PSE&G

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June 27, 1975

Mr. William A. Giambusso
Director, Division of Reactor Licensing
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Mr. Giambusso:

STEAM GENERATOR FEED LINE WATER HAMMER
NO. 1 AND 2 UNITS
SALEM NUCLEAR GENERATING STATION
DOCKET NOS. 50-272 AND 50-311

Enclosed for your review is a report on PWR steam generator feed line water hammer. This report is submitted in response to concerns that were identified at a meeting with members of the Regulatory staff on January 29, 1975.

Very truly yours,

R L Mittl

R. L. Mittl
General Manager - Projects
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REPORT ON PWR FEED LINE WATER HAMMER

I. INTRODUCTION

This report provides information in support of measures which will minimize the consequences of main feed line steam-water slugging type of water hammer (associated with recovering steam generator feed rings) in the Salem Nuclear Plant. It is concluded, as discussed in this report, that the water hammer which has been experienced in a number of PWR plants is caused by steam-water slugging. The slugging has occurred when feedwater flow rates have been in the range 200 - 300 gpm/steam generator and the steam generator water levels have been increased from below the level of the feed ring. Westinghouse NSSS which have Series 44 or 51 type steam generators contain feed rings or spargers located just below the moisture separators and, therefore, can be susceptible to this type of water hammer. The Salem plant contains Series 51 steam generators.

The information provided in this report includes a discussion of:

1. The slugging phenomenon as it is presently understood.

2. The effect of short horizontal feedwater pipe runs adjacent to the steam generator nozzle in reducing the intensity of water hammer.

3. Operating plant experience of Westinghouse PWR plants in relation to feed line steam-water slugging type of water hammer.

4. A review of in-plant water hammer testing (past, on going and anticipated) for the purpose of providing both background information and an indication of future trends.

5. The control of feedwater flow rates below the range where water hammer is likely to occur.

6. The location of the auxiliary feedwater line connections to the main feedwater lines in typical Westinghouse PWR plants (discussed in Appendix 2 of the report).

7. Specific measures being taken at the Salem plant to ensure continued feed system integrity.

II. SUMMARY

The conclusions of this report are:

1. The results of in-plant experience, both water hammer tests and inadvertant incidents, and calculations derived from model tests show that the intensity of feed line water hammer, which occurs while recovering the feed ring, is substantially reduced when the horizontal feed line runs adjacent to the steam generators are kept short. Actual pipe damage is not likely where the horizontal pipe runs are less than 8 ft. and where adequate pipe supports prevent large pipe movements and consequent pipe stress above yield.

2. Westinghouse PWR plant experience of record indicates a low rate of serious water hammer incidents compared to the total number of operating hours. Also, where water hammer has occurred on plants with short feed pipe runs adjacent to the steam generator and properly supported feed lines, feed lines have not been damaged although minor damage to pipe supports has occurred. The latter indicates that inadvertent water hammers will not compromise the integrity of the feedwater systems in such plants.

3. In-plant investigative tests have been conducted on a few plants where adequate test instrumentation was installed. These tests yielded useful information on water hammer threshold flows, the pipe movements resulting from water hammer, and the effectiveness of certain plant modifications at precluding water hammer.

   Demonstration tests in a number of plants may be desirable to show that water hammer would not occur under established operating conditions and/or to show the benefits derived from any modifications made to the system or equipment.

4. The control of feedwater flow rates at or below 150 gpm per steam generator when the feed ring is uncovered will prevent water hammer. Such control could be administratively and practically achieved without hindering the safety function of the system.

5. The horizontal run of feedwater piping adjacent to each Salem steam generator feedwater nozzle has been shortened to the greatest extent possible in order to minimize the expected magnitude of any steam-water slugging type water hammer transients encountered. Sparger modifications will be implemented if future planned tests prove successful; should such tests not be successful, serious consideration to feed flow limitations will be given.

III. THE PHENOMENON - STEAM/WATER SLUGGING

The main feed line water hammer which has occurred in PWR reactor plants has been identified as a steam-water slugging phenomenon resulting from steam entering horizontal sections of feed line pipe which are partially filled with cold water. Model tests have successfully duplicated the process, and conditions observed in several different plants which have experienced water hammer provide supporting evidence. In all the latter cases the steam generator water levels had dropped below the feed ring and the level was being recovered (to above the feed rings) by feeding the steam generators with cold auxiliary feed water. A brief qualitative description of the steam-water slugging process, as derived from model tests, is presented in Appendix 1.

IV. EFFECT OF SHORT HORIZONTAL PIPES RUNS

The feed line water hammer experience as summarized in Section V has indicated that the length of the horizontal feed pipe run adjacent to the steam generator has an effect on the intensity of the water hammer. For example, the Indian Point 2 line which failed in Nov. 1973 contained a horizontal run of about 15 ft. The Surry 1 and Turkey Point 3 and 4 incidents also involved long horizontal runs which were subsequently modified. On the other hand, the Indian Point 2 incidents and Phase II tests, and the test at Tihange, after the pipe runs were shortened, showed no apparent pipe damage, although minor damage to insulation and pipe supports did occur. Thus, the short pipe runs appear to escape damage while the longer runs have occasionally suffered breaking of the fluid boundary, particularly where the pipes supports have been inadequate.

An analytical investigation into the mechanism of feed line steam-water slugging resulted in a calculational model that compared reasonably well with small scale, low pressure experimental results. This calculational model also indicates a similar dependence of water hammer intensity on the length of horizontal run. Such a dependence is illustrated in Figure 1 where the total energy of the traveling wave is plotted against the straight length of feed line, nozzle and feed inlet tee. The latter is internal to the steam generator and is part of the feed ring (see Figure 2 of Appendix 1). Although such information is preliminary, the analytical results also indicate favorable structural advantages attributable to short horizontal pipe runs.

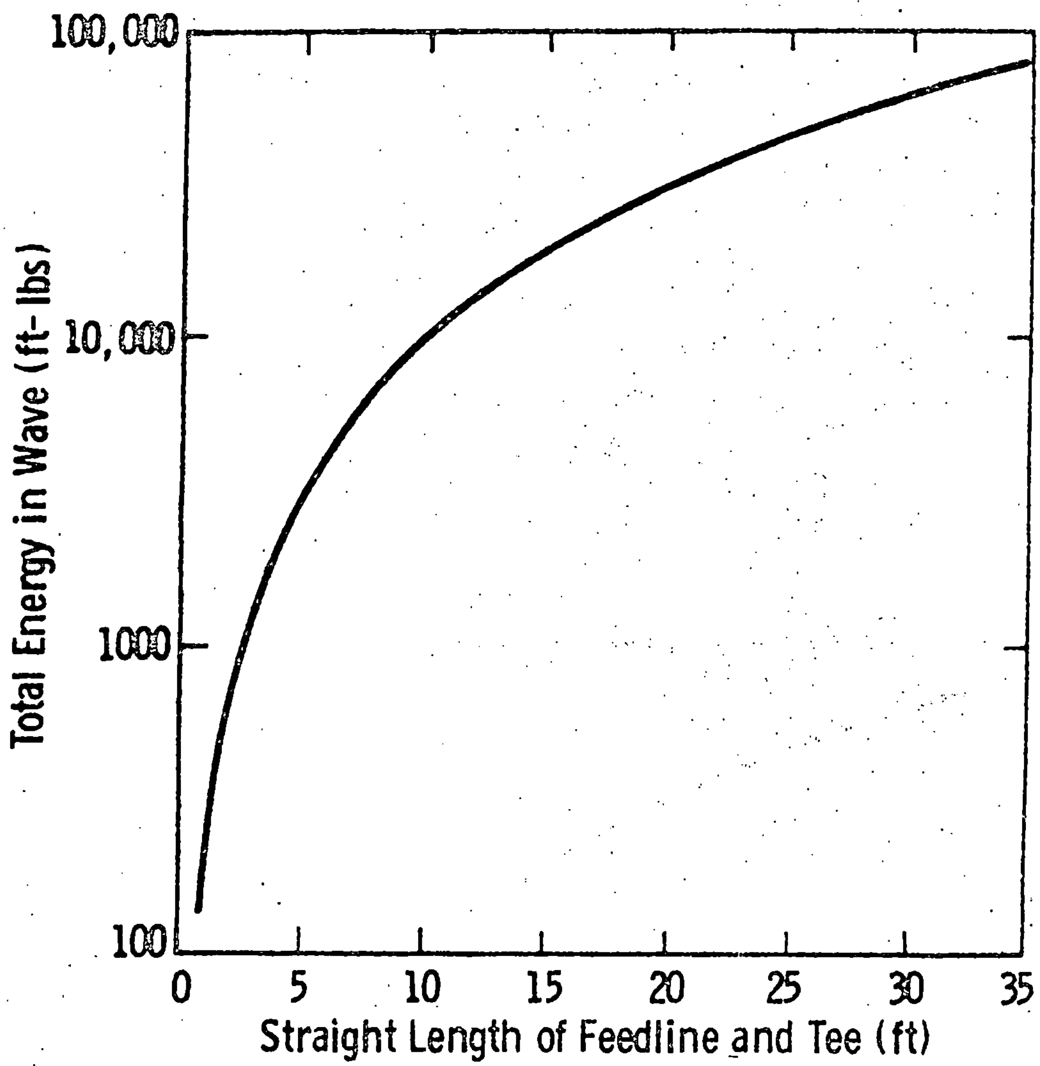

Fig. 1 — Total energy in traveling wave

These results supported earlier design recommendation that the feedwater piping layout immediately upstream of the steam generator nozzle should include a pipe loop. The pipe loop serves to minimize the length of feed line which could be drained when the steam generator level is below the feed ring. The recommended configuration consisted of a 90°EL directed vertically downward as close to the steam generator nozzle as possible followed by another 90°EL to re-establish the horizontal attitude as required further upstream. Such an arrangement had been demonstrated to have the effect of fulfilling the short pipe run objective. However, in some plants layouts, modifications of this magnitude proved impractical because of interference with existing structure whose alteration was economically prohibitive. Thus, one alternative was to install two 45°EL in series such that the bottom of the feedwater nozzle I.D. is six inches or more above the top of the horizontal feedwater pipe I.D. upstream of the 45°ELs. Model testing of the latter configuration confirmed that it was as effective as the 90°EL configuration in limiting the effects of water hammer.

V. OPERATING PLANT EXPERIENCE

The number of domestic Westinghouse PWR plants of recent design which are in commercial operation and which contain steam generators having feed rings are listed in Table 1. The list identifies three different steam generator designs in both 2, 3, and 4 loop plants. Also, reference is made to the length of the horizontal feed pipe run attached to the steam generator nozzle. As noted elsewhere, the shorter the horizontal run the lower the intensity of water hammer. Table 1 includes information on the number of operating hours accumulated to-date and an estimate of the number of start-ups. It is during start-ups, and hot shutdowns when the steam generator level is under manual control. Particularly during start-up, manual control is difficult and the probability of allowing level to drop below the feed ring is most likely. Loss of level to the extent that the feed ring is uncovered will result in a reactor trip and the automatic start of the motor driven auxiliary feedwater pumps. The susceptibility to water hammer is highest under these conditions. Exact information regarding how often water levels drop below the feed ring is not readily obtainable, but it is not unusual for operating plants to experience loss of level from low power in about 5% of the start-ups, and this normally results in uncovering the feed ring. The data of Table 1 indicate that only relatively few serious water hammer incidents have occurred in domestic plants in spite of occasional favorable conditions.

TABLE 1

DOMESTIC OPERATING PLANT EXPERIENCE

Plant/No. of Loops	Steam Generator Type	Horizontal(1) Pipe Length Max. Ft.	Operating(2) Hours	Number(3) of Start-ups 1/72-3/75	Water(4) Hammer Incidents
R.E. Ginna 2 Loop	44	3	34,848	30	No
Point Beach 1 2 Loop	44	12(5)	29,729	34	No
Point Beach 2 2 Loop	44	12(5)	20,343	54	No
Kewaunee 2 Loop	44	3.5	5,617	42	No
Prairie Island 1 2 Loop	51	8	5,897	35	No
Prairie Island 2 2 Loop	51	7.6	1,898	5	No
Conn. Yankee 4 Loop	27	2.7	51,006	20	No
San Onofre 3 Loop	27	5	48,766	27	No
H.B. Robinson 3 Loop	44	5	27,006	85	No
Turkey Point 3 3 Loop	44	6	14,440	76	Yes
Turkey Point 4 3 Loop	44	6	11,071	94	Yes
Indian Point 2 4 Loop	44	7.5	4,687	62	Yes
Surry No. 1 3 Loop	51	8	11,578	49	Yes
Surry No. 2 3 Loop	51	8	10,370	44	No

TABLE 1

Domestic Operating Plant Experience

Plant/No. of Loops	Steam Generator Type	Horizontal[1] Pipe Length Max. Ft.	Operating[2] Hours	Number[3] of Start-ups 1/72 - 3/75	Water[4] Hammer Incidents
Zion No. 1 4 Loop	51	7	6,181	23	No
Zion No. 2 4 Loop	51	7	2,833	66	No
D.C.Cook No. 1 4 Loop	51	4.4	596	4	No
			287,000		

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(1) The lengths identified were derived from available information and are approximate. They include 1.5 ft. for the steam generator nozzle. They reflect the dimensions subsequent to modifications.

(2) NRC-Operating Units Status Report - April 1975 Hours Generator On-Line.

(3) The number of start-ups were derived from yearly status reports for 1972, 1973, 1974 and 1975.

(4) On dockets submitted to NRC.

(5) The Point Beach plants have feedwater line check valves installed at the steam generator nozzles.

V. OPERATING PLANT EXPERIENCE (Cont'd)

The incidents of serious water hammer in Westinghouse PWR plants for which there is information are summarized in Table II. These are of interest because of the general similarity of conditions under which water hammer occurred, i.e., water level below the feed ring, significant auxiliary feedwater flow rates and the potential for steam to be trapped in the horizontal run of feed pipe. While the conditions were similar there were a wide variety of plant differences such as plant type, layout and steam generator designs. Thus, the water hammer experiences to date support the understanding of the nature of the phenomenon as described elsewhere in this report and a means of prevention. The in-plant tests such as Indian Point 2 and Tihange also provide information to compare with model tests and form a basis for confirming analyses.

A review of the information in Table II shows that the water hammer incidents, except those at Surry 1 in Oct. 1972 and Indian Point 2 in November 1973, resulted in only minor damage to the feedwater pipe supports, and components. The Indian Point 2 incident was aggravated not only by long horizontal pipe runs but pipe supports which allowed excessive pipe movement, leading to failure of the pipe. Furthermore, at Indian Point 2 (as demonstrated by the Phase 2 Test of Feb. 1974) and where short horizontal runs of feedwater pipe were subjected to water hammer, damage has been limited to insulation fracturing and minor damage to pipe supports. It would appear a water hammer occurrence in properly installed feedwater piping will not result in a compromise of the reactor feedwater system integrity.

VI. IN-PLANT TESTING

In-plant tests are either investigative, in support of technical decisions or analysis, or demonstrative, to assure that a plant will perform as expected when operating within established operating limits and according to established procedures. Water hammer tests of both types are of interest. The investigative type tests are important because they are the simpliest way to obtain limited full scale data points quickly and least expensively. They do require producing low intensity feed line pipe water hammer and the installation of special test instrumentation. The demonstrative type tests confirm that water hammer will not occur below a specified feedwater flow limit and, where applicable, check the method of feed flow control. A brief review of both investigative and demonstrative tests is presented below.

TABLE II

SUMMARY OF WATER HAMMER INCIDENTS

Plant	Description
Surry, 3 Loops Oct. 1, 1972 Status: Pre-operational Testing	The water hammer incident occurred while the plant was in hot shutdown and the steam generators were being fed by the auxiliary feedwater system. The incident resulted in damage to the main feed line check valve and some local displacement of the feedwater piping. Subsequent analysis confirmed that the integrity of the feedwater system piping had not been reduced. To preclude future problems, the feedwater piping to the "A" steam generator was modified to include a loop seal to reduce the length of horizontal pipe that could be drained at low flows. Loops "B" and "C" pipe arrangements already met the draining criterion. Power operation for more than two years has resulted in no additional water hammer incidents.
Indian Point 2 4 Loops Nov. 13, 1973 Status: Operating	The water hammer incident at Indian Point occurred while attempting to recover level in two steam generators following a plant trip from low power. The incident resulted in a feedwater piping failure in S.G. No. 22. Analysis indicated that the failure was caused by repeated large deflection of the piping. Following repair, the piping supports were adjusted to prevent excessive deflection and a support was added to prevent the specific large pipe movement which had caused the rupture. The piping configuration on two of the main feed lines was modified to reduce the effective length of horizontal pipe attached to the steam generator. The horizontal runs in the other loops were already short. Subsequent acceptance test in Jan. and Feb. of 1974 indicated that water hammer of reduced intensity could still occur under certain circumstances. Although administrative control of feedwater flow could prevent such occurrences, the decision was made by the Utility to install J-tube modifications to further reduce the likelihood of water hammer. The details of the original incident and subsequent modifications and test are presented in Reference 1. Normal power operation has continued at Indian Point 2 for more than fifteen months without further incidents.
Turkey Point 3 and 4 3 Loops Status: Operating	There have been three known occurrences of water hammer in the feedwater piping from the steam generator back to the feedwater check valves. The events were revealed by subsequent leakage through the body to bonnet joint on the feedwater check valve (main feedwater line 3B

TABLE II
Summary of Water Hammer Incidents

Plant	Description
	and 4B) and evidence of anchoring bolts pulled out of the concrete, deformed mounting plates for two spring hangers and slight plastic deformation at the 90^{o}EL upstream of the steam generator nozzle (main feedwater line 4A). The circumstances and times of the first two events are not known. The third event is attributed to the injection of cold feedwater into the feed line containing steam with the feed ring uncovered. The feedwater piping in both plants was modified to reduce the lengths of the horizontal runs upstream of the steam generator and modification to the pipe supports and restrains to restrict pipe movement. No further incidents have occurred.
Mihama 2 2 Loops Oct 11, 1971 Status: Hot Functional Testing	During hot functional testing a reactor trip as the result of steam generator Lo-Lo Level was simulated. To accomplish this the level was dropped below the feed ring and maintained there for approximately 20 minutes. After the test, steam generator level was being increased to normal (above the feed ring) using auxiliary feedwater. It was during level increase that the water hammer occurred. Subsequent inspection of the feedwater train revealed no damage to the main feedwater pipe. Minor damage to snubbers, the auxiliary feedwater pump mechanical seal and the auxiliary feedwater pump pressure gage was observed. A later inspection of the steam generator internals revealed no damage. It is understood that administrative controls on auxiliary feedwater flow have been instituted, and no further incidents have been reported.
Tihange 1 3 Loops Feb. 1975 Status: Hot Functional Tests and Low Power Water Hammer Tests	During hot functional tests a loss of level occurred while performing secondary system tests. While recovering level using auxiliary feedwater, water hammer occurred. The incident resulted in no apparent damage. However, a decision was made to perform a water hammer test at a later date. The test was conducted in Feb. 1975 on Steam Generator No. 1 in which the main feedwater pipe had been partially instrumented. A significant water hammer occurred while recovering the feed ring with auxiliary feedwater at a rate of 176 gpm. The feedwater pipe and valves were not damaged. A pipe support sustained minor damage and some insulation was shaken off. Operation has been restricted to reduced power until a demonstration that 120 gpm auxiliary feedwater flow is below the water hammer threshold, and piping system dynamic response calculations are completed.

TABLE II
Summary of Water Hammer Incidents

Plant	Description
Ringhals 2 3 Loops March 29, 1975 Status: Operating	During the restoration of normal water level in the steam generators following a reactor trip caused by a loss of main feed, water hammer occurred in steam generator No. 3 (feed pipe has short horizontal run to S.G.). Auxiliary feedwater flow at the time was 191 gpm. Flow was reduced to about 80 - 110 gpm and the water hammer ceased. Subsequently flow was again increased slowly to 191 gpm and maintained for about one half hour when water hammer again occurred. Flow was reduced to 110 gpm and the water hammer stopped. The No. 3 feedwater pipe and valves were not damaged. One pipe restraint rod had bent and some insulation had been shaken off. Auxiliary feedwater flow has been administratively limited to 110 gpm. Power operation has been resumed.

The investigative tests to date consist of the Indian Point 2 Phase II test performed on February 2 and 3, 1974 (Reference 1), one at Tihange in Belgium in February 1975, and one at Doel plant in Belgium in May 1975.

The first two tests were intended to obtain a better understanding of the steam-water slugging mechanism, define the circumstances under which slugging occurs and obtain data useful for confirming analytical techniques by subjecting specially instrumented feedwater pipes to water hammer conditions, while the third test investigated the effectiveness of a feed ring modification in eliminating water hammer. The methods of testing were all similar in that steam generator water level was decreased below the feed ring and then increased at a specified auxiliary feedwater flow until the feed ring was completely recovered or until a water hammer occurred. Where water hammer did occur, subsequent inspection and analysis was performed to confirm that the feed line pipe integrity was not compromised. All tests yielded useful data.

The Phase II test at Indian Point 2 produced good data on threshold flow (as presented in Section VII), time history of feedwater pipe temperatures and the magnitude of the pipe displacements. However, the time history of pipe movement and pressure pulses were not obtained.

The Tihange feed line under test experienced a water hammer early in the test program resulting in minor damage to pipe supports and test instrumentation and causing an indefinite post-ponement of further testing. However, while data from the Tihange test was sparse, good time histories of pipe displacement and pressure pulses were obtained. This data is proving useful in an ongoing effort to develop forcing functions which might be used for structural response analysis of the piping systems. The work has not yet progressed to the point, however, where analytical predictions of piping response to water hammer loadings of this type can be made with any significant degree of certainty.

The Doel plant tests showed that a relatively simple plant modification may be able to totally eliminate this water hammer phenomenon in the usually encountered range of feedwater flows. For test purposes, the Doel modification consisted of adding a small vent to the top of the feedwater sparger at a location diametrically opposite to the inlet tee. In tests at Doel to date, no feedwater water hammer has been encountered in the line having the aforementioned modification. Further testing of this concept is planned at other plants in the near future, to ensure that it is indeed a generic fix, and not one whose effectiveness is a function of some unique plant characteristic.

In the event that the planned tests of vents are unsuccessful, and additional investigative type tests are determined to be desirable, the purpose of such tests would be (1) to expand the data points and related thermal and hydraulic information for the water hammer threshold flow, and (2) provide better information for development and validation of a forcing function input for pipe structural calculations. The test method would be similar to the Indian Point 2 Phase II test in that water hammer would be produced in properly designed and supported feedwater pipes which are adequately instrumented . The emphasis would be placed on instrumenting in such a way as to obtain accurate time history recordings of most parameters, particularly during the momentary pressure pulses. These recordings would include measurements of temperature, pressure, feedwater flow, pipe displacement, acceleration and pipe strain.

Demonstrative type tests are illustrated by the Indian Point 2 Phase I and III tests where the intent was to establish that water hammer would not occur under established operating conditions. Such tests would verify the adequacy of operating limits and demonstrate satisfactory operating procedures. The general test method would be similar to that outlined for the investigative type tests except the feedwater flow rate would not exceed the operating limit. Also, the instrumentation would be simpler, consisting of accelerometer or scratch pads as necessary to show that water hammer did not occur for flow rates up to the specified limit. This type of testing may well be included as part of the pre-operational test program. Demonstrative tests may also be used to show the benefits derived form some modification to the system or equipment.

VII. CONTROL OF FEEDWATER FLOW

The in-plant tests and results from actual water hammer incidents establish that water hammer can be precluded by limiting the rate of cold feedwater flow to a value below a water hammer threshold flow. This section of the report addresses the maximum feedwater flow limit, the method for controlling feedwater flow and the adequacy of the controlled flow in regard to the auxiliary feed-water system safety function. Since feedwater can be supplied from either the main feedwater system or the auxiliary feedwater system, the control of feed water from either system is considered.

The maximum feedwater flow to preclude water hammer is derived primarily from the data obtained from the Indian Point 2 Phase II testing conducted on Feb. 2 and 3, 1974 and reported in Reference 1. This is the only test in which accurate feed flow and steam generator level data are available. The test consisted of instru-menting each steam generator main feedwater line with accelerometers, strain gages, scratch pads, pressure gages thermocouples, and with the plant hot (500°F or above), uncovering the feed ring then recovering it with a fixed auxiliary feedwater flow. The principal results are summarized in Table III. The table lists only the uppermost test flows at which water hammer did or did not occur.

VII. CONTROL OF FEEDWATER FLOW (Cont'd.)

The test results showed that water hammer did not occur at or below 200 gpm in all the feed lines and did not occur at all in two of the feed lines with feedwater flows as high as 240 gpm. It should be noted that Indian Point 2 feedwater lines had been modified prior to the Phase II test so that the horizontal runs immediately upstream from the steam generator were less than 10 ft. long.

The degree of replication of these test results is obviously limited for broad application, since uncertainties exist regarding the effect of variations in geometric, thermal and hydraulic parameters. Also, information from other plants, though not as accurate as the Indian Point 2 data, indicate occurrences at somewhat lower flows. Taking these factors into consideration as well as the Indian Point 2 results, a maximum flow limit of 150 gpm has been selected. The available evidences indicates that water hammer will not occur at or below the 150 gpm flow rate, a rate which can be achieved by administrative control and which is entirely within safeguards requirements.

TABLE III

SUMMARY OF THE INDIAN POINT 2 PHASE II TEST
FEBRUARY 2 AND 3 1974

Steam Generator	Run No.	Feedwater Flow (gpm)	Water Hammer
21	5	195	No
	6	240	Slight
22	12	200	No
	13	240	Yes
23	8	200	No
	9	240	No
24	10	200	No
	11	240	No

VIII. THE SALEM PLANT

The original design of the Salem feedwater piping adjacent to the steam generator nozzles consisted of horizontal piping runs of from 8 to 13 feet (measured from the steam generator shell O.D.) As discussed in Sections III and IV of this report, water hammer magnitudes can be reduced to acceptably low values by minimizing the length of the horizontal feed pipe run adjacent to the steam generator nozzle. As such, the Salem feed pipes were modified using two 45^{o} elbows in each line to provide a 6-inch loop seal immediately adjacent to each feedwater nozzle. This modification reduced the straight run of pipe subject to draining to approximately 4-feet, and hence has brought the expected magnitude of any water hammer events to within acceptable limits.

It is intended to follow the Doel type vent modification tests quite closely. Should they prove successful at precluding water hammer, it is expected that similar modifications would be made to the Salem steam generator feed water spargers in a timely manner. Should they not prove successful, serious consideration to feed flow limitation will be given to provide a further reduction in the probability of damage to the feed system.

IX. REFERENCES

1. Docket 50247-219 March 12, 1974 Report of Results of Test Program Following Plant Revisions Affecting Feedwater Piping

APPENDIX 1

STEAM-WATER SLUGGING IN PWR MAIN FEED LINES

The circumstances associated with severe feedwater line noise and movement in some PWR plants show consistently that the steam generator feed ring was uncovered and drained prior to recovering with cold feedwater. For this reason an investigation was made to determine the likely mechanism for the phenomenon. This investigation showed that steam-water slugging in the feed ring and horizontal sections of the adjacent feed line pipe is the most plausible cause for the noise and pipe movement. A qualitative description of the mechanism is provided in the subsequent discussion.

A possible feedwater line excitation phenomenon involves draining of the feedwater ring and level inlet section of the feedwater line following the fall of the SG liquid level below the feed ring. The feedwater line and inlet section are typically shown in Figures 1 and 2. Because the auxiliary pumps do not maintain these inlet sections full of water, a free surface is formed which is then available for condensation of counterflow steam moving up through the feedwater ring injection holes. Also, if the flow of steam is sufficient, ripple formation may be initiated on the free surface, followed by flooding of the cross section. This local flooding will cause isolation of a condensing steam bubble which will then collapse, causing the high pressure pulses characteristic of such phenomena.

In order to check on whether or not such a mechanism would be plausible a simple air-water-vacuum experiment was performed. Periodic and violent slugging was obtained with such ease that a smaller (model feed line of 1.0 inch diameter)glass model was constructed which could be operated in a steam environment. The same behavior was observed and the steam water slugging mechanism may be initiated in any one of several manners.

Referring to Figure 3, Figure 3-a shows that with the level section of feedwater line adjacent to the steam generator about half full of cold water a wave is formed at the change in cross-sectional area leading from the Tee into the feed ring. This wave will tend to fill the small feed ring cross-section, either by the drag forces of the counter-flowing steam or by slight increases in the feed line water level. In any event a seal is effected as indicated in Figure 3-b which traps a volume of steam in the feedwater line.

As the trapped volume of steam continues to condense its pressure drops drawing the sealing slug back into the feed line propelled by the high pressure S.G. steam following through the holes in the feed ring. The final collapse of the trapped steam volume causes a high pressure pulse to traverse the feedwater system. If the feed flow rate is adjusted so as to produce a rarefaction, the fluid displacement wave will move to the left in Figure 3-e while a surface wave moves to the right preparatory to initiating the conditions of Figure 3-a again.

If there is no feedwater flow after slugging initiation the intensity of the pulses will gradually diminish as the water is heated with the attendant loss in heat transfer from the trapped vapor volume to the feedwater. If the feedwater is increased the interface noted by the letter "A" in Figure 3-c moves to the right and the slugging intensity as well as time period decrease as the slug moves over shorter and shorter distances before impact. This series of events is reversed as the flow is decreased.

In the model tests the initial conditions were established in three ways. These are discussed below:

1. While the feed ring is covered with boiling water a small (or no) feed flow is maintained while the water level in the model is gradually lowered below the feed ring. Once the water level falls below the openings in the bottom of the feed ring steam bubbles rise up into the feed ring fluid and condense with the corresponding volumetric decrease pulling more vapor bubbles into the feed ring. This behavior yields a relatively low level bubble collapse "noise" in the feed ring until the fluid is hot enough to prevent vapor bubble condensation. At this time a steam void accumulates in the upper parts of the feed ring until there is sufficient vapor to start bubbling up into the Tee. As these steam bubbles move from the feed ring up into the Tee and collapse measurable pressure pulses are sensed in the feed line and, as the feed line water leaks into the S.G. conditions of Figure 3 are gradually obtained with maximum pressure pulses occurring as the slug moves the furthest distance. Observation of water hammer conditions in plants has not revealed a similar mode of operation causing the formation of water slugs.

2. If the feed ring and level section of the feed line are full of steam and the S.G. level is below the feed ring sudden and rapid feedwater flow may yield a Figure 3-b configuration directly with a subsequent cycle or two of slugging before the line is full. The pressure waves are about the same as the maximums measured in the "normal" case discussed above. If the feed flow is low apparently a hot stable fluid layer on the feedwater reduces the condensation coefficient to a safe level and slugging is not observed.

3. If there is enough positive flow to maintain either feed ring configuration full while the S.G. level is low then a sudden feed flow reversal or back-draining will lead to a Figure 3-b situation with one or two cycles of slugging. While this type of slugging is not anticipated in actual S. G. operating practice it does indicate the importance of properly operating check valves.

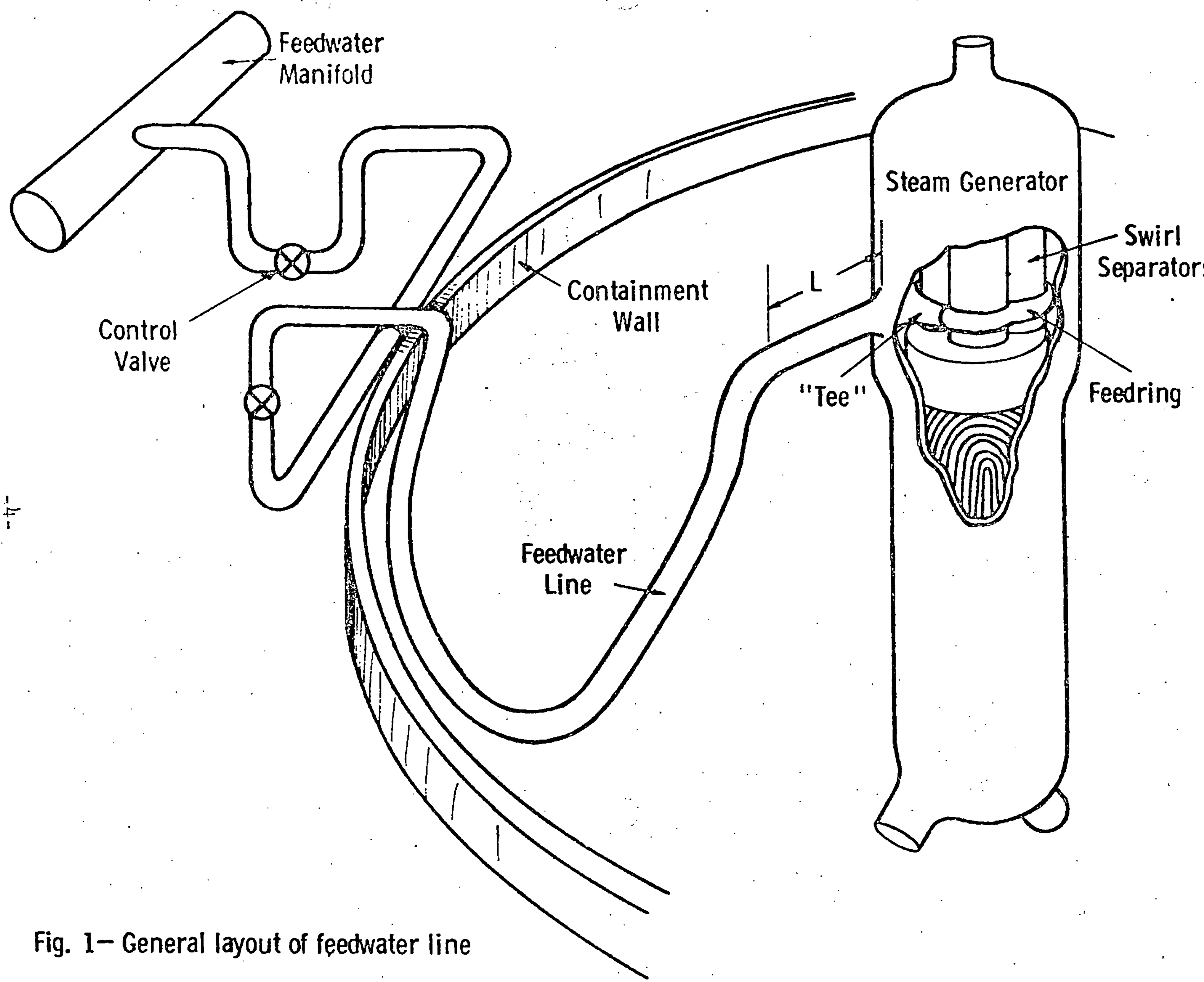

Fig. 1— General layout of feedwater line

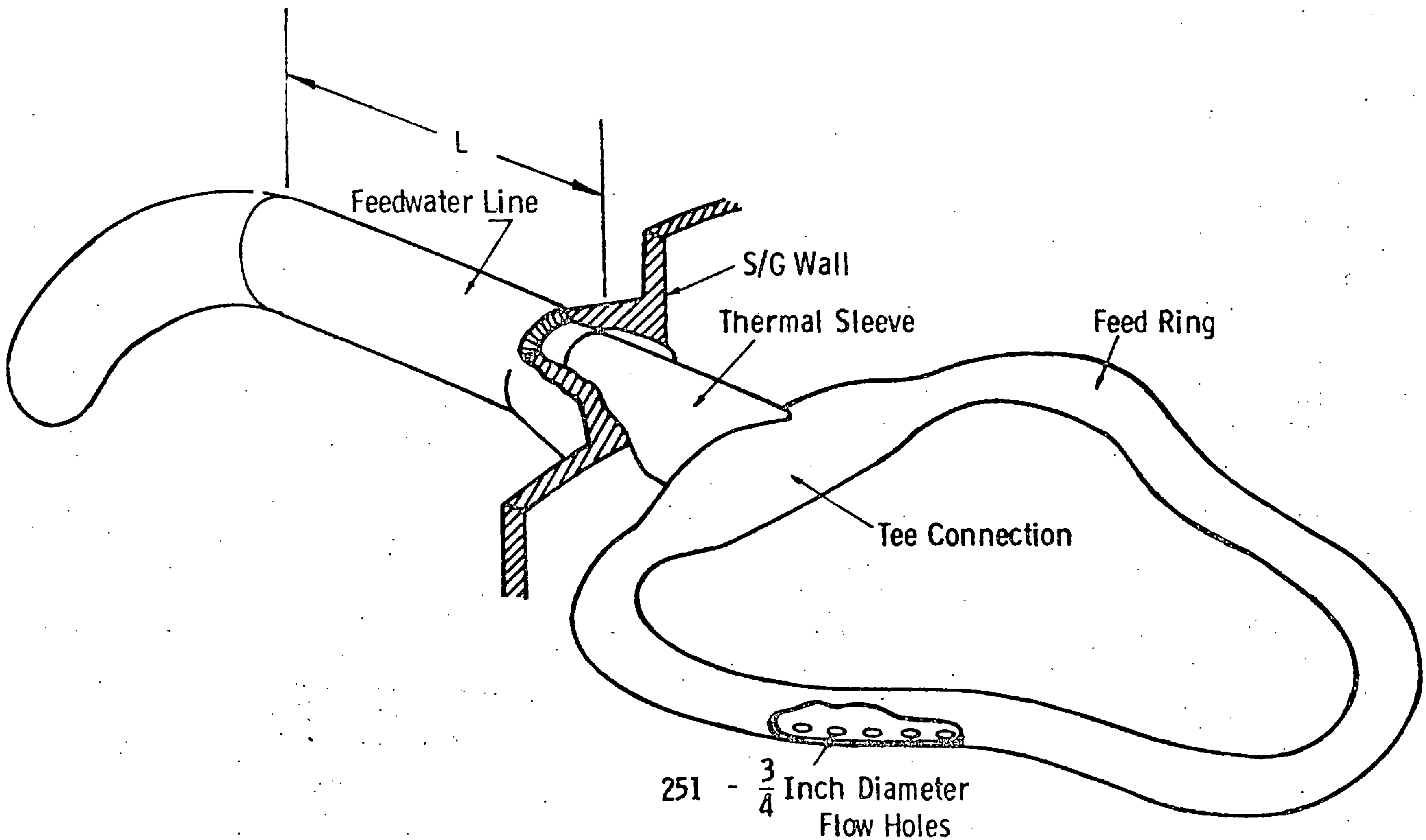

Fig. 2— Feedring assembly

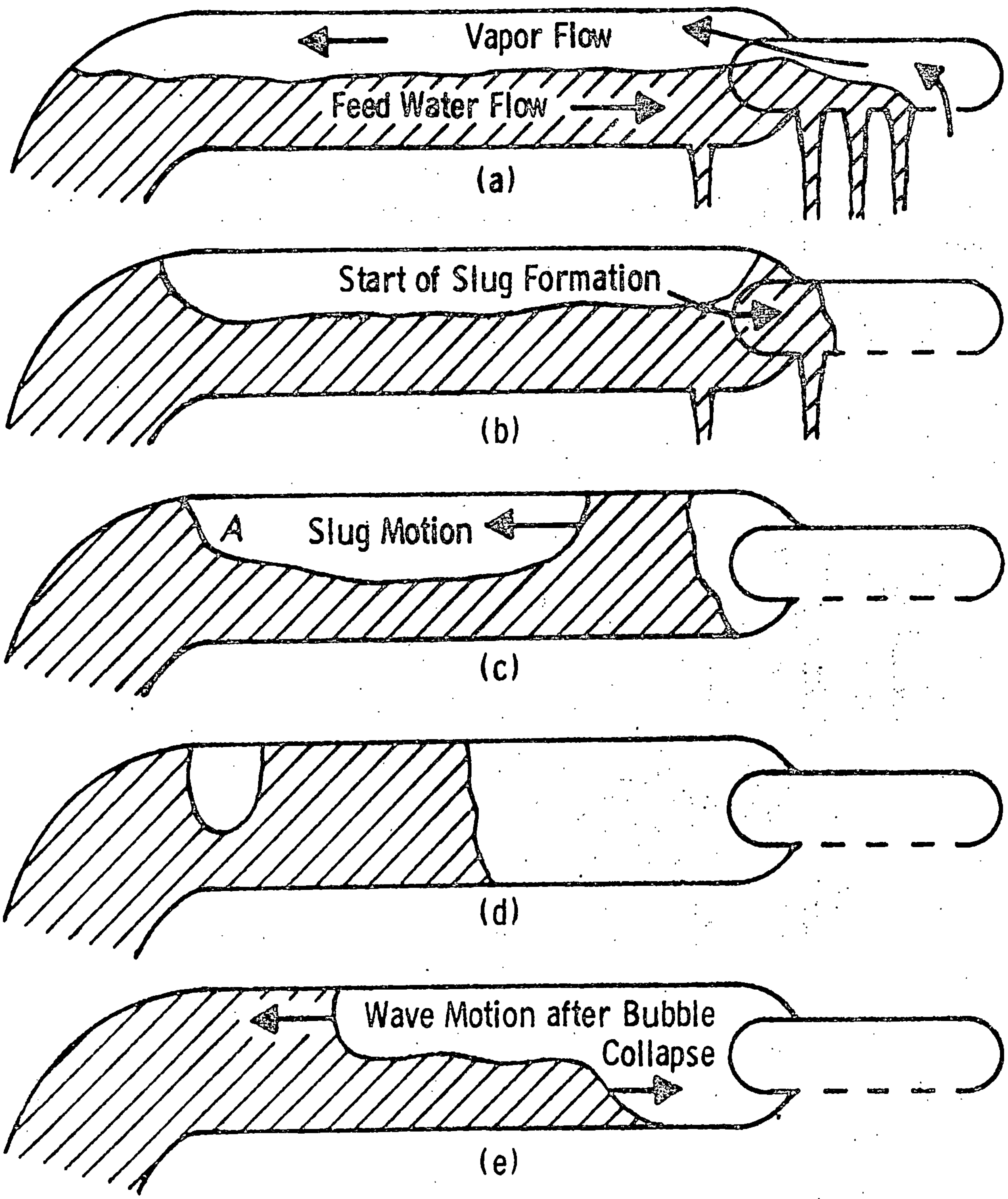

Fig. 3 – Schematic representation of slugging mechanism

APPENDIX 2

LOCATION OF AUXILIARY FEEDWATER CONNECTIONS

The location of the auxiliary feedwater (AFW) connections to the main feedwater line in the Salem plant have been compared to other Westinghouse PWR plants having Series 44 or 51 steam generators (feed ring type). In general, the AFW lines connect to the main feedwater lines a short distance downstream of the main feedwater check valves. In over two thirds of the plants the AFW connection is outside the containment boundary, usually a short distance upstream of the containment penetration. In these plants the main feedwater line enters the containment at a low elevation. Then at some point near the steam generators the feed line rises to the elevation of the steam generator feedwater nozzle (20'). The actual length of main feedwater piping between the AFW connection and the steam generator is variable even within each plant depending on the steam generator location with regard to other plant layout features and whether or not the AFW connection is inside or outside containment. Typical main feedwater line pipe lengths between the AFW connection and the steam generators where the connection is outside containment range from about 75 ft to 180 ft (eg, D.C.Cook, 76-81; Indian Pt., 158-181). The lengths of main feedwater pipe where the connection is inside containment range from about 60 to 100 ft (Point Beach 60' - 100'; Zion, 63' - 89'). The Salem plant reflects the typical layout in that the AFW connections are outside containment, the main feedwater line enters containment at a low elevation and rises about 47' near the steam generator and about another two feed just upstream of the nozzle. The length of the main feedwater pipe between the AFW connection and the steam generator ranges from about 105' to 128'.

The question may be raised as to whether or not the location of the AFW connection has any bearing on the water hammer susceptability. As noted above, the connection is invariably a considerable distance from the steam generator and at a lower elevation. Also, the water hammer experience to date has not indicated a sensitivity to where the AFW connection is located. Incidents have occurred at Surry where the connections are inside containment and relatively near the steam generators, and at Indian Point where they are outside containment and quite a distance from the steam generators. In addition, the presence of cold feedwater in the horizontal main feedwater line connected to the steam generator is inevitable at low power and hot shutdown conditions. At normal auxiliary feedwater flows the cold water will enter the feed ring in about two to five minutes after system actuation. Thus, one of the conditions for water hammer will exist regardless of the location of the AFW connections. For these reasons it is concluded that water hammer is not sensitive to the point where the cold auxiliary feedwater enters the main feedwater system in typical PWR plants.