16B (0857)	(Included in Sequence 9.21B)									
9.17A (0859)	(Included in Sequence 9.22A)									
9.17B (0859)	(Included in Sequence 9.22B)									
9.18A (0863)	(Included in Sequence 9.23A)									
9.18B (0863)	(Included in Sequence 9.23B)									
9.19A (0855)	All close	> Three fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	3.4E−3
9.19B (0855)	All close	> Three fail to close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	7E−6
9.20A (0856)	All close	> Three fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Automatically controlled	NA	Runs back as required	Fails to throttle	3.5E−5
9.20B (0856)	All close	> Three fail to close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Fails to throttle	3.5E−6
9.21A (0857)	All close	> Three fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	3.5E−5
9.21B (0857)	All close	> Three fail to close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	7E−8

Table 3.7 (Cont'd)

Sequence No.[a]	STM PORVs Close on Demand	SDVs Close on Demand	MFW Runs Back	MFW Isolates on Demand	SGs Blow Down	AFW Flow Automatically Controlled	OA: AFW Isolated to LP SG	Charging Flow Runs Back	OA: AFW Throttled	Frequency (yr^{-1})
9.22A (0859)	All close	> Three fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Automatically controlled	NA	Fails to run back	Fails to throttle	3.5E−7
9.22B (0859)	All close	> Three fail to close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Fails to run back	Fails to throttle	3.5E−8
9.23A (0863)	All close	> Three fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	2.6E−5
9.23B (0863)	All close	> Three fail to close	All lines run back	No line overfeeds	All SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	5.2E−8
9.24 (0875)	All close	> Three fail to close	All lines run back	No line overfeeds	One SG blows down	Automatically controlled	Isolation occurs	Runs back as required	Throttles prior to SG high-level alarm	2.4E−5
9.25 (2682)	One fails to close	All close	All lines run back	No line overfeeds	One SG blows down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	1.5E−1
9.26 (2683)	One fails to close	All close	All lines run back	No line overfeeds	One SG blows down	Automatically controlled	NA	Runs back as required	Fails to throttle	1.5E−3
9.27 (2684)	One fails to close	All close	All lines run back	No line overfeeds	One SG blows down	Automatically controlled	NA	Runs back run back	Fails to throttle	1.5E−3
9.28 (2686)	One fails to close	All close	All lines run back	No line overfeeds	One SG blows down	Automatically controlled	NA	Fails to run back	Fails to throttle	1.5E−5
9.29 (2690)	One fails to close	All close	All lines run back	No line overfeeds	One SG blows down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	1.1E−3
9.30 (2691)	One fails to close	All close	All lines run back	No line overfeeds	One SG blows down	Overfeeds	NA	Runs back as required	Fails to throttle	1.2E−5
9.31 (2692)	One fails to close	All close	All lines run back	No line overfeeds	One SG blows down	Overfeeds	NA	Fails to run back	Throttles prior to SG high-level alarm	1.2E−5
9.32 (2694)	One fails to close	All close	All lines run back	No line overfeeds	One SG blows down	Overfeeds	NA	Fails to run back	Fails to throttle	1.2E−7
9.33 (5550)	Two fail to close	All close	All lines run back	No line overfeeds	Two SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	1.4E−2
9.34 (5551)	Two fail to close	All close	All lines run back	No line overfeeds	Two SGs blow down	Automatically controlled	NA	Runs back as required	Fails to throttle	1.4E−4
9.35 (5552)	Two fail to close	All close	All lines run back	No line overfeeds	Two SGs blow down	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	1.4E−4
9.36 (5554)	Two fail to close	All close	All lines run back	No line overfeeds	Two SGs blow down	Automatically controlled	NA	Fails to run back	Fails to throttle	1.5E−6
9.37 (5558)	Two fail to close	All close	All lines run back	No line overfeeds	Two SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	1.1E−4

Table 3.7 (Cont'd)

Sequence No.[b]	STM PORVs Close on Demand	SDVs Close on Demand	MFW Runs Back	MFW Isolates on Demand	SGs Blow Down	AFW Flow Automatically Controlled	OA: AFW Isolated to LP SG	Charging Flow Runs Back	OA: AFW Throttled	Frequency (yr^{-1})
9.38 (5559)	Two fail to close	All close	All lines run back	No line overfeeds	Two SGs blow down	Overfeeds	NA	Runs back as required	Fails to throttle	1.1E−6
9.39 (5560)	Two fail to close	All close	All lines run back	No line overfeeds	Two SGs blow down	Overfeeds	NA	Fails to run back	Throttles prior to SG high-level alarm	1.1E−6
9.40 (Res 165)	Two fail to close	All close	All lines run back	No line overfeeds	Two SGs blow down	Overfeeds	NA	Fails to run back	Fails to throttle	1.1E−8
9.41 (8418)	All fail to close	All close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	4.1E−3
9.42 (8419)	All fail to close	All close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back run back	Fail to throttle	4.2E−5
9.43 (8420)	All fail to close	All close	All lines run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	4.2E−5
9.44 (8422)	All fail to close	All close	All lines run back	No line overfeeds	All SGs blow down	Automatically	NA	Fails to run back	Fails to throttle	4.2E−7
9.45 (8426)	All fail to close	All close	All lines run back	No line overfeeds	All SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	3.1E−5
9.46 (8427)	All fail to close	All close	All lines run back	No line overfeeds	All SGs blow down	Overfeeds	NA	Runs back as required	Fails to throttle	3.2E−7
9.47 (8428)	All fail to close	All close	All lines run back	No line overfeeds	All SGs blow down	Overfeeds	NA	Fails to run back	Throttles prior to SG high-level alarm	3.1E−7
9.48 (0002)	All close	All close	One line fails to run back	No line overfeeds	No SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	4.3E−5
9.49 (0003)	All close	All close	One line fails to run back	No line overfeeds	No SGs blow down	Automatically controlled	NA	Runs back as required	Fails to throttle	4.9E−7
9.50 (0004)	All close	All close	One line fails to run back	No line overfeeds	No SGs blow down	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	4.9E−7
9.51 (Res 2)	All close	All close	One line fails to run back	No line overfeeds	No SGs blow down	Automatically controlled	NA	Fails to run back	Fails to throttle	4.4E−9
9.52 (0010)	All close	All close	One line fails to run back	No line overfeeds	No SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	3.7E−7

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Table 3.7 (Cont'd)

Sequence No.[b]	STM PORVs Close on Demand	SDVs Close on Demand	MFW Runs Back	MFW Isolates on Demand	SGs Blow Down	AFW Flow Automatically Controlled	OA: AFW Isolated to LP SG	Charging Flow Runs Back	OA: AFW Throttled	Frequency (yr^{-1})
9.53 (Res 4)	All close	All close	One line fails to run back	No line overfeeds	No SGs blow down	Overfeeds	NA	Runs back as required	Fails to throttle	3.3E−9
9.54 (Res 5)	All close	All close	One line fails to run back	No line overfeeds	No SGs blow down	Overfeeds	NA	Fails to run back	Throttles prior to SG high-level alarm	3.3E−9
9.55 (Res 5)	All close	All close	One line fails to run back	No line overfeeds	No SGs blow down	Overfeeds	NA	Fails to run back	Fails to throttle	3.3E−9
9.56 (0022)	All close	All close	One line fails to run back	One line overfeeds	No SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	4.6E−7
9.57 (Res 46)	All close	One fails to close	One line fails to run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	8.1E−8
9.58 (Res 46)	All close	One fails to close	One line fails to run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Fails to throttle	<8.1E−8
9.59 (Res 46)	All close	One fails to close	One line fails to run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	<8.1E−8
9.60 (Res 46)	All close	One fails to close	One line fails to run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Fails to run back	Fails to throttle	<8.1E−0
9.61 (Res 46)	All close	One fails to close	One line fails to run back	No line overfeeds	All SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	<8.1E−8
9.62 (Res 57)	All close	Two fail to close	One line fails to run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	1.5E−8
9.63 (Res 57)	All close	Two fail to close	One line fails to run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Fails to throttle	<1.5E−8
9.64 (Res 57)	All close	Two fail to close	One line fails to run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	<1.5E−8
9.65 (Res 57)	All close	Two fail to close	One line fails to run back	No line overfeeds	All SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	<1.5E−8
9.66 (0047)	All close	All close	Two lines fail to run back	No line overfeeds	No SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	4.0E−6

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Table 3.7 (Cont'd)

Sequence No.[b]	STM PORVs Close on Demand	SDVs Close on Demand	MFW Runs Back	MFW Isolates on Demand	SGs Blow Down	AFW Flow Automatically Controlled	OA: AFW Isolated to LP SG	Charging Flow Runs Back	OA: AFW Throttled	Frequency (yr^{-1})
9.67 (Res 14)	All close	All close	Two lines fail to run back	No line overfeeds	No SGs blow down	Automatically controlled	NA	Runs back as required	Fails to throttle	4.1E-8
9.68 (Res 15)	All close	All close	Two lines fail to run back	No line overfeeds	No SGs blow down	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	4.1E-8
9.69 (Res 15)	All close	All close	Two lines fail to run back	No line overfeeds	No SGs blow down	Automatically controlled	NA	Fails to run back	Fails to throttle	<4.1E-8
9.70 (Res 17)	All close	All close	Two lines fail to run back	No line overfeeds	No SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	3.1E-8
9.71 (Res 17)	All close	All close	Two lines fail to run back	No line overfeeds	No SGs blow down	Overfeeds	NA	Runs back as required	Fails to throttle	<3.1E-8
9.72 (Res 17)	All close	All close	Two lines fail to run back	No line overfeeds	No SGs blow down	Overfeeds	NA	Fails to run back	Throttles prior to SG high-level alarm	<3.1E-8
9.73 (Res 17)	All close	All close	Two lines fail to run back	No line overfeeds	No SGs blow down	Overfeeds	NA	Fails to run back	Fails to throttle	<3.1E-8
9.74 (Res 19)	All close	All close	Two lines fail to run back	One line overfeeds	No SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	8.9E-8
9.75 (Res 46)	All close	One fails to close	Two lines fail to run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	8.1E-8
9.76 (Res 46)	All close	One fails to close	Two lines fail to run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Fails to throttle	<8.1E-8
9.77 (Res 46)	All close	One fails to close	Two lines fail to run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	<8.1E-8
9.78 (Res 46)	All close	One fails to close	Two lines fail to run back	No line overfeeds	All SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	<8.1E-8
9.79 (Res 57)	All close	Two fail to close	Two lines fail to run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	<1.5E-8

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Table 3.7 (Cont'd)

Sequence No.[b]	STM PORVs Close on Demand	SDVs Close on Demand	MFW Runs Back	MFW Isolates on Demand	SGs Blow Down	AFW Flow Automatically Controlled	OA: AFW Isolated to LP SG	Charging Flow Runs Back	OA: AFW Throttled	Frequency (yr^{-1})
9.80 (Res 57)	All close	Two fail to close	Two lines fail to run back	No line overfeeds	All SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	<1.5E−8
9.81 (0112)	All close	All close	All lines fail to run back	No line overfeeds	No SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	1.1E−6
9.82 (Res 24)	All close	All close	All lines fail to run back	No line overfeeds	No SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	8.6E−9
9.83 (Res 22)	All close	All close	All lines fail to run back	No line overfeeds	No SGs blow down	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	1.1E−8
9.84 (Res 22)	All close	All close	All lines fail to run back	No line overfeeds	No SGs blow down	Automatically controlled	NA	Fails to run back	Fails to throttle	<1.1E−8
9.85 (Res 24)	All close	All close	All lines fail to run back	No line overfeeds	No SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	8.6E−9
9.86 (Res 46)	All close	One fails to close	All lines fail to run back	No line overfeeds	All SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	8.1E−8
9.87 (Res 57)	All close	Two fail to close	All lines fail to run back	No line overfeeds	All SGs blow down for 30 min	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	<1.5E−8
9.88 (0525)	All close	Two fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Overfeeds	NA	Runs back as required	Fails to throttle	1.9E−7
9.89 (0526)	All close	Two fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Overfeeds	NA	Fails to run back	Throttles prior to SG high-level alarm	2.3E−7
9.90 (0864)	All close	> Three fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Overfeeds	NA	Runs back as required	Fails to throttle	2.6E−7
9.91 (0865)	All close	> Three fail to close	All lines run back	No line overfeeds	All SGs blow down for 30 min	Overfeeds	NA	Fails to run back	Throttles prior to SG high-level alarm	2.6E−7
9.92 (0876)	All close	> Three fail to close	All lines run back	No line overfeeds	One SG blows down[c]	Automatically controlled	Isolation occurs	Runs back as required	Fails to throttle	3E−7
9.93 (0877)	All close	> Three fail to close	All lines run back	No line overfeeds	One SG blows down[c]	Automatically controlled	Isolation occurs	Fails to run back	Throttles prior to SG high-level alarm	2.3E−7
9.94 (0911)	All close	> Three fail to close	All lines run back	No line overfeeds	Two SGs blow down[c]	Automatically controlled	Isolation occurs	Runs back as required	Throttles prior to SG high-level alarm	7.2E−6
9.95 (0947)	All close	> Three fail to close	All lines run back	No line overfeeds	All SGs blow down[c]	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	1.9E−6
9.96 Residual	(Equivalent to a small-break LOCA)									4.3E−8
9.97 Residual	(Equivalent to a small-break LOCA coupled with a small-pipe steam-line break)									2.2E−6
9.98 Residual	(Equivalent to a small steam-line break with continued flow to break)									5.3E−8
9.99 Residual	(Equivalent to a small-pipe steam-line break with full pressurization)									4.3E−7

[a] The branches entitled "SI Signal Generated on Demand," "AFW Actuates on Demand," "HPI Occurs on Demand," and "PZR PORV Reseats on Demand" were successful in all sequences listed. Therefore, these headings do not appear in this table. There were other sequences for which not all of the branches were successful, but they did not survive the frequency screening. These sequences are included in the residual groups.

[b] As stated in the text, the letters "A" and "B" following the sequence number signify whether or not the MSIVs are closed by the operator. In the "A" sequences the operator is assumed to close the valves 30 minutes into the transient. In the "B" sequences, it is assumed that the MSIVs remain open for the 2-hour period.

[c] All steam generators blow down for 30 minutes; at this time, the operator closes the MSIVs, but one, two, or all three of them fail to close.

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The frequencies of each of these residual groups, calculated as the sum of the constituent sequence frequencies, are included in Table 3.7.

3.5.2. Large Steam-Line Break at Hot 0% Power

In Appendix B, the frequency for a large steam-line break as an initiator is given as 1.2×10^{-3}/yr. This frequency covers both full power and hot 0% power conditions. The fraction of operating time spent at hot 0% power (1.9%) was considered as a weighting factor for determining the frequency of occurrence at hot 0% power. With this weighting factor, the initiator frequency for this category was defined as $(1.2 \times 10^{-3}/\text{yr}) \times 0.019 = 2.28 \times 10^{-5}/\text{yr}$.

Combining the initiating frequency with the branch headings probabilities given in Table 3.8 produced a total of 508 sequences. Of these, nine sequences, three of which are residual groups, were identified for analyses. The event tree for this initiator is shown in Figure 3.6, and the sequences are listed in Table 3.9. The bounding process did not reduce the residual group frequency significantly.

The frequency associated with the residual group totaled approximately 2.3×10^{-7}/yr. This total residual is indicative of the importance (or lack thereof) of the sequences which were not selected for thermal-hydraulic and fracture-mechanics analyses.

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Table 3.8. Branch probabilities for large and small steam-line breaks at hot 0% power[a]

Tree Heading	Branch	Branch Probability[b] Large Pipe Break	 Small Pipe Break
SI signal generated on demand.	(1) SI signal is generated.	0.99997	
	(2) SI signal is not generated.	3×10^{-5}	
MFW isolated on demand.	(1) No line overfeeds.	0.99999	
	(2) One line overfeeds.[c]	9.0×10^{-6}	
	(3) Two lines overfeed.[c]	8.4×10^{-7}	
	(4) All three lines overfeed.[c]	8.1×10^{-8}	
SGs blow down.	If MSIV closure is generated,[d]		
	(1) No SGs blow down.	0.5	
	(2) One SG blows down.	0.5	
	(3) Two SGs blow down.	9.9×10^{-4}	
	(4) All three SGs blow down.	1.7×10^{-4}	
	If MSIV closure is not generated,[d]		
	(1) One SG blows down.	0.5	
	(2) All three SGs blow down.	0.5	
AFW actuates on demand.	(1) AFW actuates.	0.999	
	(2) AFW does not actuate.	1×10^{-3}	
AFW flow automatically controlled.	(1) AFW flow is automatically controlled at nominal rate.	0.9925	
	(2) Flow control failure leads to abnormally high AFW flow rate (overfeeds).	7.5×10^{-3}	
OA: AFW isolated to low-pressure SG.	(1) AFW isolation occurs.	0.9977	0.9983
	(2) AFW isolation fails to occur.	2.3×10^{-3}	1.7×10^{-3}
HPI occurs on demand.	If SI signal is generated,		
	(1) HPI occurs.	0.99939	
	(2) HPI fails to occur.	6.1×10^{-4}	
	If SI signal is not generated,		
	(1) Operator manually starts HPI.	0.99	
	(2) Operator fails to start HPI.	1×10^{-2}	
Charging flow runs back on demand.	(1) Charging flow runs back as required (repressurization limited).	0.9988	0.99
	(2) Charging flow fails to run back (repressurization not limited).	1.2×10^{-3}	1×10^{-2}
OA: AFW throttled.	If operator isolates AFW,		
	(1) Operator throttles AFW flow.	0.99	
	(2) Operator fails to throttle AFW flow.	1×10^{-2}	
	If operator fails to isolate AFW,		
	(1) Operator fails to throttle AFW flow.	1.0	
	(2) Operator throttles AFW flow.	0.0	
PZR PORV reseats on demand.	(1) PZR PORV reseats if charging flow fails to run back.	0.9988	
	(2) PZR PORV fails to reseat if charging flow fails to run back.	1.2×10^{-3}	

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[a] Acronyms used in this table (listed in the order of their appearance) are: SI = safety injection, MFW = main feedwater, SG = steam generator, MSIV = main steam isolation valve, AFW = auxiliary feedwater, OA = operator action, HPI = high-pressure injection, PZR PORV = pressurizer power-operated relief valve, and MFIV = main feedwater isolation valve.

[b] Probabilities centered between the two columns apply to both break sizes.

[c] Includes failure of MFW regulating valves to run back, failure of one or both MFW pumps to trip on high level in any SG, and failure of MFIVs to close on SI signal.

[d] The MSIV closure signal may or may not be generated for a large-pipe steam-line break; it will *not* be generated for a small-pipe steam-line break at hot 0% power.

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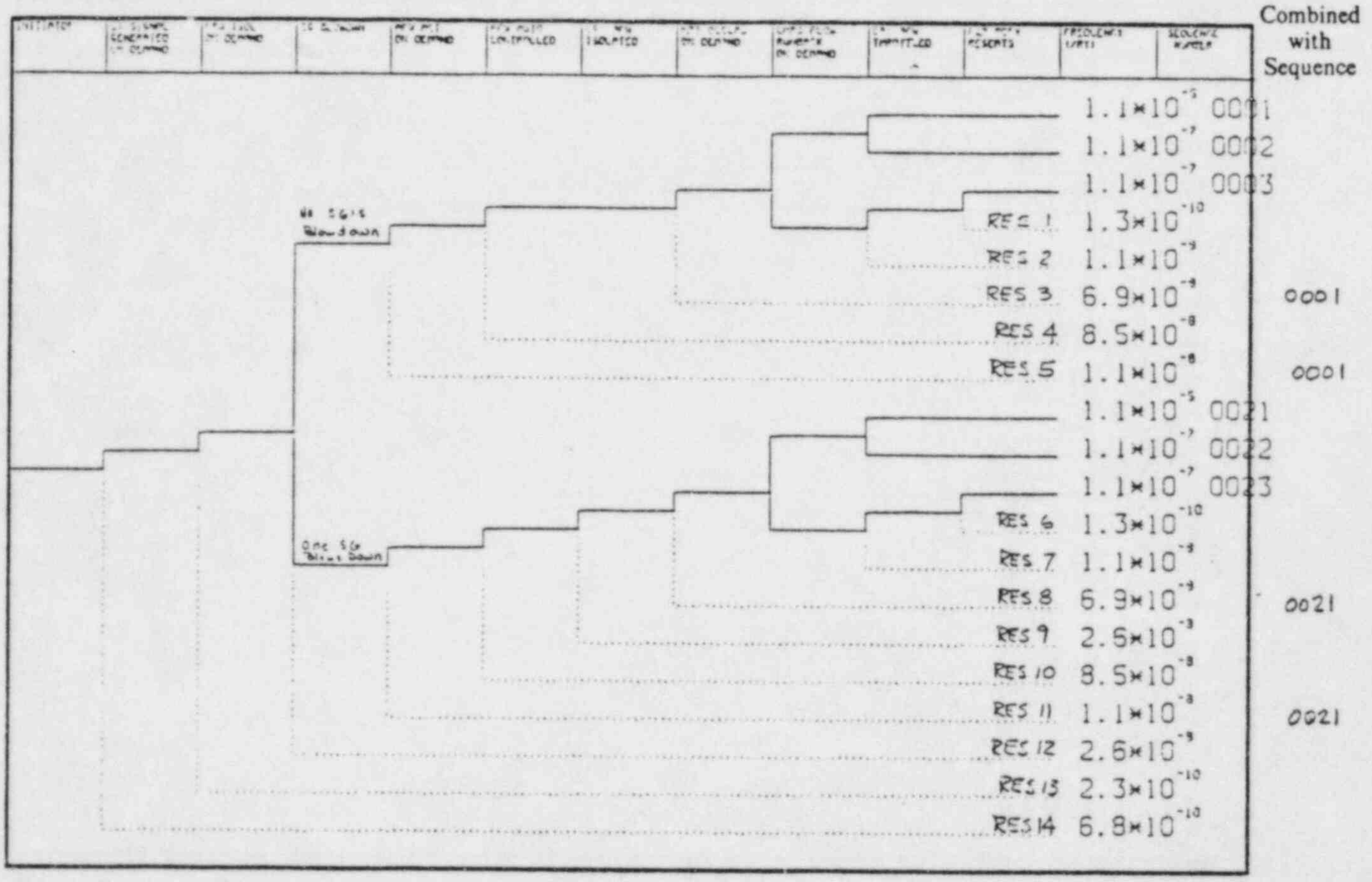

Figure 3.6. Event tree for large steam-line break at hot 0% power.

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Table 3.9. Sequences to be analyzed for small and large steam-line breaks at hot 0% power[a]

Sequence No.	SI Signal Generated on Demand	MFW Isolated on Demand	SGs Blow Down	AFW Actuates on Demand	AFW Automatically Controlled	OA: AFW Isolated to LP SG	HPI Occurs on Demand	Charging Flow Runs Back	OA: AFW Throttled	Frequency (yr^{-1})
				Small	**Steam-Line Break**					
7.1 (0001)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Automatically controlled	Isolation occurs	HPI occurs	Runs back as required	Throttles prior to SG high-level alarm	2.4E−3
7.2 (0003)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Automatically controlled	Isolation occurs	HPI occurs	Fails to run back	Throttles prior to SG high-level alarm	2.4E−5
7.3 (0002)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Automatically controlled	Isolation occurs	HPI occurs	Runs back as required	Fails to throttle	2.4E−5
7.4 (Res 4)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Automatically controlled	Fails to occur	HPI occurs	Runs back as required	Throttles prior to SG high-level alarm	0.0[b]
7.5 (Res 5)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Automatically controlled	Fails to occur	HPI occurs	Fails to run back	Throttles prior to SG high-level alarm	4.2E−8
7.6 (0009)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Automatically controlled	Fails to occur	HPI occurs	Runs back as required	Fails to throttle	4.2E−6
7.7 (0017)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Overfeeds	Isolation occurs	HPI occurs	Runs back as required	Throttles prior to SG high-level alarm	1.8E−5
7.8 (Res 10)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Overfeeds	Fails to occur	HPI occurs	Runs back as required	Throttles prior to SG high-level alarm	3.2E−8
7.9[c]	(Similar to Sequence 7.1)									
7.10[c]	(Similar to Sequence 7.4)									
7.11[c]	(Similar to Sequence 7.1)									
7.12 (0037)	Signal is generated	No line overfeeds	All SGs blow down	AFW actuates	Automatically controlled	NA[d]	HPI occurs	Runs back as required	Throttles prior to SG high-level alarm	2.4E−3
7.13 (0038)	Signal is generated	No line overfeeds	All SGs blow down	AFW actuates	Automatically controlled	NA	HPI occurs	Runs back as required	Fails to throttle	2.5E−5
7.14 (0039)	Signal is generated	No line overfeeds	All SGs blow down	AFW actuates	Automatically controlled	NA	HPI occurs	Fails to run back	Throttles prior to SG high-level alarm	2.4E−5
7.15 (0041)	Signal is generated	No line overfeeds	All SGs blow down	AFW actuates	Automatically controlled	NA	HPI occurs	Fails to run back	Fails to throttle	2.5E−7
7.16 (0005)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Automatically controlled	Isolation occurs	HPI occurs	Fails to run back	Fails to throttle	2.5E−7
7.17 (0046)	Signal is generated	No line overfeeds	All SGs blow down	AFW actuates	Overfeeds	NA	HPI occurs	Runs back as required	Fails to throttle	1.9E−7
7.18 (0018)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Overfeeds	Isolation occurs	HPI occurs	Runs back as required	Fails to throttle	1.9E−7
7.19 (0019)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Overfeeds	Isolation occurs	HPI occurs	Fails to run back	Throttles prior to SG high-level alarm	1.8E−7
7.20	Residual Group									2.5E−7

Table 3.9. (Continued)

Sequence No.	SI Signal Generated on Demand	MFW Isolated on Demand	SGs Blow Down	AFW Actuates on Demand	AFW Automatically Controlled	OA: AFW Isolated to LP SG	HPI Occurs on Demand	Charging Flow Runs Back	OA: AFW Throttled	Frequency (yr^{-1})
				Large-	Steam-Line Break					
8.1 (0021)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Automatically controlled	Isolation occurs	HPI occurs	Runs back as required	Throttles prior to SG high-level alarm	1.1E−5
8.2 (0023)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Automatically controlled	Isolation occurs	HPI occurs	Fails to run back	Throttles prior to SG high-level alarm	1.1E−7
8.3 (0022)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Automatically controlled	Isolation occurs	HPI occurs	Runs back as required	Fails to throttle	1.1E−7
8.4 (Res 9)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Automatically controlled	Fails to occur	HPI occurs	Runs back as required	Fails to throttle	2.6E−8
8.5 (Res 10)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Overfeeds	Isolation occurs	HPI occurs	Runs back as required	Throttles prior to SG high-level alarm	8.5E−8
8.6 (Res 10)	Signal is generated	No line overfeeds	One SG blows down	AFW actuates	Overfeeds	Fails to occur	HPI occurs	Runs back as required	Fails to throttle	<8.5E−8
8.7 (0001)	Signal is generated	No line overfeeds	No SGs blow down	AFW actuates	Automatically controlled	NA	HPI occurs	Runs back as required	Throttles prior to SG high-level alarm	1.1E−5
8.8 (0002)	Signal is generated	No line overfeeds	No SGs blow down	AFW actuates	Automatically controlled	NA	HPI occurs	Runs back as required	Fails to throttle	1.1E−7
8.9 (0003)	Signal is generated	No line overfeeds	No SGs blow down	AFW actuates	Automatically controlled	NA	HPI occurs	Fails to run back	Throttles prior to SG high-level alarm	1.1E−7
8.10	Residual Group									2.3E−7

[a] PZR PORVs reseat for all sequences listed; therefore, the heading "PZR PORV Reseats on Demand" does not appear in table. In some other sequences the PZR PORVs did not reseat, but these sequences did not survive the frequency screening and are included in the residual group.

[b] Because of the coupling factor imposed on the throttling of the AFW, given the failure to isolate the AFW, this sequence has a frequency of 0.0; that is, no credit is given for throttling the AFW if the operator failed to isolate the AFW.

[c] Sequences 7.9, 7.10, and 7.11 involved failure of the SDVs to isolate on demand. Subsequent analysis revealed that the SDVs probably would not open during this event; thus failure of the SDVs to close was not considered.

[d] NA = not applicable.

3.5.3. Small Steam-Line Break at Hot 0% Power

Historically, small steam-line breaks have involved single and multiple open valves. The initiating frequency given in Appendix B for small steam-line breaks independent of the reactor state is 2.0×10^{-2}/yr. At hot 0% power and during initial power increase, there is a constant need to match feed flow and steam flow. This transient condition was believed to increase the potential for a small break. The effect of this transient condition is demonstrated by the fact that ~25% of the observed scrams occurred during startup. Also, although the data base is small, one of the four observed small breaks occurred during a startup condition. Thus, based on this information, 25% of the small-break frequency was assumed to occur at hot 0% power. This results in an initiating event frequency of $(2.0 \times 10^{-2}/\text{yr}) \times 0.25 = 5.0 \times 10^{-3}/\text{yr}$.

The branch headings and probabilities for the small break are presented in Table 3.8. The event tree developed from these probabilities and the 10^{-7} truncation frequency is presented in Figure 3.7. It shows that 19 sequences (out of the 292) survived the 10^{-7} screening level. As shown in Table 3.9, the sequence bounding process reduced this number to 16. The frequency for the group composed of those residual sequences which are neither specifically analyzed nor grouped with a specifically analyzed sequence is 2.5×10^{-7}/yr.

3.5.4. Large Steam-Line Break at Full Power

The initiating frequency of a large steam-line break at full power is based on the overall frequency for a large steam-line break multiplied by the fraction of time at full power: $(1.2 \times 10^{-3}/\text{yr}) \times 0.98 = 1.18 \times 10^{-3}/\text{yr}$.

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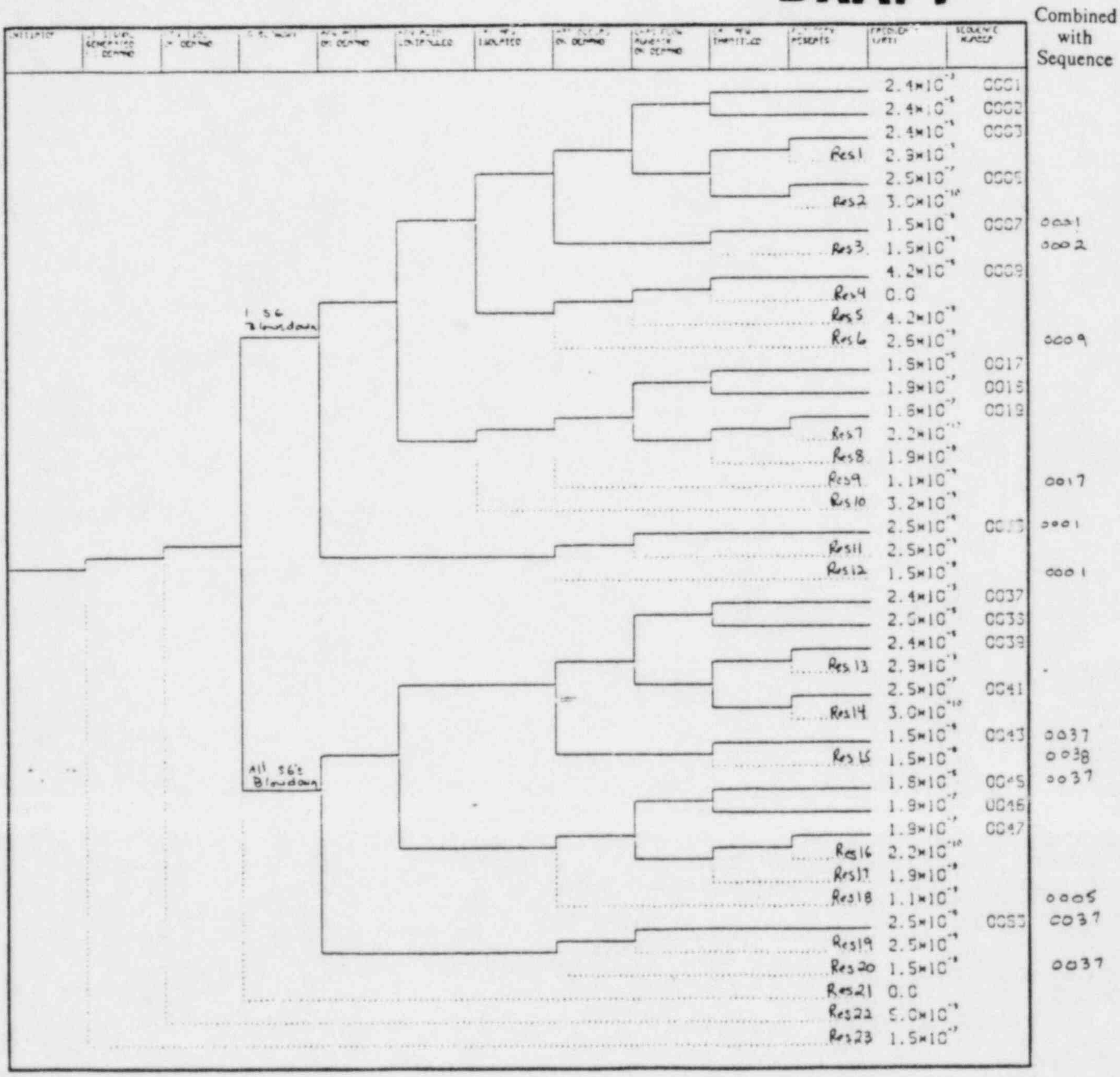

Figure 3.7. Event tree for small steam-line break at hot 0% power.

This initiating event frequency was used, together with the branch headings and probabilities given in Table 3.10, to produce the event tree shown in Figure 3.8.

Figure 3.8 shows that 21 sequences (out of the 1763) survived the 10^{-7} screening level for the large steam-line break at full power. This was reduced to the 15 sequences presented in Table 3.11 to be specifically considered for further analysis. The frequency associated with the remaining residual group totaled 4.4×10^{-7}/yr.

3.5.5. Small Steam-Line Break at Full Power

The initiating frequency for small steam-line breaks at full power is based on the overall frequency multiplied by the fraction of time spent at full power: 2.0×10^{-2}/yr x 0.75 = 1.5×10^{-2}/yr. The branch headings and probabilities are given in Table 3.10, and the resulting event tree developed for this initiating event is presented in Figure 3.9.

Table 3.11 presents the 29 sequences identified for thermal-hydraulic analysis. It should be noted that several of these are sequences which have frequencies less than 10^{-7}/yr. Based on our initial frequency analysis, these sequences were supplied to INEL for thermal-hydraulic analysis, and thus temperature, pressure and heat transfer coefficient data were developed for these sequences. As a result, these sequences were analyzed individually in order to reduce the size of the residual group. The remaining residual group has a frequency of 6.6×10^{-7}/yr.

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Table 3.10. Branch probabilities for large- and small- steam-line breaks at full power[a]

Tree Heading	Branch	Branch Probability[b] Large Pipe Break	 Small Pipe Break
SDVs close on demand.	(1) All five SDVs close.	NA[c]	0.99768
	(2) One SDV fails to close.	NA	1.6×10^{-3}
	(3) Two SDVs fail to close.	NA	3.0×10^{-4}
	(4) Three or more SDVs fail to close.	NA	4.2×10^{-4}
SI signal generated on demand.	(1) SI signal is generated.	0.99997	
	(2) SI signal is not generated.	3×10^{-5}	
MFW runs back and isolates on demand.	If SI signal is generated, MFW lines run back and isolate:		
	(1) All lines run back and MFW is isolated.	0.9999997	
	(2) One line overfeeds.[d]	2.8×10^{-7}	
	(3) Two lines overfeed.[d]	1.5×10^{-9}	
	(4) All three lines overfeed.[d]	1.0×10^{-10}	
	If SI signal is not generated, runback only occurs:		
	(1) All lines run back.	0.9999940	
	(2) One line overfeeds.[e]	5.3×10^{-6}	
	(3) Two lines overfeed.[e]	5.0×10^{-7}	
	(4) All three lines overfeed.[e]	1.4×10^{-7}	
SGs blow down.	If MSIV closure signal is generated,		
	(1) No SG blows down.	0.5	
	(2) One SG blows down.	0.5	
	(3) Two SGs blow down.	9.9×10^{-4}	
	(4) All three SGs blow down.	1.7×10^{-4}	
	If MSIV closure signal is not generated,		
	(1) One SG blows down.	0.5	
	(2) All three SGs blow down.	0.5	
AFW actuates on demand.	(1) AFW actuates.	0.999	
	(2) AFW does not a actuate.	1×10^{-3}	
AFW flow automatically controlled.	(1) AFW flow is automatically controlled at nominal flow rate.	0.9925	
	(2) Flow control failure leads to abnormally high AFW flow rate (overfeeds).	7.5×10^{-3}	
OA: AFW isolated to low-pressure SG	(1) AFW isolation occurs.	0.9977	0.9983
	(2) AFW isolation fails to occur.	2.3×10^{-3}	1.7×10^{-3}
HPI occurs on demand.	If SI signal is generated,		
	(1) HPI occurs.	0.99939	
	(2) HPI fails to occur.	6.1×10^{-4}	
	If SI signal is not generated,		
	(1) Operator manually starts HPI.	0.99	
	(2) Operator fails to start HPI.	1×10^{-2}	
Charging flow runs back on demand.	(1) Charging flow runs back as required (repressurization limited).	0.99	
	(2) Charging flow fails to run back (repressurization not limited).	1×10^{-2}	
OA: AFW throttled.	If operator isolates AFW,		
	(1) Operator throttles AFW flow.	0.99	
	(2) Operator fails to throttle AFW flow.	1×10^{-2}	
	If operator fails to isolate AFW,		
	(1) Operator fails to throttle AFW flow.	1.0	
	(2) Operator throttles AFW flow.	0.0	
PZR PORV reseats on demand.	(1) PZR PORV reseats if charging flow fails to run back.	0.9988	
	(2) PZR PORV fails to reseat if charging flow fails to run back.	1.2×10^{-3}	

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[a] Acronyms used in this table (in the order of their appearance) are: SDV = steam dump valve, SI = safety injection, MFW = main feedwater, SG = steam generator, MSIV = main steam isolation valve, AFW = auxiliary feedwater, OA = operator action, HPI = high-pressure injection, PZR PORV = pressurizer power-operated relief valve, and MFIV = main feedwater isolation valve.

[b] Probabilities centered between the two columns apply to both break sizes.

[c] NA = Not applicable.

[d] Includes failure of MFW regulating valves to run back, failure of one or both MFW pumps to trip on high level in any SG, and failure of MFIVs to close on SI signal.

[e] Includes failure of MFW regulating valves to run back, and failure of MFW pumps to trip on high level in any SG.

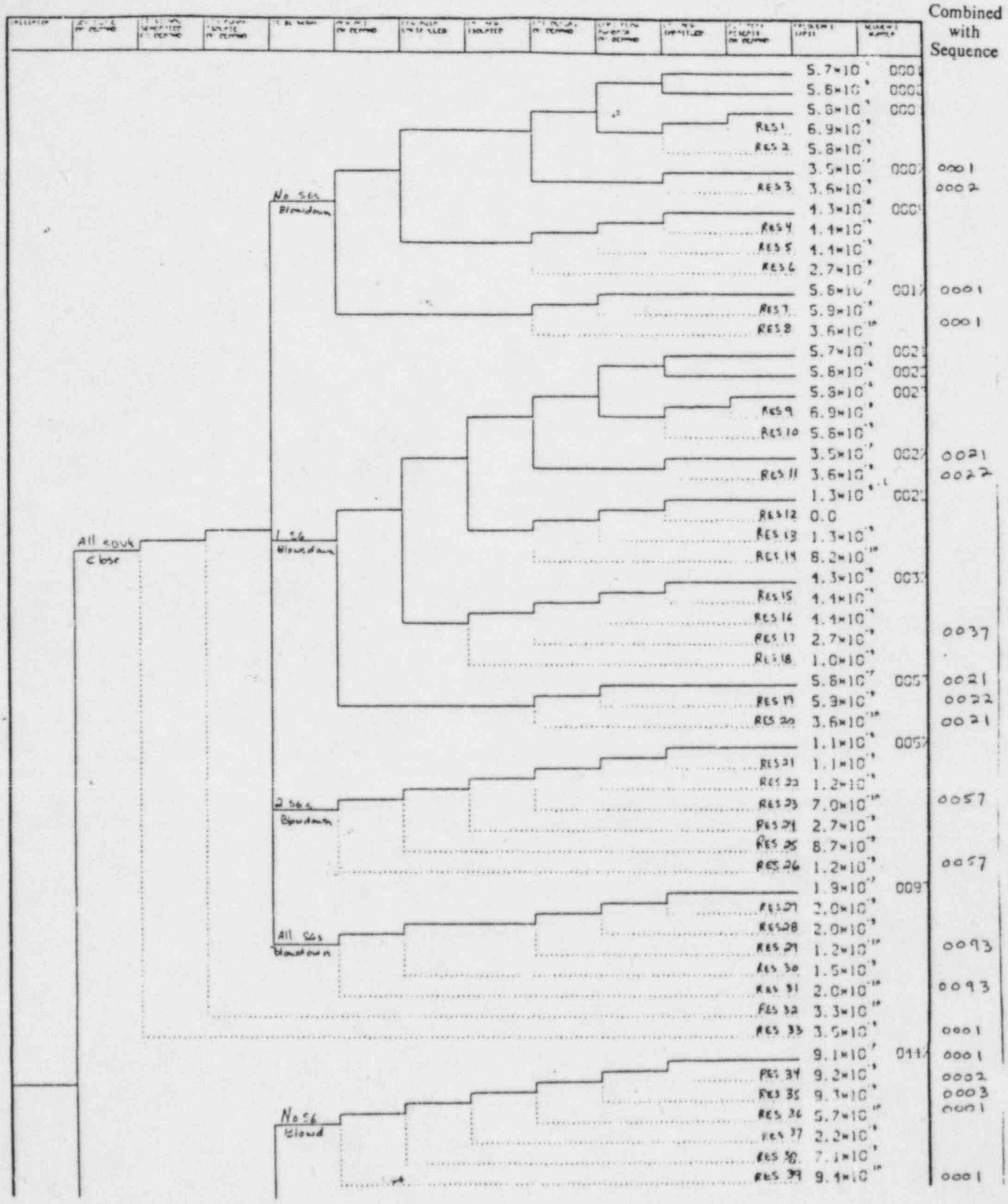

Figure 3.8. Event tree for large steam-line break at full power.

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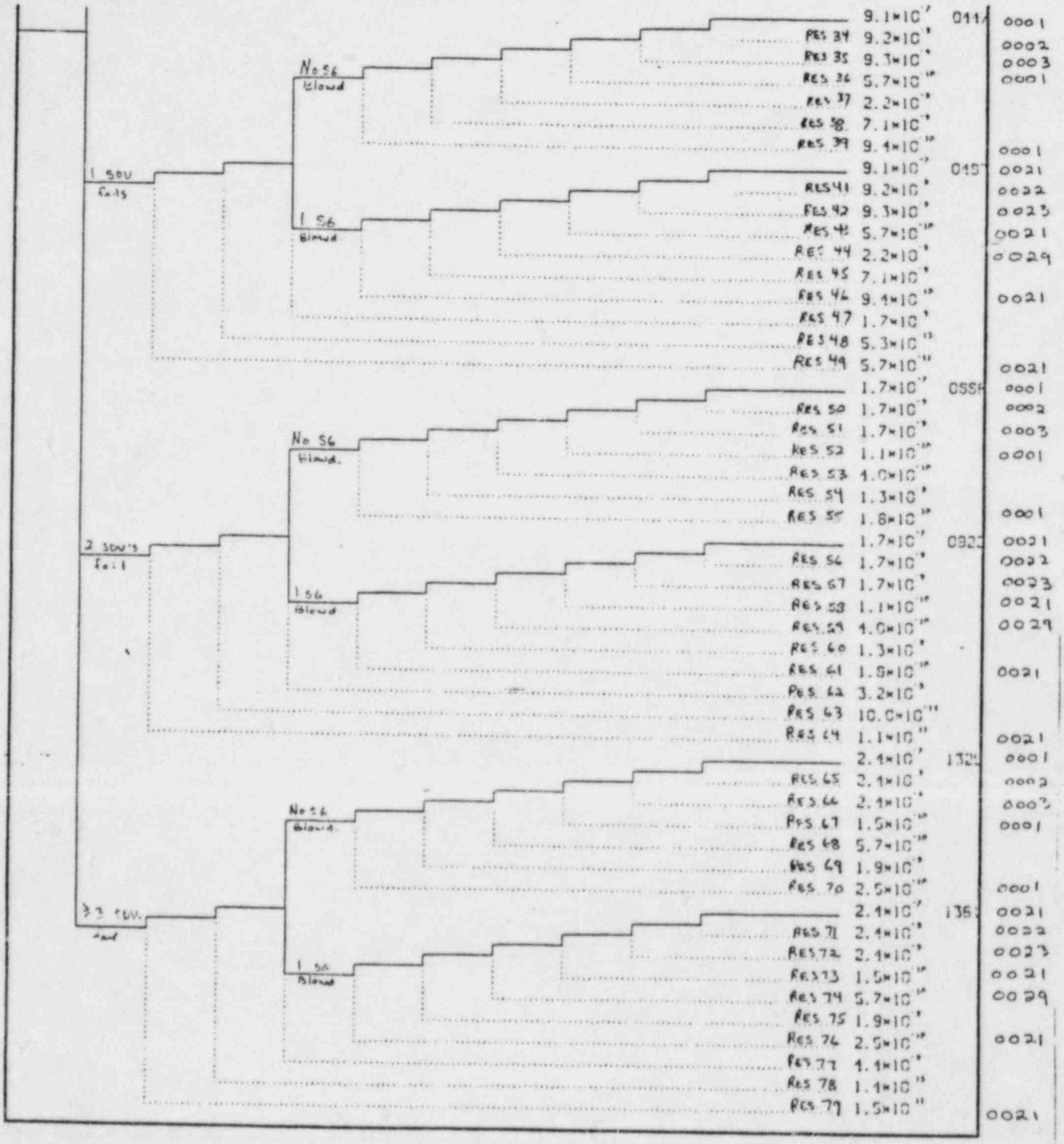

Figure 3.8. (Continued)

Table 3.11. Sequences to be analyzed for small- and large-pipe steam-line breaks at full power[a]

Sequence No.	SDVs Close on Demand	MFW Runs Back and Isolates on Demand	SGs Blow Down	AFW Automatically Controlled	OA: AFW Isolated to LP SG	Charging Flow Runs Back	OA: AFW Throttled	Frequency (yr^{-1})
				Small-Pipe Steam-Line Break				
5.1 (0001)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Isolation occurs	Runs back as required	Throttles prior to SG high-level alarm	7.3E−3
5.2 (0003)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Isolation occurs	Fails to run back	Throttles prior to SG high-level alarm	7.3E−5
5.3 (0002)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Isolation occurs	Runs back as required	Fails to throttle	7.3E−5
5.4 (0005)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Isolation occurs	Fails to run back	Fails to throttle	7.4E−7
5.5 (Res 4)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Fails to occur	Runs back as required	Throttles prior to SG high-level alarm	0.0[b]
5.6 (Res 6)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Fails to occur	Fails to runback	Throttles prior to SG high-level alarm	0.0[b]
5.7 (0009)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Fails to occur	Runs back as required	Fails to throttle	1.2E−5
5.8 (0011)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Fails to occur	Fails to run back	Fails to throttle	1.3E−7
5.9 (0017)	All close	Runs back and isolates	One SG blows down	Overfeeds	Isolation occurs	Runs back as required	Throttles prior to SG high-level alarm	5.5E−5
5.10 (0019)	All close	Runs back and isolates	One SG blows down	Overfeeds	Isolation occurs	Fails to run back	Throttles prior to SG high-level alarm	5.5E--7
5.11 (0018)	All close	Runs back and isolates	One SG blows down	Overfeeds	Isolation occurs	Runs back as required	Fails to throttle	5.5E−7
5.12 (Res 11)	All close	Runs back and isolates	One SG blows down	Overfeeds	Fails to occur	Runs back as required	Throttles prior to SG high-level alarm	0.0[b]
5.13 (Res 11)	All close	Runs back and isolates	One SG blows down	Overfeeds	Fails to occur	Runs back as required	Fails to throttle	9.5E−8
5.14 (0279)	One fails to close	Runs back and isolates	All SGs blow down[c]	Automatically controlled	NA[d]	Runs back as required	Throttles prior to SG high-level alarm	2.3E−5
5.15 (0281)	One fails to close	Runs back and isolates	All SGs blow down[c]	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	2.4E−7
5.16 (0280)	One fails to close	Runs back and isolates	All SGs blow down[c]	Automatically controlled	NA	Runs back as required	Fails to throttle	2.4E−7
5.17[e]	(Included in Sequence 5.14)							
5.18 (0287)	One fails to close	Runs back and isolates	All SGs blow down[c]	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level	1.8E−7

Table 3.11. (Continued)

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Table 3.11. (Continued)

Sequence No.	SDVs Close on Demand	MFW Runs Back and Isolates on Demand	SGs Blow Down	AFW Automatically Controlled	OA: AFW Isolated to LP SG	Charging Flow Runs Back	OA: AFW Throttled	Frequency (yr^{-1})
5.19 (0382)	Two fail to close	Runs back and isolates	All SGs blow down[c]	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	4.4E−6
5.20[e]	(Included in Sequence 5.19)							
5.21 (0037)	All close	Runs back and isolates	All SGs blow down[c]	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	7.3E−3
5.22 (0039)	All close	Runs back and isolates	All SGs blow down[c]	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	7.3E−5
5.23 (0038)	All close	Runs back and isolates	All SGs blow down[c]	Automatically controlled	NA	Runs back as required	Fails to throttle	7.3E−5
5.24 (0045)	All close	Runs back and isolates	All SGs blow down[c]	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	5.5E−5
5.25 (0041)	All close	Runs back and isolates	All SGs blow down[c]	Automatically controlled	NA	Fails to run back	Fails to throttle	7.4E−7
5.26 (0046)	All close	Runs back and isolates	All SGs blow down[c]	Overfeeds	NA	Fails to run back	Fails to throttle	5.5E−7
5.27 (0047)	All close	Runs back and isolates	All SGs blow down[c]	Overfeeds	NA	Fails to run back	Throttles prior to SG high-level alarm	5.5E−7
5.28 (0485)	>Three fail to close	Runs back and isolates	All SGs blow down for 30 min[f]	Automatically controlled	Isolation occurs	Runs back as required	Throttles prior to SG high-level alarm	3.1E−6
5.29 (0521)	>Three fail to close	Runs back and isolates	One SG blows down	Automatically controlled	Isolation occurs	Runs back as required	Throttles prior to SG high-level alarm	3.1E−6
5.30	Residual Group							6.6E−7
Large-Pipe Steam-Line Break								
6.1 (0021)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Isolation occurs	Runs back as required	Throttles prior to SG high-level alarm	5.7E−4
6.2 (0023)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Isolation occurs	Fails to run back	Throttles prior to SG high-level alarm	5.8E−6
6.3 (0022)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Isolation occurs	Runs back as required	Fails to throttle	5.8E−6
6.4 (Res 10)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Isolation occurs	Fails to run back	Fails to throttle	5.8E−8
6.5 (Res 12)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Fails to occur	Runs back as required	Throttles prior to SG high-level alarm	0.0[b]
6.6 (Res 13)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Fails to occur	Fails to run back	Fails to throttle	1.3E−8
6.7 (0029)	All close	Runs back and isolates	One SG blows down	Automatically controlled	Fails to occur	Runs back as required	Fails to throttle	1.3E−6
6.8 (0037)	All close	Runs back and isolates	One SG blows down	Overfeeds	Isolation occurs	Runs back as required	Throttles prior to SG high-level alarm	4.3E−6

Table 3.11. (Continued)

Sequence No.	SDVs Close on Demand	MFW Runs Back and Isolates on Demand	SGs Blow Down	AFW Automatically Controlled	OA: AFW Isolated to LP SG	Charging Flow Runs Back	OA: AFW Throttled	Frequency (yr^{-1})
6.9 (Res 18)	All close	Runs back and isolates	One SG blows down	Overfeeds	Fails to occur	Runs back as required	Fails to throttle	1.0E−8
6.10 (0057)	All close	Runs back and isolates	Two SGs blow down	Automatically controlled	Isolation occurs	Runs back as required	Throttles prior to SG high-level alarm	1.1E−6
6.11 (0093)	All close	Runs back and isolates	All SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	1.9E−7
6.12 (0001)	All close	Runs back and isolates	No SGs blow down	Automatically controlled	NA	Runs back as required	Throttles prior to SG high-level alarm	5.7E−4
6.13 (0002)	All close	Runs back and isolates	No SGs blow down	Automatically controlled	NA	Runs back as required	Fails to throttle	5.9E−6
6.14 (0003)	All close	Runs back and isolates	No SGs blow down	Automatically controlled	NA	Fails to run back	Throttles prior to SG high-level alarm	5.8E−6
6.15 (0009)	All close	Runs back and isolates	No SGs blow down	Overfeeds	NA	Runs back as required	Throttles prior to SG high-level alarm	4.3E−6
6.16	Residual Group							4.4E-7

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[a] The branches entitled "SI Signal Generated on Demand," "AFW Actuates on Demand," "HPI Occurs on Demand," and "PZR PORV Reseats on Demand" were successful in all sequences listed. Therefore, these headings do not appear in this table. There were sequences other than those included in the table for which not all of the branches were successful, but they did not survive the frequency screening. These sequences are included in the residual groups.

[b] Because of the coupling factor imposed on the throttling of the AFW, given the failure to isolate the AFW, this sequence has a frequency of 0.0; that is, no credit is given for throttling the AFW if the operator fails to isolate the AFW.

[c] For a small steam-line break downstream of the MSIVs, no credit was taken for closure of MSIVs; this was used as a bounding situation and did not have a major impact on the results.

[d] NA = not applicable.

[e] Sequence is no longer applicable and does not appear on event tree, since operator would not be called upon to isolate AFW if all steam generators were blowing down.

[f] All steam generators blow down for 30 minutes; at this time the operator closes the MSIVs, but one, two, or all three of them fail to close.

Figure 3.9. Event tree for small steam-line break at full power.

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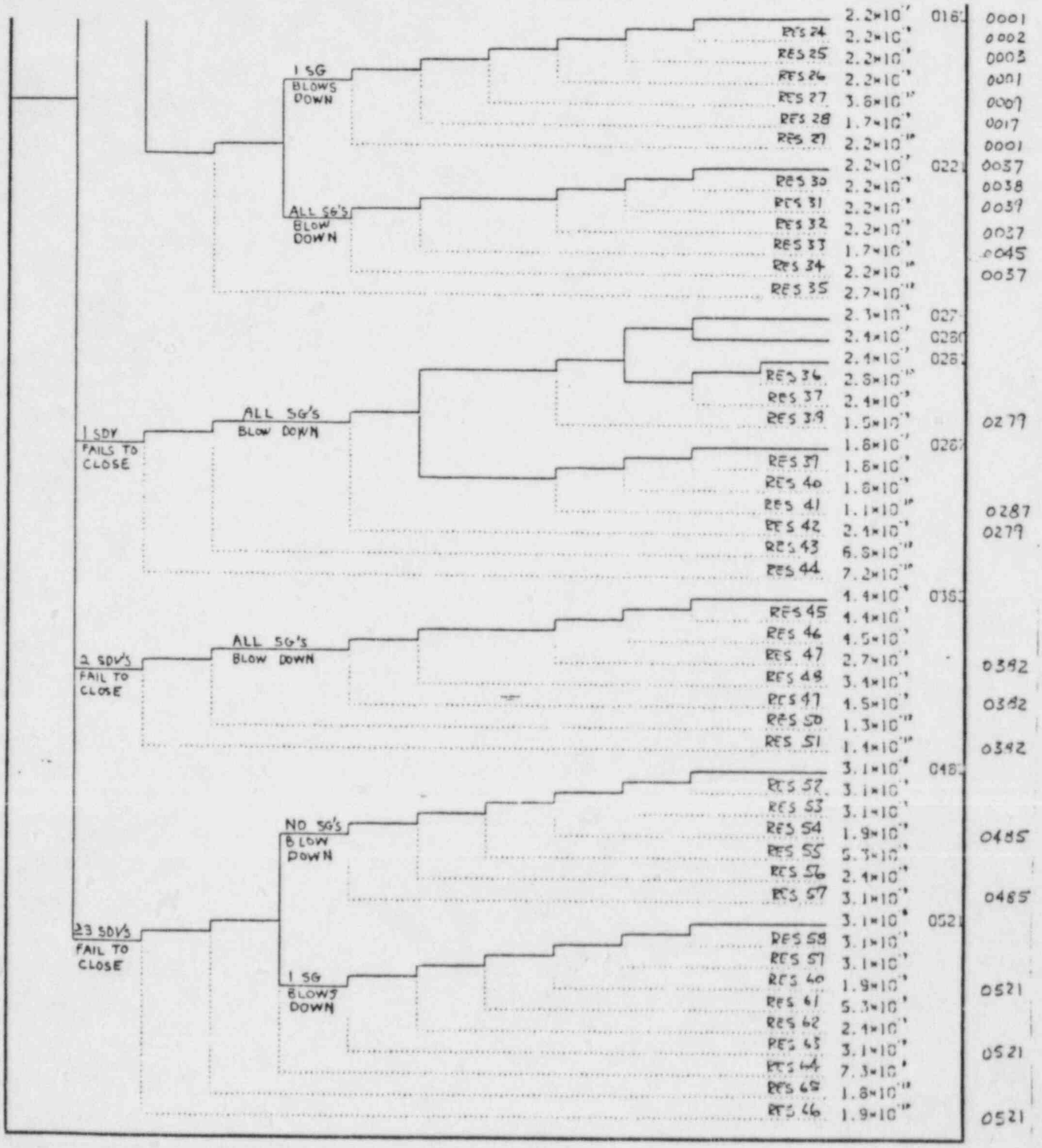

Figure 3.9. (Continued)

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3.5.6. Small-Break LOCA at Full Power

The small-break LOCA includes pressurizer PORV and SRV single failures, pump seal failures and small pipe breaks. The most probable failure is the PORV failure, but there is a very high probability of isolating the PORV early in the transient.

The initiating frequency for this event at full power is based on a frequency of 8.9×10^{-3}/yr for small-break LOCAs under all operating conditions times a factor of 0.91 to account for the fraction of full-power operations. The resulting initiating frequency is 8.1×10^{-3}/yr, which, when combined with the branch probabilities presented in Table 3.12, lead to the event tree shown in Figure 3.10. Thirty-one sequences out of a total 6,938 sequences remained for further analysis after the screening process.* These are shown in Table 3.13. The frequency associated with the residual group is 9.4×10^{-7}/yr.

T. 3.12
F. 3.10
T. 3.13

3.5.7. Medium-Break LOCA at Full Power

The initiating frequency for a medium-break LOCA at full power is 9.8×10^{-4}/yr, based on an overall estimate for a medium-break LOCA of 1.0×10^{-3}/yr and 98.1% operation at full power. This event includes breaks equivalent to 2 or 2.5-in.^{2} lines which cannot be isolated. The branch headings and probabilities are shown in Table 3.12, and the resulting event tree is shown in Figure 3.11. Fourteen sequences out of a total of 6,824 sequences had frequencies of $\geq 10^{-7}$/yr and 12 were retained for thermal-hydraulic and fracture-mechanics analyses, as shown in Table 3.13. The

F. 3.11

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*It should be noted that of the 31 sequences, nine included a late isolation of the break. These sequences are labeled as Sequence Series 12 in Table 3.15.

Table 3.12. Branch probabilities for small- and medium-break LOCAs at full power[a]

Tree Heading	Branch	Branch Probability[b] Small-Break LOCA	 Medium-Break LOCA
Turbine trips on demand.	(1) Turbine trips on demand.	0.99996	
	(2) Turbine fails to trip.	4×10^{-5}	
STM PORVs close on demand.	(1) All three STM PORVs close.	0.97981	
	(2) One STM PORV fails to close.	1.8×10^{-2}	
	(3) Two STM PORVs fail to close.	1.7×10^{-3}	
	(4) Three STM PORVs fail to close.	4.9×10^{-4}	
SDVs close on demand.	(1) All five SDVs close.	0.99768	
	(2) One SDV fails to close.	1.6×10^{-3}	
	(3) Two SDVs fail to close.	3.0×10^{-4}	
	(4) Three or more SDVs fail to close.	4.2×10^{-4}	
SI signal generated on demand.	(1) SI signal is generated.	0.99997	
	(2) SI signal is not generated.	3×10^{-5}	
MFW runs back and isolates on demand.	If SI signal is generated, MFW lines run back and isolate:		
	(1) All lines run back and MFW is isolated.	0.9999997	
	(2) One line overfeeds.[c]	2.8×10^{-7}	
	(3) Two lines overfeed.[c]	1.5×10^{-9}	
	(4) Three lines overfeed.[c]	1.0×10^{-10}	
	If SI signal is not generated, run back only occurs:		
	(1) All lines run back.	0.9999940	
	(2) One line overfeeds.[d]	5.3×10^{-6}	
	(3) Two lines overfeed.[d]	5.0×10^{-7}	
	(4) Three lines overfeed.[d]	1.4×10^{-7}	
HPI occurs on demand.	If SI signal is generated,		
	(1) HPI occurs.	0.99939	
	(2) HPI fails to occur.	6.1×10^{-4}	
	If SI signal is not generated,		
	(1) Operator manually starts HPI.	0.99	
	(2) Operator fails to start HPI.	1×10^{-2}	
SGs blow down.	If one or more SDVs fail,		
	(1) Three SGs blow down.	1.0	
	If three or more SDVs fail,		
	(1) No SGs blow down.	0.99087	
	(2) One SG blows down.	6.6×10^{-3}	
	(3) Two SGs blow down.	2.0×10^{-3}	
	(4) All three SGs blow down.	5.3×10^{-4}	
	If one, two, or three STM PORVs fail, then, respectively,		
	(1) One SG blows down.	1.0	
	(2) Two SGs blow down.	1.0	
	(3) All three SGs blow down.	1.0	
	If MSIV closure signal is not generated,		
	(1) All three SGs blow down.	1.0	
AFW actuates on demand.	(1) AFW actuates.	0.999	
	(2) AFW does not actuate.	1×10^{-3}	
AFW flow automatically controlled.	(1) AFW is automatically controlled at nominal rate.	0.9925	
	(2) Flow control failure leads to abnormally high AFW flow rate (overfeeds).	7.5×10^{-3}	
OA: AFW isolated to low-pressure SG.	(1) AFW isolation occurs.	0.9983	
	(2) AFW isolation fails to occur.	1.7×10^{-3}	

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Table 3.12 (Cont'd)

<table>
<tr><th rowspan="2">Tree Heading</th><th rowspan="2">Branch</th><th colspan="2">Branch Probability[b]</th></tr>
<tr><th>Small Break LOCA</th><th>Medium-Break LOCA</th></tr>
<tr><td>OA: AFW isolated to low-pressure SG.</td><td>(1) AFW isolation occurs.</td><td colspan="2">0.9983</td></tr>
<tr><td></td><td>(2) AFW isolation fails to occur.</td><td colspan="2">1.7 × 10^{−3}</td></tr>
<tr><td>Accumulators discharge.</td><td>(1) Accumulators discharge when required.</td><td colspan="2">0.99999</td></tr>
<tr><td></td><td>(2) Accumulators fail to discharge.</td><td colspan="2">1 × 10^{−5}</td></tr>
<tr><td>OA: Break not isolated.[e]</td><td>(1) Break not isolatable or operator fails to isolate break.</td><td>0.9610</td><td>1.0</td></tr>
<tr><td></td><td>(2) Operator isolates break.</td><td>3.9 × 10^{−2}</td><td>1.0</td></tr>
<tr><td>Charging flow runs back on demand.[e]</td><td>(1) Charging flow runs back as required (repressurization limited).</td><td>0.99</td><td>NA[f]</td></tr>
<tr><td></td><td>(2) Charging flow fails to run back (repressurization not limited).</td><td>1 × 10^{−2}</td><td>NA</td></tr>
<tr><td>OA: AFW throttled.</td><td>If operator isolates AFW,</td><td colspan="2"></td></tr>
<tr><td></td><td>(1) Operator throttles AFW flow.</td><td colspan="2">0.99</td></tr>
<tr><td></td><td>(2) Operator fails to throttle AFW flow.</td><td colspan="2">1 × 10^{−2}</td></tr>
<tr><td></td><td>If operator fails to isolate AFW,</td><td colspan="2"></td></tr>
<tr><td></td><td>(1) Operator fails to throttle AFW flow.</td><td colspan="2">1.0</td></tr>
<tr><td></td><td>(2) Operator throttles AFW flow.</td><td colspan="2">0.0</td></tr>
<tr><td>LPI occurs on demand.</td><td>If SI signal is generated,</td><td colspan="2"></td></tr>
<tr><td></td><td>(1) LPI occurs as required.</td><td colspan="2">0.99975</td></tr>
<tr><td></td><td>(2) LPI fails to occur.</td><td colspan="2">2.5 × 10^{−4}</td></tr>
<tr><td></td><td>If SI signal is not generated,</td><td colspan="2"></td></tr>
<tr><td></td><td>(1) Operator manually starts LPI.</td><td colspan="2">0.99</td></tr>
<tr><td></td><td>(2) Operator fails to start LPI.</td><td colspan="2">1 × 10^{−2}</td></tr>
<tr><td></td><td>If SI signal is not generated and if operator fails to start HPI,</td><td colspan="2"></td></tr>
<tr><td></td><td>(1) Operator fails to start LPI.</td><td colspan="2">1.0</td></tr>
<tr><td></td><td>(2) Operator manually starts LPI.</td><td colspan="2">0.0</td></tr>
</table>

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[a] Acronyms used in this table (in the order of their appearance) are: STM PORV = steam power-operated relief valve, SDV = steam pump valve, SI = safety injection, MFW = main feedwater, HPI = high-pressure injection, SG = steam generator, AFW = auxiliary feedwater, OA = operator action, LPI = low-pressure injection, and MFIV = main feedwater isolation valve.

[b] Probabilities centered between the two columns apply to both break sizes.

[c] Includes failure of MFW regulating valves to run back, failure of one or both MFW pumps to trip on high level in any SG, and failure of MFIVs to close on SI signal.

[d] Includes failure of MFW regulating valves to run back, and failure of MFW pumps to trip on high level in any SG.

[e] These headings apply only to small-break LOCAs and not to medium-break LOCAs.

[f] NA = not applicable.

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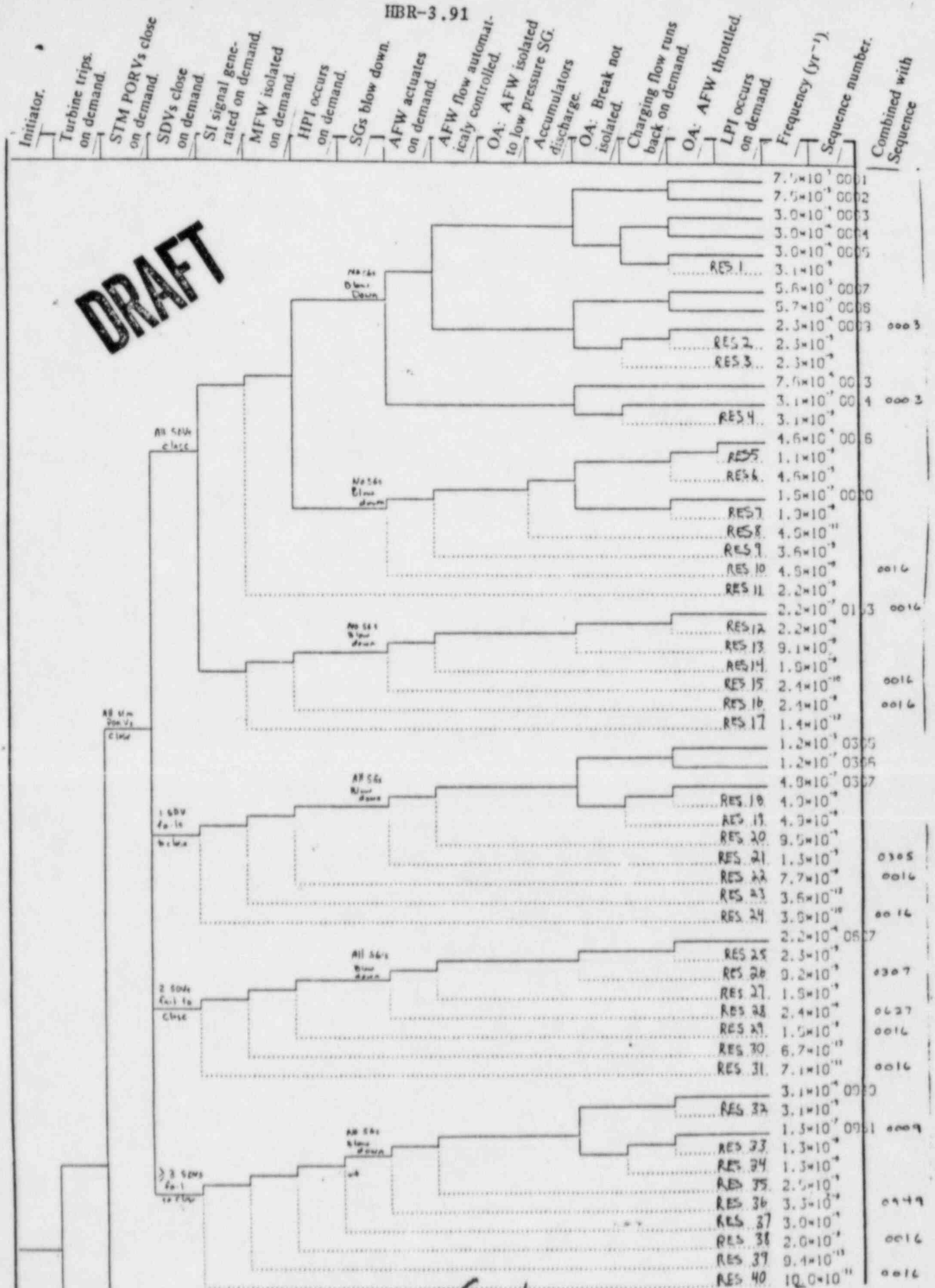

Figure 3.10. Event tree for small-break LOCA at full power.

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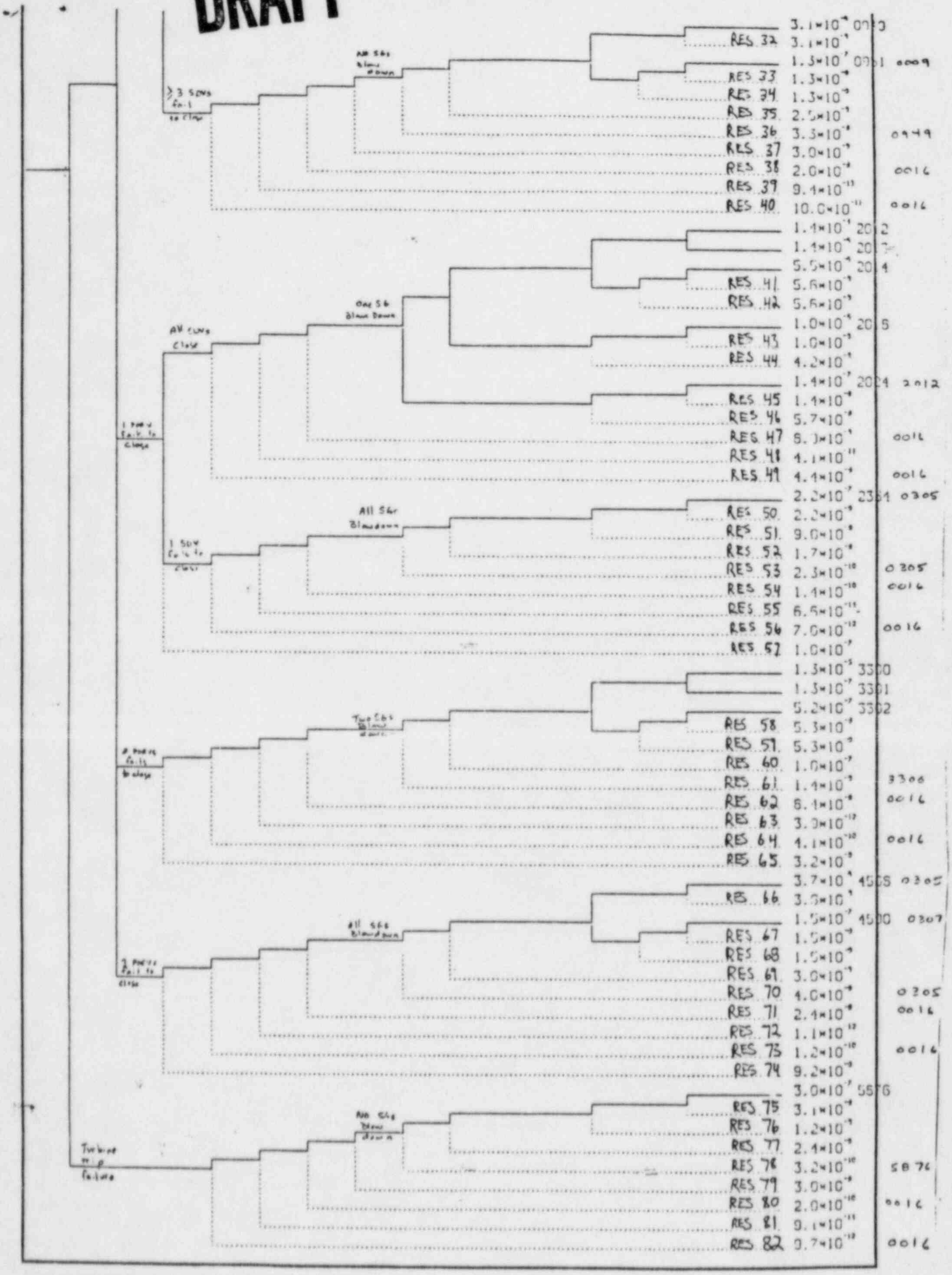

Figure 3.10. (Continued)

Table 3.13. Sequences to be analyzed for small- and medium-break

Sequence No.[b]	Turbine Trips on Demand	STM PORVs Close on Demand	SDVs Close on Demand	MFW Runs Back and Isolates on Demand	HPI Occurs on Demand	SGs Blow Down	AFW Automatically Controlled	OA: AFW Isolates to LP SG	OA: Break Not Isolated[c]	Charging Flow Runs Back[c]	OA: AFW Throttled	Frequency (yr^{-1})
						Small-Break LOCA						
1.1 (0001)	Trips	All close	All close	Runs back and isolates	HPI occurs	No SGs blow down	Automatically controlled	NA[d]	Fails to isolate break	Runs back as required	Throttles prior to SG high-level alarm	7.5E−3
1.2 (0002)	Trips	All close	All close	Runs back and isolates	HPI occurs	No SGs blow down	Automatically controlled	NA	Fails to isolate break	Runs back as required	Fails to throttle	7.5E−5
1.3 (0007)	Trips	All close	All close	Runs back and isolates	HPI occurs	No SGs blow down	Overfeeds	NA	Fails to isolated break	Runs back as required	Throttles prior to SG high-level alarm	5.6E−5
1.4 (0008)	Trips	All close	All close	Runs back and isolates	HPI occurs	No SGs blow down	Overfeeds	NA	Fails to isolate break	Runs back as required	Fails to throttle	5.7E−7
1.5 (0305)	Trips	All close	One fails to close	Runs back and isolates	HPI occurs	All SGs blow down	Automatically controlled	NA	Fails to isolate break	Runs back as required	Throttles prior to SG high-level alarm	1.6E−5
1.6 (0627)	Trips	All close	Two fail to close	Runs back and isolates	HPI occurs	All SGs blow down	Automatically controlled	NA	Fails to isolate break	Runs back as required	Throttles prior to SG high-level alarm	2.2E−6
1.7 (0949)	(Included in Sequence 1.8)											
1.8 (0949)	Trips	All close	> Three fail to close	Runs back and isolates	HPI occurs	All SGs blow down for 30 min	Automatically controlled	NA	Fails to isolate break	Runs back as required	Throttles prior to SG high-level alarm	3.1E−6
1.9 (2012)	Trips	One fails to close	All close	Runs back and isolates	HPI occurs	One SG blows down	Automatically controlled	NA	Fails to isolate break	Runs back as required	Throttles prior to SG high level alarm	1.4E−4
1.10 (2013)	Trips	One fails to close	All close	Runs back and isolates	HPI occurs	One SG blows down	Automatically controlled	NA	Fails to isolate break	Runs back as required	Fails to throttle	1.4E−6
1.11 (2018)	Trips	One fails to close	All close	Runs back and isolates	HPI occurs	One SG blows down	Overfeeds	NA	Fails to isolate break	Runs back as required	Throttles prior to SG high-level alarm	1.0E−6
1.12 (3300)	Trips	Two fail to close	All close	Runs back and isolates	HPI occurs	Two SGs blow down	Automatically controlled	NA	Fails to isolate break	Runs back as required	Throttles prior to SG high-level alarm	1.3E−5
1.13 (0001)	(Included in Sequence 1.1)[e]											
1.14 (0002)	(Included in Sequence 1.2)[e]											
1.15 (0007)	(Included in Sequence 1.3)[e]											
1.16 (0305)	(Included in Sequence 1.5)[e]											
1.17 (0001)	(Included in Sequence 1.1)[e]											
1.18 (0001)	(Included in Sequence 1.1)[e]											

1.19 (0016)	Trips	All close	All close	Runs back and isolates	Fails to occur	No SGs blow down	Automatically controlled	NA	Fails to isolate break	Runs back as required	Throttles prior to SG high-level alarm	5.0E−6
1.20 (0306)	Trips	All close	All close	Runs back and isolates	HPI occurs	All SGs blow down	Automatically controlled	NA	Fails to isolate break	Runs back as required	Fails to throttle	1.2E−7
1.21 (3304)	Trips	Two fail to close	All close	Runs back and isolates	HPI occurs	Two SGs blow down	Automatically controlled	NA	Fails to isolate break	Runs back as required	Fails to throttle	1.3E−7
1.22 (5876)	Fails to trip	All close	All close	Runs back and isolates	HPI occurs	No SGs blow down	Automatically controlled	NA	Fails to isolate break	Runs back as required	Throttles prior to SG high-level alarm	3.0E−7
11.1 (0003)	Trips	All close	All close	Runs back and isolates	HPI occurs	No SGs blow down	Automatically controlled	NA	Isolates break	Runs back as required	Throttles prior to SG high-level alarm	3.0E−4
11.2 (0005)	Trips	All close	All close	Runs back and isolates	HPI occurs	No SGs blow down	Automatically controlled	NA	Isolates break	Fails to run back	Throttles prior to SG high-level alarm	3.0E−6
11.3 (0003)	(Included in Sequence 11.1)[e]											
11.4 (0005)	(Included in Sequence 11.2)[e]											
11.5 (0004)	Trips	All close	All close	Runs back and isolates	HPI occurs	No SGs blow down	Automatically controlled	NA	Isolates break	Runs back as required	Fails to throttle	3.0E−6
11.6 (0020)	Trips	All close	All close	Runs back and isolates	Fails to occurs	No SGs blow down	Automatically controlled	NA	Isolates break	Runs back as required	Throttles prior to SG high-level alarm	1.8E−7
11.7 (0307)	Trips	All close	One fails to close	Runs back and isolates	HPI occurs	All SGs blow down	Automatically controlled	NA	Isolates break	Runs back as required	Throttles prior to SG high-level alarm	7.2E−7
11.8 (2014)	Trips	One fails to close	All close	Runs back and isolates	HPI occurs	One SG blows down	Automatically controlled	NA	Isolates break	Runs back as required	Throttles prior to SG high-level alarm	5.5E−6
11.9 (3302)	Trips	Two fails to close	All close	Runs back and isolates	HPI occurs	Two SGs blow down	Automatically controlled	NA	Isolates break	Runs back as required	Throttles prior to SG high-level alarm	5.2E−7
11.10	Residual Group											
												9.4E−7

Table 3.13 (Cont'd)

Sequence No.[b]	Turbine Trips on Demand	STM PORVs Close on Demand	SDVs Close on Demand	MFW Runs Back and Isolates on Demand	HPI Occurs on Demand	SGs Blow Down	AFW Automatically Controlled	OA: AFW Isolates to LP SG	OA: Break Not Isolated[c]	Charging Flow Runs Back[c]	OA: AFW Throttled	Frequency (yr^{-1})
Medium-Break LOCA												
2.1 (0001)	Trips	All close	All close	Runs back and isolates	HPI occurs	No SGs blow down	Automatically controlled	NA	-	-	Throttles prior to SG high-level alarm	9.4E−4
2.2 (0003)	Trips	All close	All close	Runs back and isolates	HPI occurs	No SGs blow down	Automatically controlled	NA	-	-	Fails to throttle	9.5E−6
2.3 (0009	Trips	All close	All close	Runs back and isolates	HPI occurs	No SGs blow down	Overfeeds	NA	-	-	Throttles prior to SG high-level alarm	7.1E−6
2.4 (Res 4)	Trips	All close	All close	Runs back and isolates	HPI occurs	No SGs blow down	Overfeeds	NA	-	-	Fails to throttle	7.2E−8
2.5 (0321)	Trips	All close	One fails to close	Runs back and isolates	HPI occurs	All SGs blow down	Automatically controlled	NA	-	-	Throttles prior to SG high-level alarm	1.5E−6
2.6 (0665)	Trips	All close	Two fail to close	Runs back and isolates	HPI occurs	All SGs blow down	Automatically controlled	NA	-	-	Throttles prior to SG high-level alarm	2.8E−7
2.7 (1009)	(Included in Sequence 2.8)											
2.8 (1009)	Trips	All close	> Three fail to close	Runs back and isolates	HPI occurs	All SGs blow down for 30 min	Automatically controlled	NA	-	-	Throttles prior to SG high-level alarm	3.9E−7
2.9 (1853)	Trips	All close	All close	Runs back and isolates	HPI occurs	One SG blows down	Automatically controlled	NA	-	-	Throttles prior to SG high-level alarm	1.7E−5
2.10 (1856)	Trips	All close	All close	Runs back and isolates	HPI occurs	One SG blows down	Automatically controlled	NA	-	-	Fails to throttle	1.7E−7
2.11 (3229)	Trips	All close	All close	Runs back and isolates	HPI occurs	Two SGs blow down	Automatically controlled	NA	-	-	Throttles prior to SG high-level alarm	1.6E−6
2.12 (4605)	Trips	All close	All close	Runs back and isolates	HPI occurs	All SGs blow down	Automatically controlled	NA	-	-	Throttles prior to SG high-level alarm	4.7E−7
2.13 (0021)	Trips	All close	All close	Runs back and isolates	Fails to occur	No SGs blow down	Automatically controlled	NA	-	-	Throttles prior to SG high-level alarm	6.2E−7
2.14	Residual Group											2.1E−7

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[a] The branches entitled "SI Signal Generated on Demand," "AFW Actuates on Demand," "Accumulators Discharge," and "LPI Occurs on Demand" were successful in all sequences listed. Therefore, these headings do not appear in this table. There were other sequences for which not all of the branches were successful, but they did not survive the frequency screening. These sequences are included in the residual groups.

[b] During the analysis of sequences by Idaho National Engineering Laboratory (INEL), the LOCAs in which the break could not be isolated were identified as Sequence Series 11. The original sequence numbers are maintained here for easy cross reference.

[c] These headings apply only to small-break LOCAs and not to medium-break LOCAs.

[d] NA = not applicable.

[e] These sequences include the failure of one feedwater regulating valve which subsequently was found to have zero impact because of a feedwater pump trip.

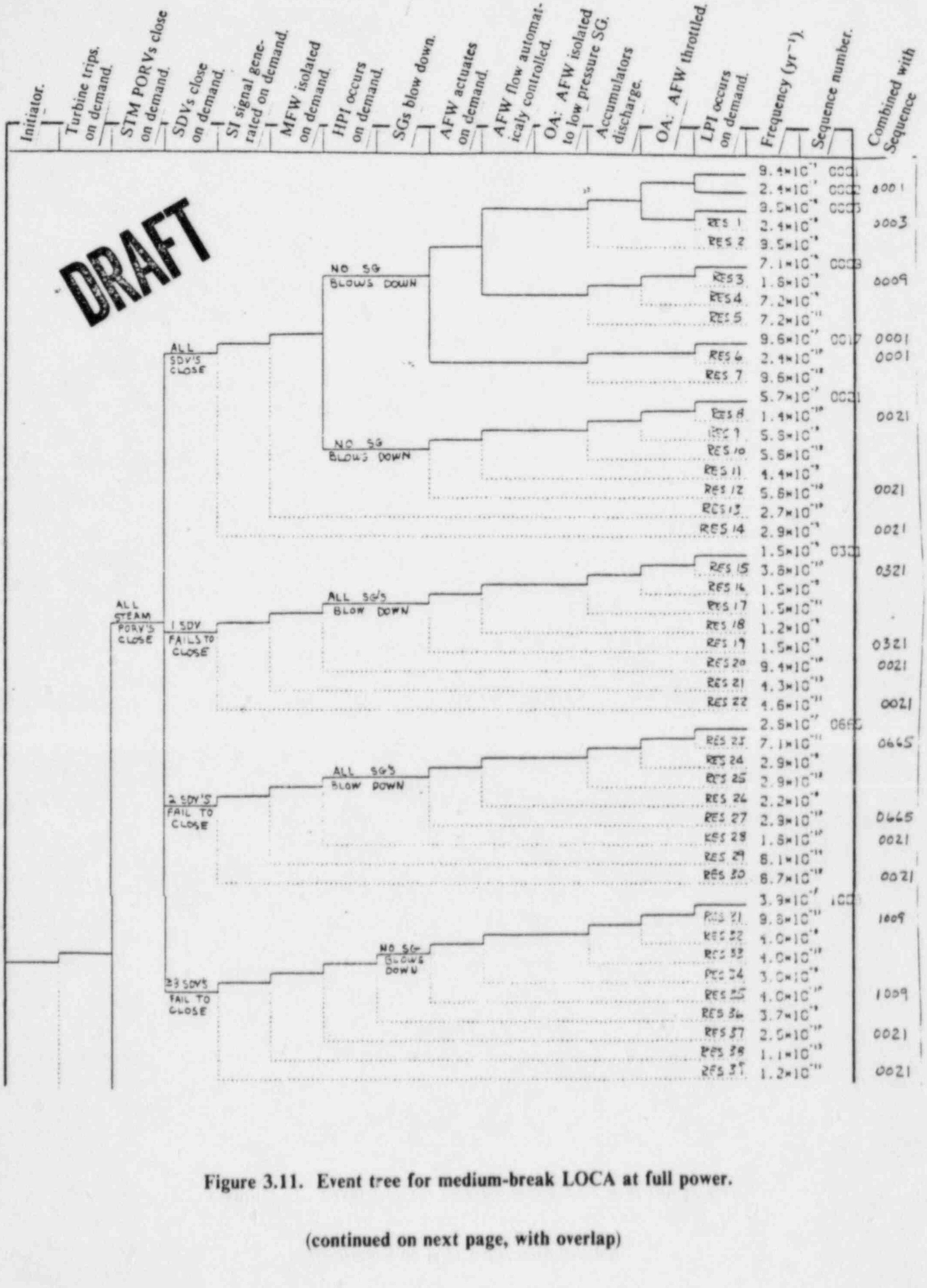

Figure 3.11. Event tree for medium-break LOCA at full power.

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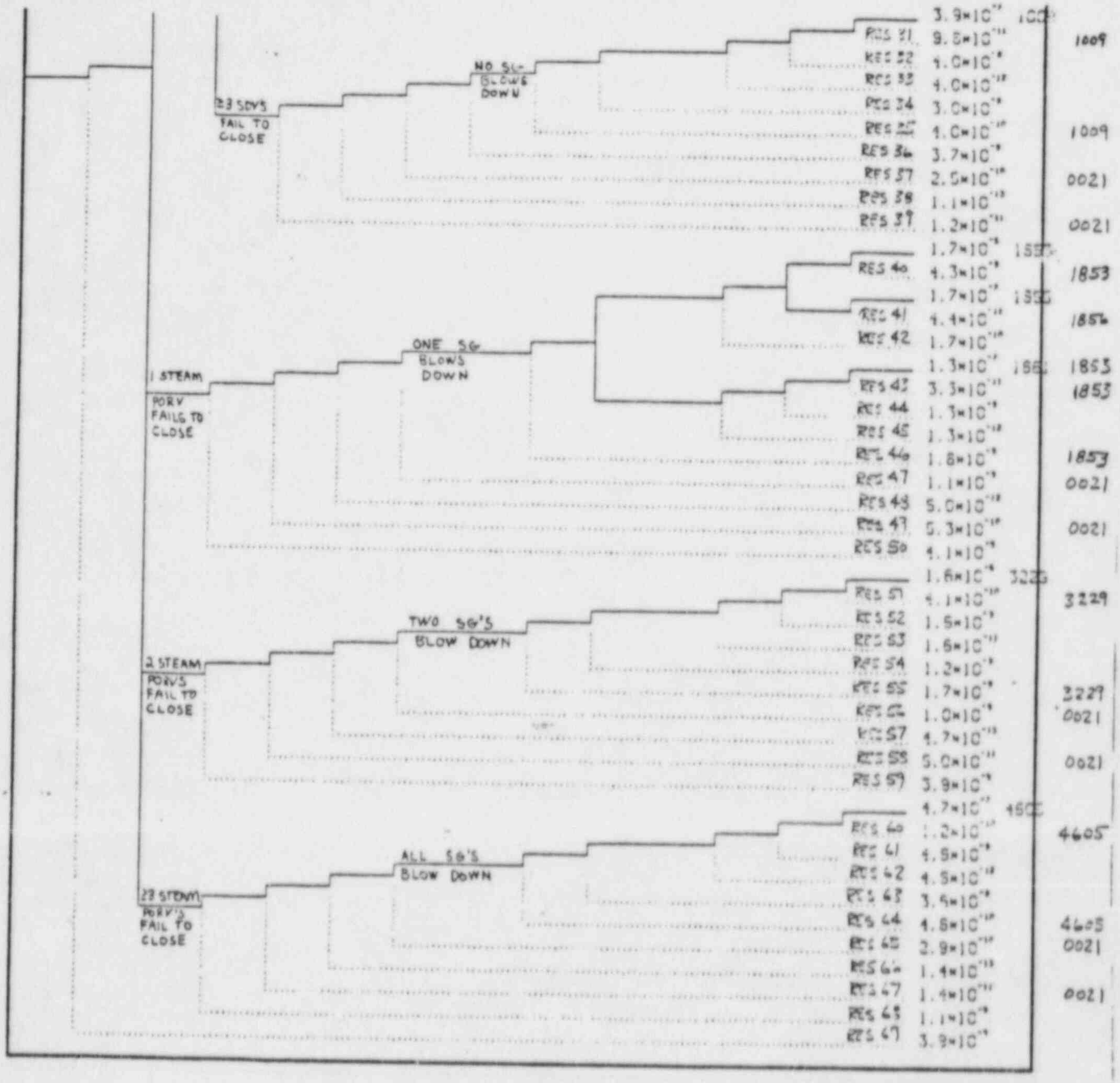

Figure 3.11. (Continued)

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frequency associated with the residual group is 2.1 x 10^{-7}/yr.

3.5.8. Small-Break LOCA at Hot 0% Power

An initiating frequency of 8.01 x 10^{-4}/yr was used for this event based on the overall estimate for a small-break LOCA of 8.9 x 10^{-3}/yr and a factor of 0.09 to account for those occurrences at hot 0% power. The branch headings and probabilities for the event are shown in Table 3.14, and the resulting event tree is shown in Figure 3.12. Out of the nine sequences with frequencies of $\geq 10^{-7}$/yr (out of a total of 158 sequences), five sequences were identified for further analysis. These are shown in Table 3.15. The frequency associated with the residual group is 1.1 x 10^{-7}/yr.

T. 3.14
F. 3.12
T. 3.15

3.5.9. Medium-Break LOCA at Hot 0% Power

The initiating frequency used for a medium-break LOCA at hot 0% power was 1.9 x 10^{-5}/yr, based on 1.9% operation at hot 0% power. The branch headings and probabilities for the event are presented in Table 3.14, and the resulting event tree is shown in Figure 3.13. Three sequences out of a total of 124 sequences survived the screening criterion of 10^{-7}/yr. Two of these were selected for thermal-hydraulic and fracture-mechanics analyses as shown in Table 3.15. The residual group frequency totals 6.5 x 10^{-9}/yr.

F. 3.13

3.5.10. Tube Rupture

Event tree branches for a steam generator tube rupture initiating event

Table 3.14. Branch probabilities for small- and medium-break LOCAs at hot 0% power[a]

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<table>
<tr><th rowspan="2">Tree Heading</th><th rowspan="2">Branch</th><th colspan="2">Branch Probability[b]</th></tr>
<tr><th>Small-Break LOCA</th><th>Medium-Break LOCA</th></tr>
<tr><td>SI signal generated on demand.</td><td>(1) SI signal is generated.</td><td colspan="2">0.99997</td></tr>
<tr><td></td><td>(2) SI signal is not generated.</td><td colspan="2">3×10^{-5}</td></tr>
<tr><td>MFW isolated on demand.</td><td>(1) No line overfeeds.</td><td colspan="2">0.99999</td></tr>
<tr><td></td><td>(2) One line overfeeds.[c]</td><td colspan="2">9.0×10^{-6}</td></tr>
<tr><td></td><td>(3) Two lines overfeed.[c]</td><td colspan="2">8.4×10^{-7}</td></tr>
<tr><td></td><td>(4) All three lines overfeed.[c]</td><td colspan="2">8.1×10^{-8}</td></tr>
<tr><td>HPI occurs on demand.</td><td>If SI signal is generated,</td><td colspan="2"></td></tr>
<tr><td></td><td>(1) HPI occurs.</td><td colspan="2">0.99939</td></tr>
<tr><td></td><td>(2) HPI fails to occur.</td><td colspan="2">6.1×10^{-4}</td></tr>
<tr><td></td><td>If SI signal is not generated,</td><td colspan="2"></td></tr>
<tr><td></td><td>(1) Operator manually starts HPI.</td><td colspan="2">0.99</td></tr>
<tr><td></td><td>(2) Operator fails to start HPI.</td><td colspan="2">1×10^{-2}</td></tr>
<tr><td>AFW actuates on demand.</td><td>(1) AFW actuates.</td><td colspan="2">0.999</td></tr>
<tr><td></td><td>(2) AFW does not actuate.</td><td colspan="2">1×10^{-3}</td></tr>
<tr><td>AFW flow automatically controlled.</td><td>(1) AFW flow is automatically controlled at nominal rate.</td><td colspan="2">0.9925</td></tr>
<tr><td></td><td>(2) Flow control failure leads to abnormally high AFW flow rate (overfeeds).</td><td colspan="2">7.5×10^{-3}</td></tr>
<tr><td>Accumulators discharge.</td><td>(1) Accumulators discharge when required.</td><td colspan="2">0.99999</td></tr>
<tr><td></td><td>(2) Accumulators fail to discharge.</td><td colspan="2">1×10^{-5}</td></tr>
<tr><td>OA: Break not isolated.[d]</td><td>(1) Break not isolatable or operator fails to isolate break.</td><td>0.9610</td><td>1.0</td></tr>
<tr><td></td><td>(2) Operator isolates break.</td><td>3.9×10^{-2}</td><td>1.0</td></tr>
<tr><td>Charging flow runs back on demand.[d]</td><td>(1) Charging flow runs back as required (repressurization limited).</td><td>0.99</td><td>NA</td></tr>
<tr><td></td><td>(2) Charging flow fails to run back (repressurization not limited).</td><td>1×10^{-2}</td><td>NA</td></tr>
<tr><td>OA: AFW throttled.</td><td>If operator isolates AFW,</td><td colspan="2"></td></tr>
<tr><td></td><td>(1) Operator throttles AFW flow.</td><td colspan="2">0.99</td></tr>
<tr><td></td><td>(2) Operator fails to throttle AFW flow.</td><td colspan="2">1×10^{-2}</td></tr>
<tr><td></td><td>If operator fails to isolate AFW,</td><td colspan="2"></td></tr>
<tr><td></td><td>(1) Operator fails to throttle AFW flow.</td><td colspan="2">1.0</td></tr>
<tr><td></td><td>(2) Operator throttles AFW flow.</td><td colspan="2">0.0</td></tr>
<tr><td>LPI occurs on demand.</td><td>If SI signal is generated,</td><td colspan="2"></td></tr>
<tr><td></td><td>(1) LPI occurs as required.</td><td colspan="2">0.99975</td></tr>
<tr><td></td><td>(2) LPI fails to occur.</td><td colspan="2">2.5×10^{-4}</td></tr>
<tr><td></td><td>If SI signal is not generated,</td><td colspan="2"></td></tr>
<tr><td></td><td>(1) Operator manually starts LPI.</td><td colspan="2">0.99</td></tr>
<tr><td></td><td>(2) Operator fails to start LPI.</td><td colspan="2">1×10^{-2}</td></tr>
<tr><td></td><td>If SI signal is not generated and if operator fails to start HPI,</td><td colspan="2"></td></tr>
<tr><td></td><td>(1) Operator fails to start LPI.</td><td colspan="2">1.0</td></tr>
<tr><td></td><td>(2) Operator manually starts LPI.</td><td colspan="2">0.0</td></tr>
</table>

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[a] Acronyms used in this table (listed in the order of their appearance) are: SI = safety injection, MFW = main feedwater, HPI = high-pressure injection, AFW = auxiliary feedwater, OA = operator action, LPI = low-pressure injection, and MFIV = main feedwater isolation valve.

[b] Probabilities centered between the two columns apply to both break sizes.

[c] Includes failure of MFW regulating valves to run back, failure of one or both MFW pumps to trip on high level in any SG, and failure of MFIVs to close on SI signal.

[d] These headings apply only to small-break LOCAs and not to medium-break LOCAs.

[e] NA = not applicable.

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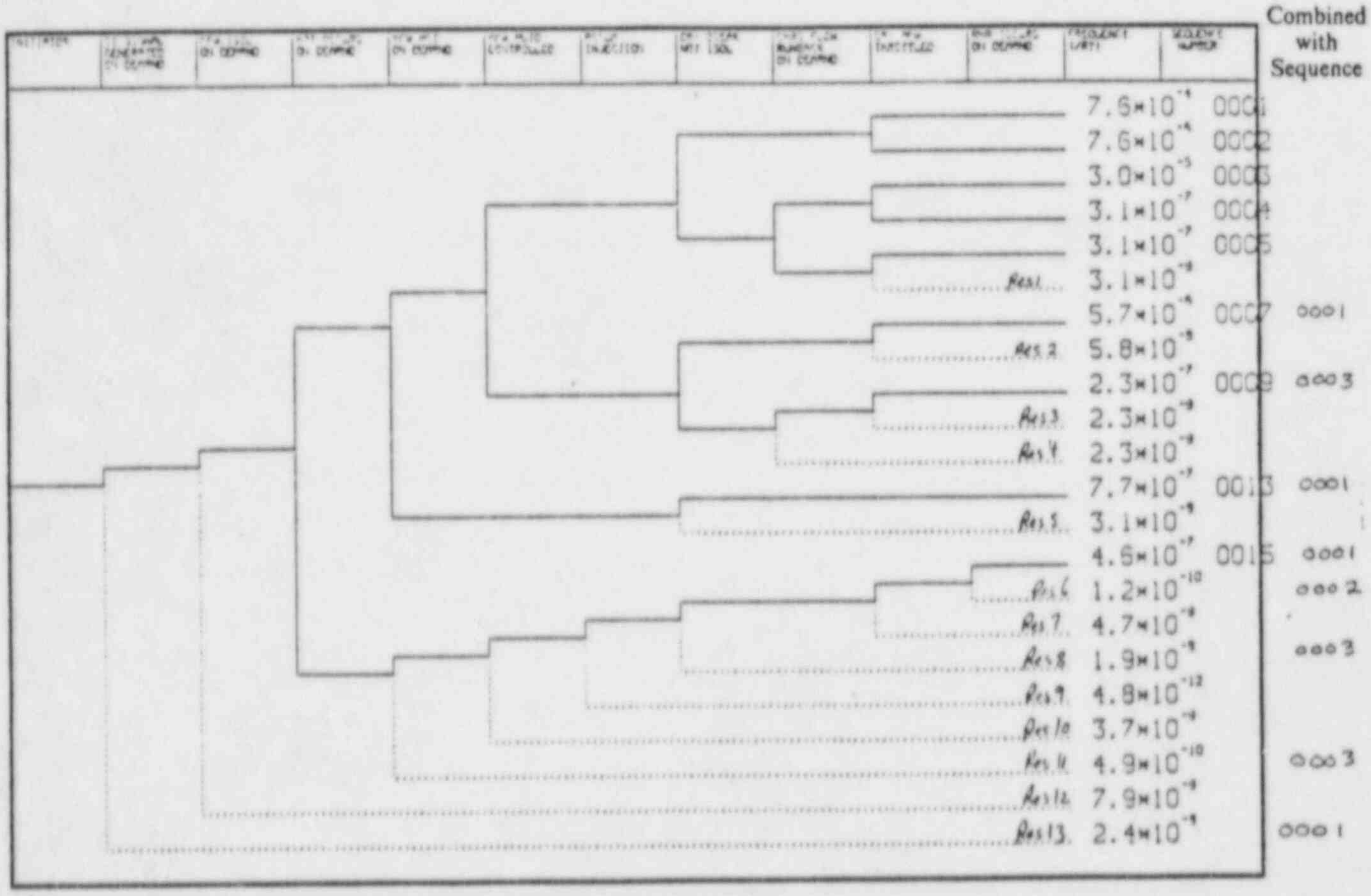

Figure 3.12. Event tree for small-break LOCA at hot 0% power.

Table 3.15. Sequences to be analyzed for small- and medium-break LOCAs at hot 0% power

Sequence No.[a]	SI Signal Generated on Demand	MFW Isolated on Demand	HPI Occurs on Demand	AFW Actuates on Demand	AFW Automatically Controlled	Accumulator Discharge	OA: Break Not Isolated[b]	Charging Flow Runs Back	OA: AFW Throttled	LPI Occurs on Demand	Frequency (yr^{-1})
					Small-Break LOCA						
3.1 (0001)	Signal is generated	No line overfeeds	HPI occurs	AFW actuates	Automatically controlled	Not demanded	Fails to isolate break	Runback not required	Throttles prior to SG high-level alarm	LPI not required	7.7E−4
3.2 (0002)	Signal is generated	No line overfeeds	HPI occurs	AFW actuates	Automatically controlled	Not demanded	Fails to isolate break	Runback not required	Fails to throttle	LPI not required	7.6E−6
3.3	(Sequence not applicable)[c]										
12.1 (0005)	Signal is generated	No line overfeeds	HPI occurs	AFW actuates	Automatically controlled	Not demanded	Isolates break	Fails to run back	Throttles prior to SG high-level alarm	LPI not required	3.1E−7
12.2 (0004)	Signal is generated	No line overfeeds	HPI occurs	AFW actuates	Automatically controlled	Not demanded	Isolates break	Runs back as required	Fails to throttle	LPI not required	3.1E−7
12.3 (0009)	Signal is generated	No line overfeeds	HPI occurs	AFW actuates	Overfeeds	Not demanded	Isolates break	Runs back as required	Throttles prior to SG high-level alarm	LPI not required	2.5E−7
12.4 (0003)	Signal is generated	No line overfeeds	HPI occurs	AFW actuates	Automatically controlled	Not demanded	Isolates break	Runs back as required	Throttles prior to SG high-level alarm	LPI not required	3E−5
12.5	Residual Group										1.1E−7
					Medium-Break LOCA						
4.1 (0001)	Signal is generated	No line overfeeds	HPI occurs	AFW actuates	Automatically controlled	Discharges when required	-	-	Throttles prior to SG high-level alarm	LPI occurs as required	1.9E−5
4.2 (0003)	Signal is generated	No line overfeeds	HPI occurs	AFW actuates	Automatically controlled	Discharges when required	-	-	Fails to throttle	LPI occurs as required	1.9E−7
4.3	Residual Group										6.5E−9

[a] During the analysis of sequences by Idaho National Engineering Laboratory (INEL), the LOCAs in which the break could be isolated were identified as Sequence Series 3 and the LOCAs in which the break could not be isolated were identified as Sequence Series 12. The original sequence numbers are maintained here for easy cross reference.

[b] These headings apply only to small-break LOCAs and not to medium-break LOCAs.

[c] All SDVs are expected to remain closed under hot 0% power conditions; Sequence 3.3 covered the possibility of the SDVs failing to close, and thus it is not applicable to this series. It is included only for cross reference to the INEL series.

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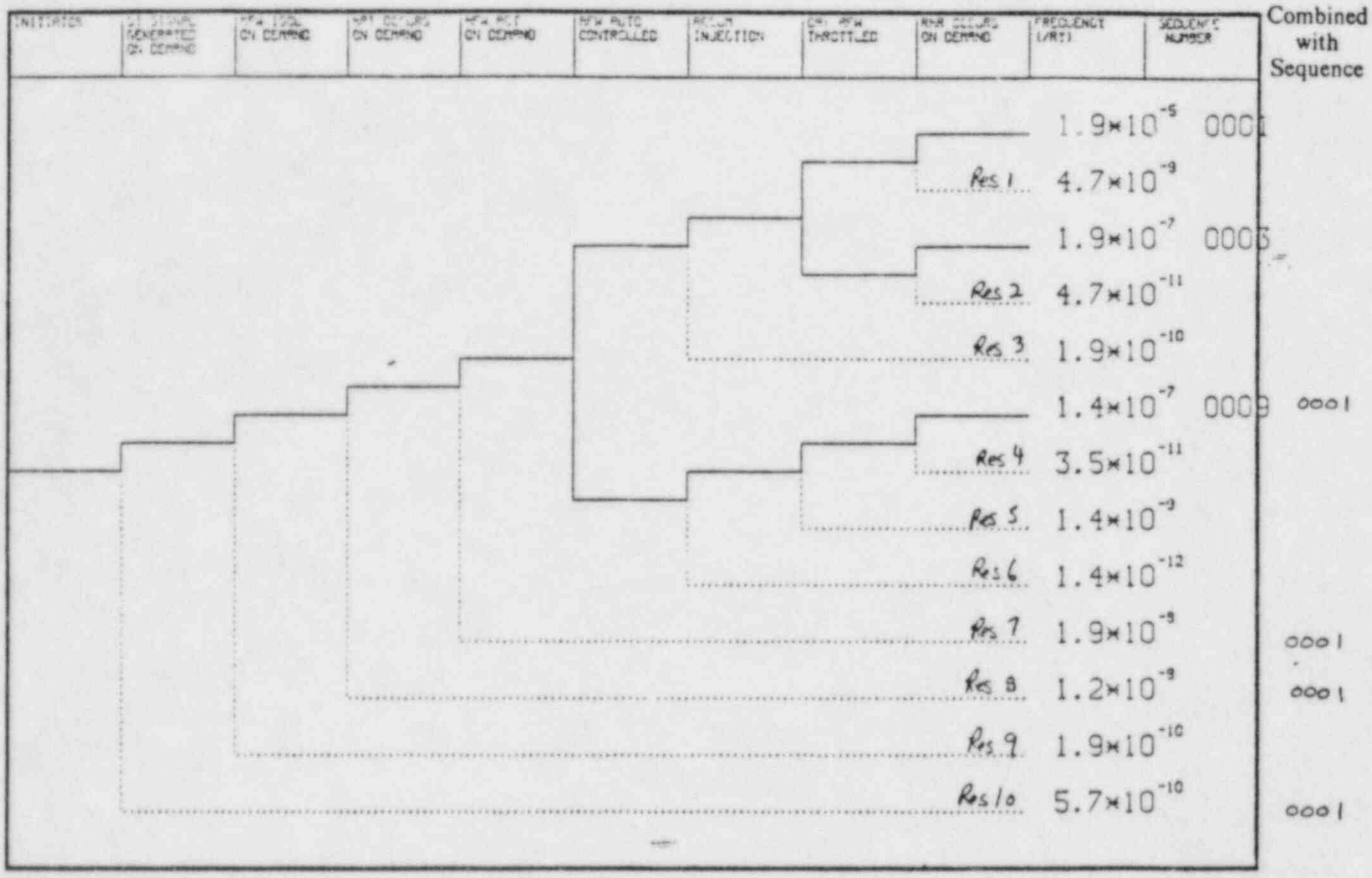

Figure 3.13. Event tree for medium-break LOCA at hot 0% power.

were described in Section 3.4.8. A review of this tree revealed the sequence descriptions would be dominated by operator actions, which means that the timing of the operator actions would be very important. Thus it was felt that a series of tube rupture calculations would be more appropriate than an analysis of the event tree. This led to the identification of five tube rupture sequences, each of which represents a type of tube rupture event. These five sequences are described in Table 3.16. It should be noted that in the interest of bounding the consequences associated with the tube rupture sequences, all tube rupture calculations were performed from the hot 0% power (low decay heat) initial condition.

Comments on the five tube rupture sequences are as follows:

Sequence 10.1: This sequence is representative of the nominal tube rupture sequence. The frequency assigned to it is the tube rupture initiator frequency of 5×10^{-3}/yr identified in Appendix B.

Sequence 10.2: This sequence is identical to sequence 10.1, but the SDVs fail to close for 10 minutes after the subcooling requirement is met. For failure of any one of five valves to close on demand, Appendix B reports a frequency of 1.6×10^{-3}. This frequency is used to represent one or more SDVs failing to close. This gives a total frequency for this transient of 8×10^{-6}/yr.

Sequence 10.3: In this sequence a pressurizer PORV is assumed to stick open for 10 minutes following the first opening. A value of 0.054 (0.027 for each valve as presented in Appendix B) is used as the frequency for

Table 3.16. Sequences to be analyzed for steam generator tube ruptures at hot 0% power[a]

Sequence No.	Description of Sequences	Frequency (yr^{-1})
10.1	(1) If SIAS is generated, operator trips RCPs when RCS pressure reaches 1300 psig. (2) Operator throttles AFW flow to maintain 40% SG level. (3) At 500 seconds, operator closes affected SG MSIV. (4) At 10 minutes, operator fully opens three SDVs and cools primary system to 45°F. (Core outlet temperature and saturation temperature in the affected SG secondary are used to measure subcooling.) (5) When subcooling is attained, operator closes SDVs. (6) After waiting 260 seconds following Event 5, operator opens one PZR PORV to depressurize primary system. (7) When pressures of pressurizer and affected SG dome have equalized, operator closes PZR PORV. (8) After waiting 500 seconds following Event 7 operator opens a second PZR PORV to depressurize primary system to 1000 psia. (9) When depressurization is accomplished, operator closes the second PZR PORV. (10) After waiting 100 seconds following Event 8, operator secures HPI.	5×10^{-3}
10.2	Same as Sequence 10.1 except that SDVs fail to close for 10 minutes after subcooling has been achieved.	8×10^{-6}
10.3	Same as Sequence 10.1 except that PZR PORV sticks open for 10 minutes on first opening.	3×10^{-4}
10.4	Same as Sequence 10.1 except that second PZR PORV fails to open and operator throttles HPI and charging flow when pressurizer set point level is attained.	5×10^{-3}
10.5	Same as Sequence 10.4 except that operator does not throttle flow.	5×10^{-4}

[a] Acronyms used in this table are: SIAS = safety injection actuation signal, RCP = reactor coolant pump, RCS = reactor coolant system, AFW = auxiliary feedwater, SG = steam generator, MSIV = main steam isolation valve, PZR PORV = pressurizer power-operated relief valve, and HPI = high-pressure injection.

either of two valves to fail to close once open. This gives a sequence frequency of 0.005 x 0.054 = 3 x 10^{-4}/yr.

Sequence 10.4: There was some concern expressed by Westinghouse representatives that ORNL's representation of a typical tube rupture (sequence 10.1) was incorrect and that only one PORV lift might be more typical. To address the potential effects of the different assumptions, sequence 10.1 was analyzed without the second PORV lift. The frequency used for the sequence was the tube rupture initiating frequency of 5 x 10^{-3}/yr.

Sequence 10.5: In this sequence, HPI and charging flow are not throttled. This is an action performed by the operator in an attempt to stabilize primary and secondary system pressure. For screening purposes, a 0.1 failure frequency* was assigned to this operation, resulting in a frequency of 5 x 10^{-4}/yr for this sequence.

3.5.11. Loss of Main Feedwater

As described in Section 3.3.4, a loss of feedwater (LOFW) with subsequent auxiliary feedwater overfeed can result in sequences that potentially could be of concern with respect to PTS. Event sequences are similar to those identified for a reactor trip followed by main feedwater isolation (caused, for example, by a high steam generator level feedwater trip or safety injection), although the sequence frequencies are different from those in the reactor trip event tree. Six LOFW sequences have been identified. Utilizing a LOFW initiating event frequency of 0.3/yr and the branch probabilities given in Table 3.6 for "AFW automatically controlled," "Charging

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*The feeling was that the failure frequency for this action should probably be lower than the 0.1 value used. However, an early review of the thermohydraulics of this event revealed that a conservative frequency estimation for this sequence would not impact the overall frequency for a through-the-wall crack. Therefore, the 0.1 value was used.

flow runs back on demand," and "AFW throttled" results in the LOFW-related sequences and frequencies given in Table 3.17. T.3.17

3.5.12. Support System Failures

Of the support system failures postulated in Chapter 2 (Section 2.9.3), 12 were identified as being of potential concern with respect to PTS. These included loss of instrument air; loss of component cooling water; loss of service water; and several electrical bus failures, most of which involved the 4KV bus 3 or the dc power supplies. The plant responses to these support system failures are summarized in Table 3.18. T.3.18

In this section, the selected support system failures are evaluated as initiators in potential PTS sequences. Initiator and sequence frequencies were then developed for those failures considered to be important. The potential PTS sequences associated with the selected support system initiators are discussed below.

Initiators 7, 8, and 9 (from Table 3.18), which involve the failure of vital instrument buses while tied into the 4KV bus 3 for maintenance, are effective loss of feedwater (LOFW) events. Main feedwater would isolate as a result of the SI actuation caused by the bus failure. The support system failure also results in charging flow runback. Sequences of potential PTS concern include an effective LOFW with initiation of AFW, successful or unsuccessful automatic control of AFW, and failure of the operator to manually throttle AFW.

Table 3.17. Sequences to be analyzed for loss of main feedwater

Sequence No.	AFW Actuates on Demand	AFW Automatically Controlled	Charging Flow Runs Back	OA: AFW Throttled	Frequency (yr^{-1})	Thermal Hydraulically Equivalent Reactor Trip Sequence
13.1	AFW actuates	Automatically controlled	Runs back as required	Fails to throttle	3E−3	9.49
13.2	AFW actuates	Automatically controlled	Fails to run back	Fails to throttle	3E−5	9.51
13.3	AFW actuates	Overfeeds	Runs back as required	Throttles prior to SG high-level alarm	2.1E−3	9.52
13.4	AFW actuates	Overfeeds	Runs back as required	Fails to throttle	2.1E−5	9.53
13.5	AFW actuates	Overfeeds	Fails to run back	Throttles prior to SG high-level alarm	2.1E−5	9.54
13.6	AFW actuates	Overfeeds	Fails to run back	Fails to throttle	2.1E−7	9.55

Table 3.18. System/component responses to selected postulated support system failures[a]

		System/Component Response												
No.	Postulated Failure	Reactor	Turbine	RCPs	Pressurizer and PZR PORVs	SDVs	STM PORVs	MSIVs	MFW Isolation	MFW Runback	AFW	Safety Injection[b]	Charging Pump Flow	Letdown Flow
							Electrical System Failures							
1	125V dc panel A and associated 4KV buses 1 and 2 fail[c]	Trips	Trips	RCPs A and C off	PZR heaters off; auxiliary spray valve closed; RC-456 stays closed	Closed	Closed	Closed	Isolated	NA[d]	Actuates	Train B actuates	Operable	Isolated
2	125V dc panel P fails	Trips	Trips	Operable	PORVs fail closed; control heaters on	A-2 and B-3 closed	Operable	Closed	Isolated	NA	Actuates (only one motor-driven pump available)	Train A actuates	Operable	Isolated
3	125V dc auxiliary panel "DC" fails	Operable	Operable	Operable	RC-456 closed; auxiliary spray valve closed	A-1, B-1, and B-2 closed	Closed	Closed	Isolated	NA	Operable	Operable	Operable	Isolated
4	DC buses A and B fail	Trips	Immediate turbine trip fails	Cannot be be tripped off	PORVs closed; auxiliary spray valve closed; PZR heaters failed on	Closed	Closed	Closed	Isolated	NA	Not operable	HPI and LPI not operable	Operable	Operable
5	4KV buses 2 and 3 and associated D/G's fail	Trips	Trips	RCP C off; potential seal failure	RC-455C closed; block valves fail open; RC-456 eventually closes[e]	Closed	Eventual closure[e]	Eventual closure[e]	Loop 1 isolated, and eventual isolation of other MFW loops[e]	Operable	Not operable	HPI and LPI not operable	No flow; pumps fail	Isolated
6	4KV buses 1 and 2 and associated D/G's fail	Trips	Trips	RCPs A and C off	PZR heaters off	Closed	Operable	Operable	Loop 1 isolated	Operable	Operable	Operable	Operable, but discharge throttle valve fails open	Operable

Table 3.18 (Cont'd)

		System/Component Response												
No.	Postulated Failure	Reactor	Turbine	RCPs	Pressurizer and PZR PORVs	SDVs	STM PORVs	MSIVs	MFW Isolation	MFW Runback	AFW	Safety Injection[b]	Charging Pump Flow	Letdown Flow
7	4KV bus 3 with maintenance tie to instrument bus 2 fails[c]	Trips	Trips	Operable	RC-455C closed; block valves fail open	Closed	Closed[f]	Operable	Loop 2 isolated	Operable	Actuated	Actuated (only one SI pump available)	Low flow[g]	Isolated
8	4KV bus 3 with maintenance tie to instrument bus 3 fails[c]	Trips	Trips	Operable	PORVs closed	Closed	Closed[f]	Operable	Loop 3 isolated	Operable	Actuated	Actuated (only one SI pump available)	Low flow[g]	Isolated
9	4KV bus 3 with maintenance tie to instrument buses 2 and 3 fail[c]	Trips	Trips	Operable	PORVs closed	Closed	Closed[f]	Operable	Loops 2 and 3 isolated	Operable	Actuated	Actuated (only one SI pump available)	Low flow[g]	Isolated
Instrument Air System														
10	Loss of instrument air	Operable	Operable	Operable	PORVs closed	Operable	Closed	Closed	Isolated	NA	Overfeed if turbine pump is actuated	Operable	Overfeed (loss of speed control and throttle valve open)	Isolated
Component Cooling Water System														
11	Loss of CCW	Operable	Operable	Potential RCP	Operable	Operable	Operable	Operable	Operable	Operable	Operable	LPI and SI pump seal failure	Pump seal failure	Operable
Service Water System														
12	Loss of SWS	Operable	Operable	Potential RCP bearing failure	PORVs closed[e]	Operable	Eventual closure[e]	Eventual closure[e]	Isolated	NA	Inoperable	SI pumps inoperable	Overfeed[e] (loss of speed control and throttle valve open)	Isolated[e]

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[a] Acronyms used in this table are RCP = reactor coolant pump, PZR PORV = pressurizer power-operated relief valve, SDV = steam dump valve, STM PORV = steam power-operated relief valve, MSIV = main steam-line isolation valve, MFW = main feedwater, AFW = auxiliary feedwater, SI = safety injection, HPI = high-pressure injection, LPI = low-pressure injection, CCW = coolant water system; and SWS = service water system.

[b] Accumulator discharge remains operable under all failures postulated.

[c] Includes unavailability of associated diesel generator.

[d] NA = not applicable.

[e] Failure results in loss of SWS, which can fail the instrument air compressors.

[f] STM PORVs only fail closed if load reject signal from PM-447 exists.

[g] Manual recovery may be required.

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Initiator 1, loss of the 125V dc panel A, also results in main feedwater isolation and SI actuation; however, charging pump flow remains fully operable. Sequences of potential PTS concern include those that would be initiated by an effective LOFW with the possibility of charging flow runback failure and failure of the operable pressurizer PORV to close.

Initiators 2, 3, 10, and 12 would also result in main feedwater isolation and, except for initiator 3, would also result in the pressurizer PORVs failing closed. Modeling of the PTS sequences of potential concern includes considering the closure of the pressurizer safety relief valves (which would be demanded if charging flow runback failed) in those sequences where the support system initiator would result in inoperability of the PORVs.

The failure of 4KV buses 1 and 2 and associated diesel generator (initiator 6) results in a reactor trip initiator with operable primary and secondary side PORVs, closed SDVs, and operable MFW, AFW, MSIVs, SI, and charging flow. The expected frequency of this support system failure, though, is orders of magnitude smaller than that of an unspecified reactor trip.

Three of the support system initiators identified in Table 3.18 are considered to be benign from a PTS standpoint. Initiator 4, loss of dc buses A and B, could be modeled as a steam-line break initiator owing to the potential turbine trip failure induced. However, minimal cooldown would occur since the dc bus failure would also cause MSIV closure and HPI and AFW failure. Loss of 4KV buses 2 and 3 and associated diesels (initiator 5) is similar in that SI, AFW, and charging flow are inoperable while the secondary side is isolated. Failure of the component cooling water system (initiator 11) could result in an RCP-seal-failure-type LOCA via loss of seal water to the charging pumps. However, failure of all three charging pumps would be required, as well as failure of the operator to trip the RCPs. This event is bounded by other LOCA initiators.

T. 3.19

Table 3.19 summarizes the support system initiators modeled and the sequences with estimated frequencies greater than 10^{-7}/yr. The frequencies of most of the PTS sequences that could be initiated by these support system failures are bounded by the frequencies for sequences initiated by LOFW and nonspecific reactor trip events. Of the support system failures evaluated, three sequences resulting from support system initiators could not be bounded in this manner. These sequences involve LOFW resulting from failure of the instrument air system caused by failure of the service water system. The sequences of concern require the normal recovery of service water but not the consequently failed instrument air, failure to throttle AFW, and, in one case, failure to manually run back charging flow. From a thermal-hydraulics standpoint, the sequences are approximated by reactor trip sequences 9.53 (for the sequences involving effective manual runback of charging flow) and 9.55 (for the remaining two sequences). These sequences have been designated as sequences 14.1 and 14.2, respectively, for analysis purposes (see footnotes e and f in Table 3.19).

3.5.13. Sequence Summary

The procedure described in this section to quantify and collapse the event tree sequences produced 209 sequences for which thermal-hydraulic and

Table 3.19. PTS sequence modeling of support system initiators[a]

Support System Initiator				Sequences > 10^{-7}/yr	
No.[b]	Description	Estimated Frequency (yr^{-1})	Impact	Description	Frequency (yr^{-1})
1	Loss of 125V dc panel A and associated 4KV buses 1 and 2[c]	1.8E−3[d]	LOFW with AFW and SI actuated; SDVs closed; STM PORVs closed	Since no overcooling or pressurization is forced by the initiator beyond what would be typically demanded in resulting transients, the associated sequences are bounded in frequency by those associated with LOFW.	Bounded by LOFW sequences
2	Loss of 125V dc panel B	1.8E−3	LOFW with AFW actuated; PZR PORVs fail closed; STM PORVs operable; MSIVs closed	Same as No. 1	
3	Loss of 125V dc auxiliary panel "DC"	1.8E−3	LOFW with STM PORVs closed; one PZR PORV operable; MSIVs closed; AFW actuated	Same as No. 1	
6	Loss of 4KV buses 1 and 2 and associated D/G	3.5E−4	Reactor trip with STM PORVs and SDVs closed	Since no overcooling or pressurization is forced by the initiator beyond what would be typically demanded in resulting transients, the associated sequences are bounded in frequency by those of the reactor trip event tree.	Bounded by reactor trip sequences
7	Loss of 4KV bus 3 with maintenance tie to instrument bus 2[c]	4.1E−5	LOFW with AFW actuated; STM PORVs operable; SDVs closed; charging flow at minimum	Same as No. 1	
8	Loss of 4KV bus 3 with maintenance tie to instrument bus 3[c]	4.1E−5	Same as No. 7	Same as No. 1	
9	Loss of 4KV bus 3 with maintenance tie to instrument buses 2 and 3[c]	4.1E−6	Same as No. 7	Same as No. 1	

Table 3.19 (Cont'd)

Support System Initiator				Sequences > 10^{-7}/yr	
No.[b]	Description	Estimated Frequency (yr^{-1})	Impact	Description	Frequency (yr^{-1})
10	Instrument air system failure	1.0E−4	LOFW with STM PORVs closed; MSIVs closed; AFW auto-control failure; PZR PORVs closed; loss of charging flow control (overfeed)	10a. Initiator with operator manually running back charging flow but failing to throttle AFW	Bounded by LOFW sequences
				10b. Initiator with operator failing to manually run back charging flow but successfully throttling AFW	Bounded by LOFW sequences
				10c. Initiator with operator failing to manually run back charging flow and failing to throttle AFW	Bounded by LOFW sequences
12	SWS	0.01	LOFW with AFW inoperable; STM PORVs closed; MSIVs closed; loss of charging flow control (overfeed)	Initiator with recovery of service water but not instrument air. Same three sequences as in No. 10 above, but with initiator frequency based on the SWS failure and a probability of 0.9 for recovery of SSW; that is:	
				12a. Initiator with operator manually running back charging flow but failing to throttle AFW	8.1E−4[e]
				12b. Initiator with operator failing to manually run back charging flow but successfully throttling AFW	9.0E−4[f]
				12c. Initiator with operator failing to manually run back charging flow and failing to throttle AFW	9.0E−4[f]
				Note: Without recovery of SWS, the event is not an overcooling transient.	

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[a] Acronyms used in this table are: LOFW = loss of feedwater, AFW = auxiliary feedwater, SI = safety injection, SDV = steam dump valve, PZR PORV = pressurizer power-operated relief valve, STM PORV = steam power-operated relief valve; MSIV = main steam isolation valve; SWS = service water system.

[b] Failures 4, 5, and 11 listed in Table 3.18 are considered to be benign.

[c] Includes unavailability of associated diesel generators.

[d] Read; 1.8 × 10^{-3}.

[e] Initiator 12a is subsequently identified as Sequence 14.1.

[f] Initiators 12b and 12c are subsequently jointly identified as Sequence 14.2.

fracture-mechanics analyses were performed. The number of sequences identified for analysis for each initiator and the frequencies of the associated residual groups are summarized in Table 3.20.

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Table 3.20. Summary of event tree sequence collapse

		Number of Sequences				Residual Group Frequency (yr^{-1})	
				Grouped with Other Sequences[a]			
Sequence Series No.	Initiator (Event Tree)	To Be Analyzed	In Event Tree	Above 10^{-7}/yr	Below 10^{-7}/yr	Before Analysis	After Analysis
1, 11	Small-break LOCA[b] at full power	22	6938	8	27	1.3×10^{-6}	9.4×10^{-7}
2	Medium-break LOCA at full power	12	6824	2	32	2.6×10^{-7}	2.1×10^{-7}
3, 12	Small-break LOCA at hot 0% power	5	158	4	4	2.8×10^{-7}	1.1×10^{-7}
4	Medium-break LOCA at hot 0% power	2	124	1	3	3.8×10^{-8}	6.5×10^{-9}
5	Small-pipe steam-line break at full power	29	923	6	28	9.1×10^{-6}	6.6×10^{-7}
6	Large-pipe steam-line break at full power	15	1763	10	41	4.6×10^{-7}	4.4×10^{-7}
7	Small-pipe steam-line break at hot 0% power	16	292	4	7	3.8×10^{-7}	2.5×10^{-7}
8	Large-pipe steam-line break at hot 0% power	9	508	0	4	2.3×10^{-7}	2.3×10^{-7}
9	Reactor trip	90	9773	54	174	3.1×10^{-6}	2.7×10^{-6}
10	Tube rupture	5	NA[c]	NA	NA	NA	NA
13	Loss of feedwater	6	NA	NA	NA	NA	NA
14	Support system failure	3	NA	NA	NA	NA	NA

[a] A screening frequency of 10^{-7}/yr was used to initially identify sequences which should be analyzed on an individual basis.

[b] LOCA = loss-of-coolant accident.

[c] NA = not applicable.