UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

BEFORE THE ATOMIC SAFETY AND LICENSING BOARD

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| In The Matter of | ) | |
| | ) | |
| COMMONWEALTH EDISON COMPANY | ) | Docket Nos. 50-454 OL |
| | ) | 50-455 OL |
| (Byron Nuclear Power Station, Units 1 & 2) | ) | |

AFFIDAVIT OF ROBERT W. CARLSON

The attached questions and answers constitute my testimony in the above-captioned proceeding. The testimony is true and accurate to the best of my knowledge, information and belief.

Robert W Carlson
Robert W. Carlson

Subscribed and sworn to before me this 4th day of June, 1982.

[signature]
Notary Public

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# TESTIMONY OF ROBERT W. CARLSON

Q1: Please state your name, present position, and present occupation.

A1: My name is Robert W. Carlson. I work for the Westinghouse Electric Corporation. I am a Principal Engineer in the Balance of Plant Systems Design Group of the Nuclear Technology Division.

Q2: Could you please describe your educational and professional background?

A2: I received a Mechanical Engineering degree from Stevens Institute of Technology in 1953 and a Master of Science degree in Nuclear Engineering from Massachusetts Institute of Technology in 1959. I also attended Case Institute of Technology for two years, from 1965 to 1967, as a full-time graduate student in the field of Thermal Sciences.

I accepted a position in 1953 as a Boiler Division student engineer with the Babcock & Wilcox Company. After the one-year program, I joined the Babcock & Wilcox Atomic Power Division. In 1955, I took a leave of absence for military service and MIT Graduate School. I returned to Babcock & Wilcox in 1959 and was later promoted to the position of Senior Engineer with the Atomic Power Division.

I joined the Westinghouse PWR Division as a Senior Engineer in 1967. My initial duties were as a reactor core thermal and hydraulic designer. In 1975, I was promoted to my present position of Principal Engineer.

Since 1977, I have been intimately involved in test programs designed to investigate the bubble collapse waterhammer phenomenon in steam generators. In 1977, Westinghouse initiated a test program to investigate and define the effects of this type of waterhammer in the two different preheat steam generator designs. I designed the 1/8th scale test models for the Byron Station type steam generators and supervised the related testing program.

I meet, on behalf of Westinghouse, with utility customers and their architect-engineers to provide assistance in the design and operation of the plant modifications recommended by Westinghouse to minimize the likelihood of bubble collapse waterhammer. One of these systems, the Feedwater Bypass System, has been installed at the Byron Station. I also provide assistance with respect to start-up testing of operating plants to verify that the Feedwater Bypass System performs as designed.

Q3: To which Contention is this testimony addressed?

A3: DAARE/SAFE Contention 9a. The Contention reads as follows:

> "Intervenors contend that there are many unresolved safety problems with clear health and safety implications and which are demonstrably applicable to the Byron Station design, but are

not dealt with adequately in the FSAR. These issues include but are not limited to:

a. Serious waterhammer problems. We understand that a waterhammer caused by rapid condensation of steam in feedwater lines of a PWR constitutes the most serious of this sort of event. Damage to pipes and valves are some potential hazards. Ultimately, under the most serious circumstances successive waterhammer incidents might lead to a loss-of-coolant accident. Applicant has already had waterhammer problems in its Zion plant in 1977, and a plant shutdown was required to repair the damage. The similarity of plant equipment, management, and operator training programs between the Zion and Byron stations raises serious questions about the Applicant's ability to operate the Byron plant safely, with respect to waterhammer phenomenon. Evidence with respect to demonstrated efficacy of new nozzle designs to be used at Byron to mitigate waterhammers is not presented at FSAR 10.4.7.3."

Q4: Could you please describe the waterhammer phenomenon?

A4: In general, there are two forms of waterhammer, classical and bubble collapse. In both cases, a change in water velocity requires a change in pressure because of the inertia of the water. The two forms differ with respect to the mechanisms by which the change in velocity is brought about. An example of classical waterhammer would involve the following sequence of events. As water flows through a pipe, a valve at the downstream end of the pipe is closed quickly. The water flowing in the pipe will be brought to rest and as a consequence a pressure increase will result at the valve. This change in pressure will travel back and forth in the pipe until it dissipates due to friction.

Bubble collapse waterhammer refers to a situation where initially a bubble of steam is formed within an enclosed region, for example, within a section of pipe, with water slugs on both sides. If the temperature of the water in the slugs is the same as the temperature of the steam, nothing will happen. However, if colder water comes into contact with the steam, it will condense rapidly resulting in a sudden decrease in pressure. The higher pressure behind the water slugs will cause them to accelerate towards each other. When they impact, an increase in pressure will result. This change in pressure will propagate back and forth in the water similar to the classical waterhammer case.

The magnitude of the pressure change produced at the valve in the classical waterhammer example depends on the rate at which the valve is closed, the initial water velocity, and the density of the water. In the bubble collapse waterhammer example, the pressure change magnitude depends on the rate at which the steam is condensed and the pressure behind the water slugs.

Q5: What are the potential effects of waterhammer?

A5: Waterhammer, whether classical or bubble collapse, will result in a change in water pressure. The change in pressure has the potential for damaging piping system components, for example, the pipe itself or valves. The pressure change, if large enough, may produce pipe wall deformation and in severe cases, even rupture. It may also result in valve damage, for example, damage to valve packing and gaskets. The change in water pressure inside the system is accompanied by forces transmitted to the pipe supports. These, in turn, may also be damaged.

With respect to structures such as the steam generator, waterhammer could result in deformation of internal components such as baffle plates, possibly degrading the steam generator performance.

Q6: Which type of waterhammer does the Contention refer to?

A6: The Contention as I understand it refers specifically to bubble collapse waterhammer and in a general way alludes to classical waterhammer. Specific reference is made to the bubble collapse waterhammer events caused by rapid condensation and the problem which occurred at the Zion Station which was caused by a bubble collapse waterhammer.

Q7: Could you please describe the Byron Station steam generator design?

A7: Before discussing steam generator features, the terms primary side and secondary side should be explained. The primary side and secondary side of the steam generator refer to the fluid volumes inside and outside the steam generator tubes, respectively. The steam generator is one of the components in the primary loop which includes the reactor. The primary side water carries thermal energy from the reactor core to the steam generator. The hot primary water is directed into the inlet half of the inverted U shaped tube bundle. The first part of the bundle where the primary water flows upward is referred to as the hot leg side. The second part where the water flows downward is referred to as the cold leg side because the primary water is somewhat cooler having given up some of its thermal energy.

The secondary side is the volume outside the tube bundle and inside the steam generator vessel. During normal operation, the lower part of the vessel contains water and the upper part steam. The fact that both steam and water are present on the secondary side account for bubble collapse waterhammer being a design consideration.

There are two basic types of Westinghouse steam generators, the feedring type and preheat type. In the former, the main feedwater nozzle is located in the upper shell. The feedwater is distributed internally by means of a feedring. In the latter, the main feedwater nozzle is located in the lower shell where the feedwater enters a baffled tube bundle preheater region. A smaller diameter auxiliary nozzle is located in the upper shell and is used during low power operation and for addition of auxiliary feedwater.

The Byron plant has steam generators of the preheat type referred to by Westinghouse as the D Model. Within the preheat classification, there are two subtypes: the split flow type (D2 and D3) and the counterflow type (D4 and D5). The Byron No. 1 unit has Model D4's and Byron No. 2 unit has Model D5's. The counterflow type (Models D4 and D5) is shown in Figure 1. For purposes of this discussion, the difference in design between Models D4 and D5 steam generators is not relevant.

In the Byron models, the main feedwater nozzle is located in the lower shell. The overall height of the Byron generators is approximately 68 feet. The main 16 inch feedwater nozzle is located approximately 13 feet from the bottom of the vessel. The 6 inch diameter auxiliary nozzle is approximately 45 feet from the bottom of the vessel.

A diagram showing the preheater region of the Byron steam generators is presented in Figure 2. The main features are a vertical partition plate, five horizontal baffle plates, and a waterbox. The partition plate divides the lower part of the tube bundle into two halves, the hot leg side and the cold leg side. The preheater section is located on the cold leg side. The waterbox guides the entering feedwater into the preheater first pass. From this point, the feedwater is directed by the baffle plates back and forth across the tube bundle in a generally upward direction. The crossflow path and relatively high water velocities maximize the transfer of thermal energy from the primary to secondary sides.

The auxiliary nozzle is part of the feedwater bypass system, the purpose of which is to minimize the likelihood of bubble collapse waterhammer in the preheater region of preheat type steam generators.

Q8: Please explain how the feedwater bypass system addresses the bubble collapse waterhammer phenomenon.

A8: As stated earlier, one of the elements required for bubble collapse waterhammer to take place is cold water. Cold water acts as a heat sink which causes the condensation of the steam and therefore collapse of the bubble. In those circumstances where it is necessary to introduce cold water into the steam generator, the bypass system operates to direct the cold water to the upper auxiliary nozzle.

The basics of the feedwater bypass system as implemented at the Byron Station are shown in Figure 3. The system includes a 16 inch main feedwater line which connects to the main feedwater nozzle and four principal valves, the feedwater control valve, the feedwater control bypass valve, the check valve and the feedwater isolation valve. A smaller diameter bypass line, 6 inches in diameter, connects the main feedwater line, between the check valve and the feedwater isolation valve, to the auxiliary nozzle. The bypass line itself contains an isolation valve and two check valves.

Q9: On what is the design of the feedwater bypass system based?

A9: The design of the feedwater bypass system and the manner in which it should be operated are based on results of a comprehensive waterhammer test program carried out by Westinghouse, under my supervision, in 1977 and 1978. One-eighth scale models of the counterflow and split flow preheat steam generator designs were tested at plant operating conditions, including pressures up to 1,000 psia. The test objective was to determine those conditions where bubble collapse waterhammer would occur in the steam generator and immediately adjacent upstream feedwater piping. All the tests consisted of two steps: first, establishing conditions where steam would be present in the preheater region, and, second, introducing water at different conditions to condense the steam.

Two different type tests were conducted. In one, referred to as Type A, the water level in the test vessel was lowered below the preheater section, a situation which could conceivably occur following the faulted condition of a main feedpipe rupture. Once the water level was verified to be below the preheater section, feedwater was introduced through the feedwater nozzle. Any pressure pulses resulting from waterhammer were measured and recorded. In the second type, Type B, the water level was maintained above the preheater section and steam was generated in the preheater region by means of electrically heated rods which simulated the steam generator tubes. Again, after the desired conditions were established, feedwater was introduced through the feedwater nozzle and any pressure pulses produced were measured and recorded. The Type B condition simulated normal and upset conditions such as plant loading and are considered in the fatigue analysis of the steam generator.

Recognizing that the presence of air in the test apparatus would influence the results of the test, special pretest degassing procedures were implemented prior to each test series to drive off most of the air present. In addition, several water samples were taken from the test apparatus during each test to verify that the degassing procedure was effective.

As discussed earlier, initial water level in the test vessel was a test variable. The other principal variables were test pressure, feedwater flowrate, and feedwater temperature. Tests were conducted at different pressures up to steam generator normal operating pressure. The feedwater temperature was varied from ambient of approximately 80°F to 250°F.

In applying the test data to the design of the steam generator, it was necessary to consider a scale effect, that is, how to apply test data obtained from a 1/8th scale model to the full size unit. A major effort, involving two independent consultants, was undertaken to address this issue. The unanimous conclusion was that in applying the scale model results to the full size unit the pressure change magnitudes scale one to one and the pressure change time durations scale one to eight.

The most significant result of the test program was that waterhammer did not occur if the temperature of the feedwater was 250°F or higher. The design of the feedwater bypass system is based largely on this result. Results of this test program also indicated that the number of waterhammer occurrences was significantly reduced at the high pressures at which the steam generator normally operates.

Although this further reduces the likelihood of a waterhammer event, no credit was taken for this finding in designing the bypass system.

In order to assure that introducing water at a temperature of less than 250°F at the upper auxiliary nozzle would not result in a waterhammer in the preheater, we conducted an additional series of tests. In these tests cold water was introduced at the bottom of the preheater section. No waterhammer events were detected.

Q10: Can you please describe how the feedwater bypass system at the Byron Station will operate?

A10: The feedwater bypass system as implemented at the Byron Station will automatically determine which nozzle, main or auxiliary, is used for supplying feedwater to the steam generator. During the plant loading operation, the sytem will automatically switch feeding from the auxiliary to the main nozzle only when the following criteria are satisfied:

(1) A minimum feedwater flowrate of approximately 20% of the full power flowrate is provided.

(2) The feedwater temperature as measured at the low points in the main feedwater piping is 250°F or higher.

(3) The section of main feedwater piping between the bypass line branch point (Point A, Figure 3) and the main feedwater nozzle has been purged of cold water.

(4) The steam generator pressure is greater than 700 psia.

(5) The steam generator water level is within a specified range.

The fact that all five criteria must be satisfied before feedwater is introduced through the main nozzle makes it extremely unlikely that cold water will be introduced through the main nozzle.

When the plant is being unloaded, the feedwater flow is automatically switched from the main to the auxiliary nozzle when the flowrate drops to slightly below the value for loading. This will prevent flipflopping of the flow between the main and auxiliary nozzles by the control system.

Q11: To your knowledge, will there be procedures by which the Byron feedwater bypass system will operate?

A11: General feedwater bypass system operating procedures for the Byron Station steam generators have been prepared by Westinghouse and transmitted to Commonwealth Edison Company.

Q12: The Contention refers to the waterhammer problems experienced at Zion in 1977. Are you familiar with these matters?

A12: Yes, I am. In Unit 1, waterhammer occurred while a feedwater control valve was being cooled to permit repair. Cold feedwater was being fed through the valve into the steam generator and apparently came into contact with a steam volume resulting in a waterhammer event. In Unit 2, bubble collapse waterhammer occurred during the refilling of steam generators following a plant trip. The feedwater supplied by the Auxiliary Feedwater System was cold. When the flowrate was increased above the recommended value, waterhammer occurred.

Q13: Has the design of the Zion steam generators been modified as a result of these waterhammer events?

A13: Yes, the design has been modified. To facilitate the understanding of the modifications, I should first describe Zion steam generators. The Zion Station Model 51 steam generator is illustrated in Figure 4. Feedwater is introduced through a single 16 inch nozzle in the upper portion of the vessel. The unit does not have an auxiliary nozzle similar to the Byron Station steam generator. The overall height of the vessel is approximately 68 feet, the same as the Byron Station steam generator. The main feedwater nozzle is located approximately 46 feet from the bottom, about the same elevation as the Byron Station auxiliary nozzle. Internally, the nozzle connects to a feedring, a lobed ring which serves to distribute the feedwater within the cross-sectional area of the upper vessel. Normally, the water level in the vessel is above the ring (with steam above the water).

Bubble collapse waterhammer could occur with the original Zion feedring design and adjacent piping as a result of the following sequence of events. First, the steam generator water level falls below the feedring and as a consequence the water in the feedring and adjacent piping drains into the steam generator through flow holes around the bottom of the ring. Second, cold water is introduced through the main feedwater line at such a flowrate that a pocket of steam is trapped and subsequently is condensed by the cold water. A slug of water rushes in to fill the void, impacting on a water interface or the pipe, creating a pressure change.

A number of design changes and changes to the operating procedures were implemented at Zion to address these problems. The most important design change was to provide J tubes on the feedring and close off the ring bottom flow holes. The J tubes are short tube sections shaped like the letter J which are welded in an inverted position along the top surface of the feedring as shown in Figure 5. The feedwater entering the feedring flows up through the J tubes and then, because of the J shape, is directed downward. The purpose of the J tubes is to prevent draining of the feedring when the water level falls below it. In the case of the Zion steam generator, J tubes do not prevent the feedring from draining, but slow it down. There is another much smaller flow path through which the feedring can drain, an annular gap between the inside of the nozzle and the pipe section connecting the nozzle to the feedring.

In addition to the J tube modification discussed above, Zion also limits the maximum flowrate during refilling following a reactor trip. To my knowledge, bubble collapse waterhammer in the feedring and adjacent feedpipe sections has not been observed in any Westinghouse plant with feedring type steam generators after the installation of J tubes and where the feedwater flowrate is administratively controlled.

Q14: Is the design of the Byron steam generators different from the design of the Zion steam generators?

A14: Yes, the designs are significantly different. Zion and Byron Station have different types of steam generators, each with its own set of design features to minimize the probability of bubble collapse waterhammer. The Zion Station steam generators are Westinghouse Model 51 feedring units, with J tubes installed on the feedring to minimize waterhammer events.

The Byron Station steam generators are Westinghouse Model D4 and D5 preheat units. The Byron steam generator design includes a feedwater bypass system. This system and associated operating conditions are based on extensive test program data, and provides reasonable assurance that bubble collapse waterhammer events do not pose a threat to safety.

Q15: Are you aware of the waterhammer event that occurred at KRSKO?

A15: Yes, I am.

Q16: Can you please describe that event and its relevance to operation of the Byron Station?

A16: A bubble collapse waterhammer event is believed to have occurred at the KRSKO Nuclear Power Plant, which contains a Westinghouse NSSS, during July 1981 hot functional testing. The first indication of an unusual event was the discovery on August 9, 1981 that the paint was blistered on the Auxiliary Feedwater System piping. Apparently, hot water and/or steam from the associated steam generator had pushed back into the normally ambient temperature system.

The Auxiliary Feedwater System is a safety grade source of feedwater to the steam generators following a loss of heat sink accident, such as a feedpipe rupture. It is also a safety grade source of feedwater to achieve and maintain plant shutdown condition. It connects to the bypass feedwater line of each steam generator.

Further examination revealed that the feedwater bypass piping between the point of connection of the Auxiliary Feedwater System and the auxiliary nozzle had suffered a small permanent displacement and some bulging of about 1/4th inch in the area of the secondary shield wall.

The evidence indicates that the damage was a result of bubble collapse waterhammer in the bypass line. Steam and/or hot water had apparently pushed back into the bypass line and then into the Auxiliary Feedwater System piping. Subsequently, the Auxiliary Feedwater System pumps were started introducing cold water into the piping. Thus, the two elements needed for a waterhammer event were present, i.e., a volume of steam and cold water.

For steam generator hot water and/or steam to push back into the piping required that the check valve provided to prevent reverse flow in the Auxiliary Feedwater System was leaking. In addition, if steam, and not hot water, was pushed back into the piping the steam generator water level was below the auxiliary nozzle internal extension.

As a consequence of the KRSKO experience, Westinghouse has recommended that several additional measures be taken to avoid bubble collapse waterhammer events in the bypass system. The recommendations are:

(1) Temperature measurements should be provided on the bypass piping to detect backleakage of hot water or steam. If backleakage is detected, the piping should be slowly refilled at the rate specified or the plant brought to a cold shutdown condition, depending on the circumstances.

(2) The steam generator water level should be maintained above the auxiliary nozzle discharge pipe so that if backleakage does occur, water and not steam will leak back into the pipe.

(3) The bypass line check valve and the Auxiliary Feedwater System check valve should be maintained to minimize backleakage.

Q17: Do you have an opinion as to whether these recommendations are adequate?

A17: Yes, if these recommendations are adopted and implemented, the likelihood of occurrence of a KRSKO-type water hammer event is greatly reduced. Therefore, it is my opinion that the steam generator bypass system design, with the KRSKO modifications described earlier, is adequate to minimize the likelihood of bubble collapse waterhammer events in the steam generators to an acceptable level.

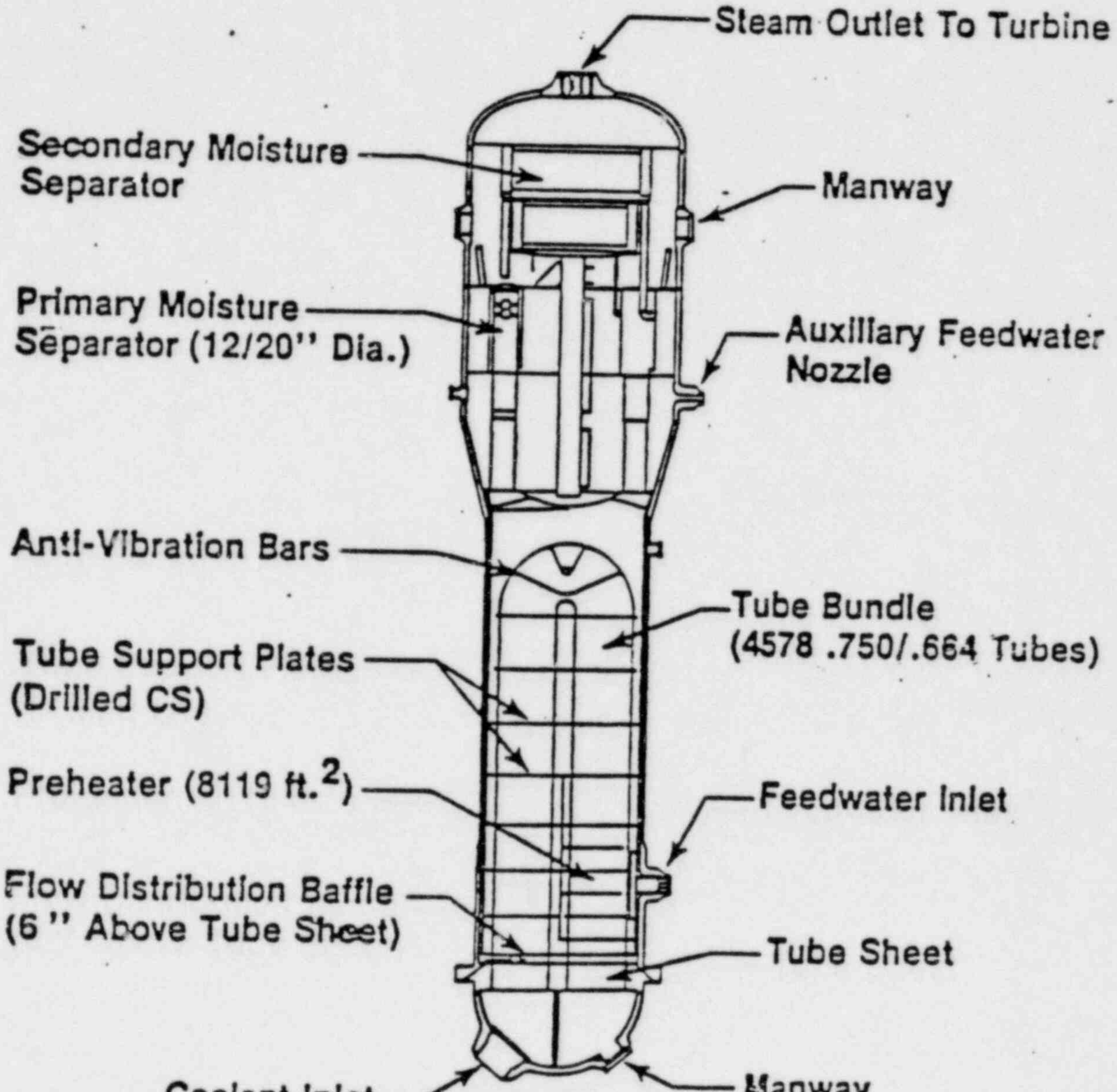


Figure 1
Byron Station Preheat Type Steam Generator

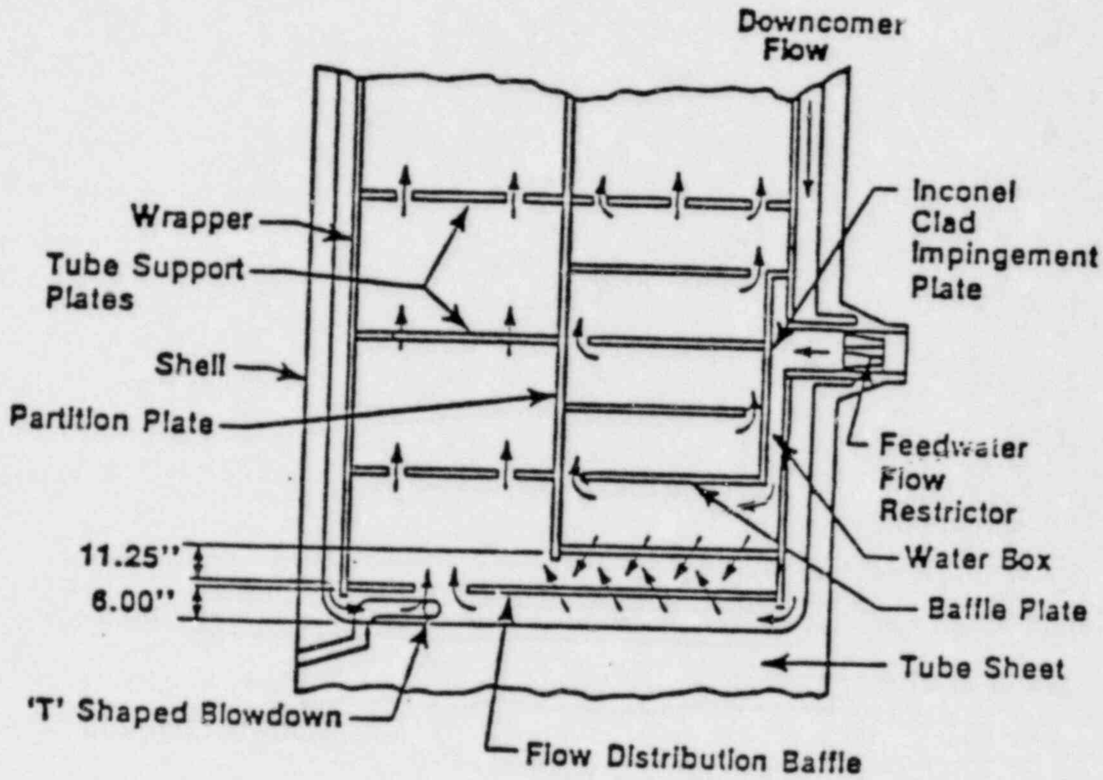


Figure 2
Model D4 & D5 Counterflow Steam Generator
Main Feedwater Nozzle & Preheater

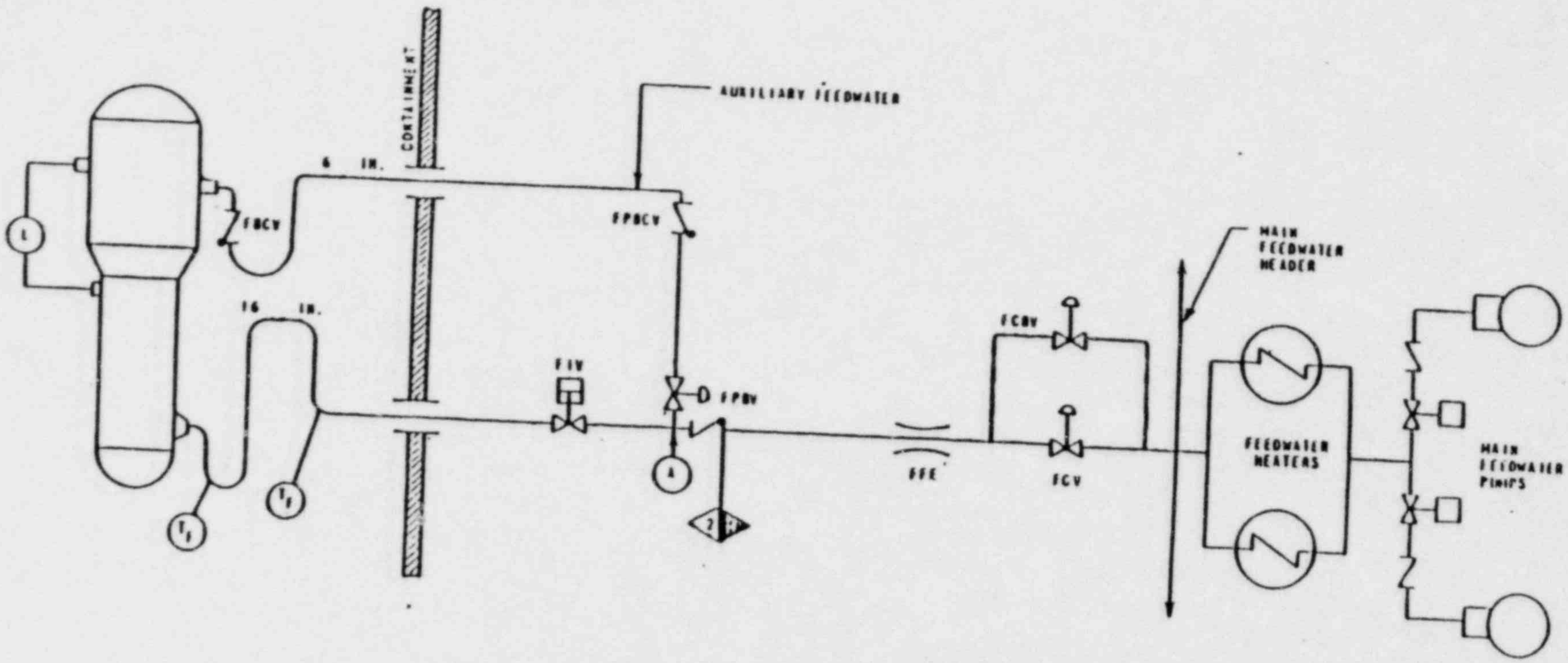


Figure 3

Main Feedwater Bypass Arrangement

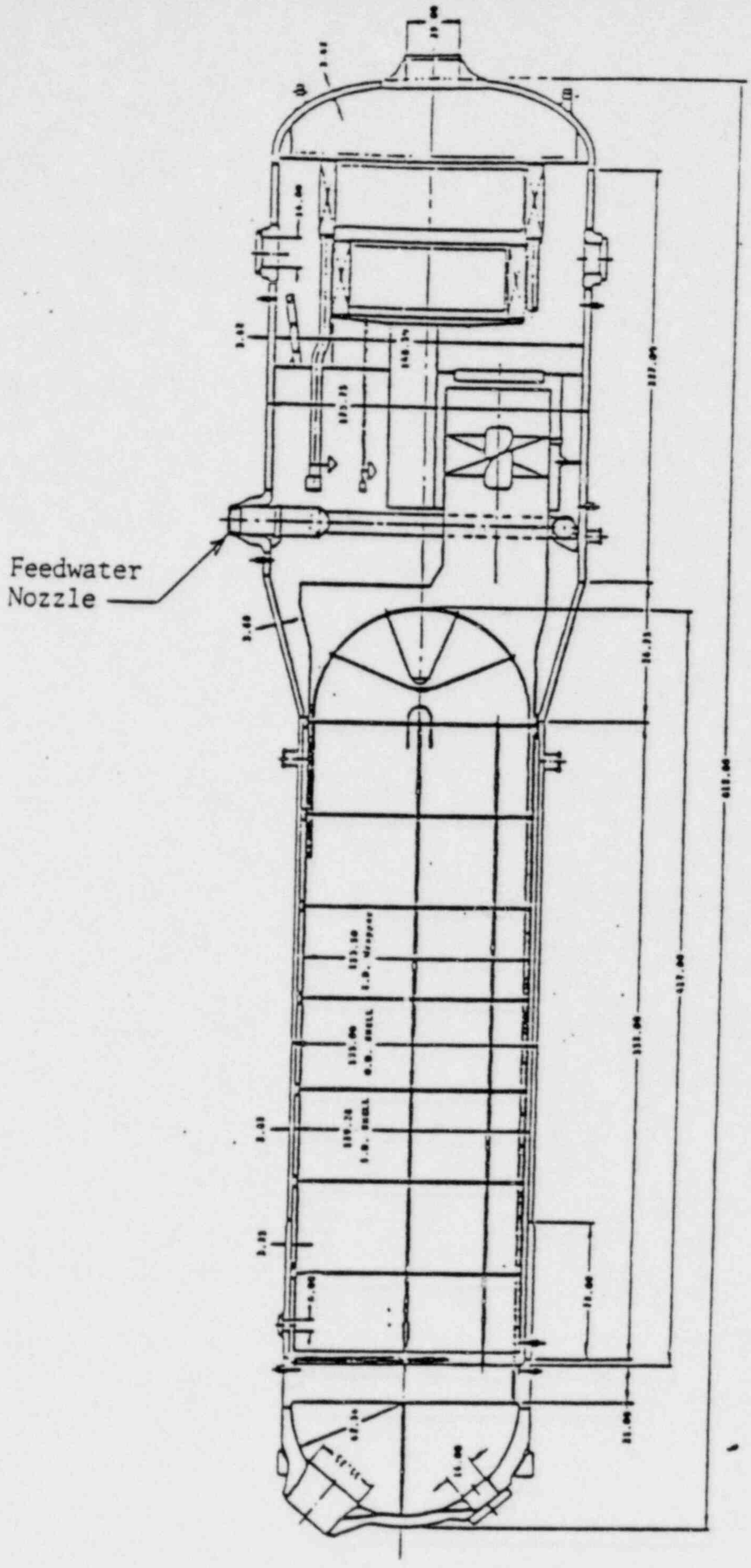


Figure 4
Zion Station Feedring Type Steam Generator

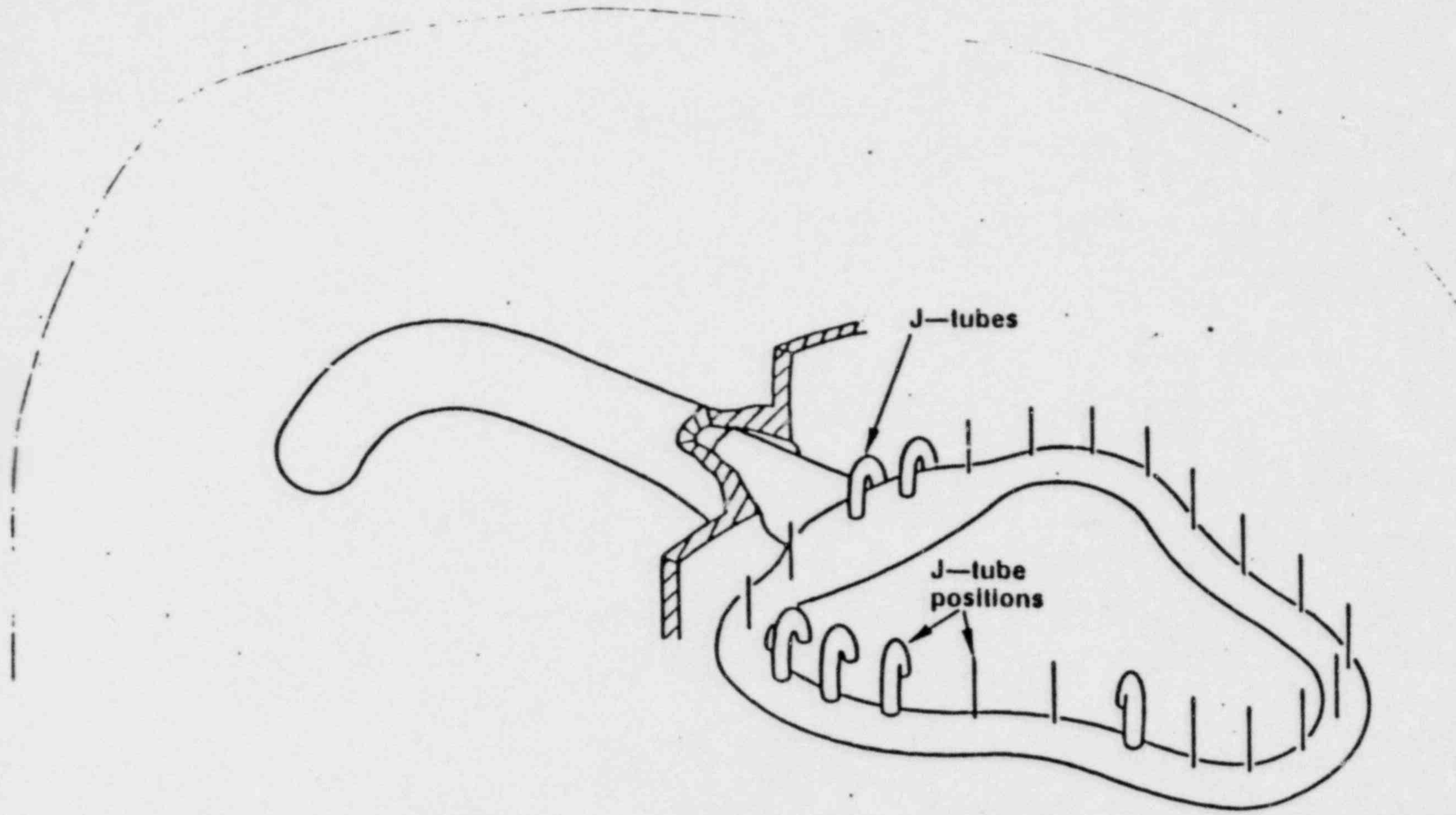


Figure 5

Typical Feedring - J Tube Design