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Enclosure 3

COOPER NUCLEAR STATION

NON-PROPRIETARY REPORT

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“Evaluation of Steam Ingestion
in the ECCS Suction Strainers”
for
Cooper Nuclear Station

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Cooper Nuclear Station
Containment Analysis Project,
Evaluation of Steam Ingestion in the Emergency Core Cooling (ECCS) Suction Strainers

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EXECUTIVE SUMMARY

At the request of the Nebraska Public Power District (NPPD), an evaluation of the likelihood of steam ingestion in the Emergency Core Cooling System (ECCS) suction strainers during Safety Relief Valve (SRV) actuation was performed for the Cooper Nuclear Station. The analysis was based on input received from NPPD and the conservative assumption that the suppression pool is locally saturated in the region around the SRV quenchers and ECCS suction strainers.

The analysis was performed for the Residual Heat Removal (RHR) and the Core Spray (CS) suction strainers. Suction strainers for High Pressure Core Injection (HPCI) and the Reactor Coolant Inventory Control (RCIC) systems were also investigated and determined not to be at risk. The size of the steam plume generated from a SRV quencher and the envelope of flow drawn into the suction strainers were evaluated to see if there was overlap, which could result in steam ingestion. The results of these evaluations show that the steam plume, resulting from the activation of the SRV, whose quencher is located closest to a suction strainer, does not intersect either the suction strainers or the envelope of flow (entrainment envelope) drawn into the strainer when the reactor is operating at the maximum SRV set-point pressure. The analysis assumes no RHR operation. With the RHR operating in the pool cooling mode, there is sufficient pool mixing to avoid local conditions in the pool that are necessary for the steam plume to exist.

The steam ingestion analysis has considered the most limiting geometry and steam ingestion was not predicted. It is concluded that steam ingestion will not limit ECC system operation at the Cooper Nuclear Station.

ACKNOWLEDGEMENT

The author acknowledges the previous work by Fred Moody and Jiny Ree in developing the steam ingestion models used in this study. Also, the verification of the study by Fred Moody and Charles Sayes. Finally, the help and timely support of Brian McClanahan and the detailed review by John Wright, both from the Cooper Nuclear Station.

1.0 INTRODUCTION

The objective of this analysis is to conservatively evaluate the likelihood of steam ingestion into the Emergency Core Cooling System (ECCS) suction strainers during Safety Relief Valve (SRV) actuation. Work on this analysis is authorized under WIN number 435-10 [1]. At the Cooper Nuclear Station, suction strainers are used on the Reactor Heat Removal (RHR), Core Spray (CS), High Pressure Core Injection (HPCI) and the Reactor Core Isolation Cooling (RCIC) systems, all of which draw cooling water from the suppression pool. Of those systems, the suction strainers on the RHR and CS systems are the most likely to be subject to steam ingestion because of their location with respect to nearby SRV quenchers. The suction strainers for the RHR and CS systems are located in suppression pool bays adjacent to quenchers and both systems are used for accident mitigation. The suction strainers for the HPCI and RCIC systems are located in the same torus bays as quenchers but below the quencher arm and far enough away that ingestion is not a problem. Also, the RCIC system is not accident mitigating and not expected to be in continuous operation when torus temperatures are elevated.

In those suppression pool bays containing an ECCS suction strainer, which are also near an SRV discharge quencher, the top of the suction strainer is near or slightly above the elevation of the quencher arm. Steam discharge from the quencher, when the pool has become saturated or nearly saturated, will provide a source of steam that could be drawn into a strainer. Steam leaving the SRV quenchers is expected to form a circular plume over the end of each quencher arm. Near the steam plume, relatively high velocities will be induced in the pool, while the velocities induced by the suction flow into the strainers, a short distance away from the strainer, will be very low. Therefore it is unlikely that the plume itself would be sucked into the strainer. Steam entrainment could occur if the plume is sufficiently large that it intersects the strainer, or if individual steam bubbles from the plume boundary are drawn into the strainer. To investigate if entrainment is possible, estimates are made of both the size of the quencher steam plume, to insure it does not intersect the strainer, and of the envelope of flow into the strainer, to make sure it is not intersected by the steam plume.

Reference 5 examines the likelihood of steam ingestion into ECCS strainers for the FitzPatrick Nuclear Power Station. The analysis performed here uses similar models as were used for the FitzPartick study. When appropriate, conclusions are drawn from the work performed for FitzPatrick.

2.0 ASSUMPTIONS

Plant parameters used in this analysis are listed in Appendix A. In addition, several assumptions were made when necessary to obtain a conservative evaluation of whether steam ingestion will occur. These assumptions are as follows:

1. The suppression pool is at its saturation temperature in the region surrounding the SRV discharge quenchers. Under these conditions, steam bubbles from the SRV quenchers will persist in the suppression pool.
2. RHR operation in the pool-cooling mode is not considered since locally saturated conditions will not occur in the pool with the mixing provided by RHR operation.
3. The quencher steam flow is based on the SRV technical specification maximum set-point limit pressure of 1133 psig.
4. (See footnote)*
5. The steam discharge from the SRV quencher expands isentropically from the reactor pressure to the pressure in the pool at the quencher submergence.
6. The ECCS flows are taken to be at the maximum of the various operational modes for each system.
7.
8. Ingestion into the suction strainer is assumed to occur if the quencher steam plume intersects either the suction strainer or the entrainment envelope for flow into the strainer.

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* Proprietary information to the General Electric Company has been deleted

3.0 APPLICATION TO THE COOPER NUCLEAR STATION

As noted earlier, at the Cooper Nuclear Station suction strainers are used on the Reactor Heat Removal (RHR), Core Spray (CS), High Pressure Core Injection (HPCI) and the Reactor Core Isolation Cooling (RCIC) systems, all of which draw cooling water from the suppression pool. Of those systems, the strainers on the RHR and CS systems are the new GE optimized stacked-disk strainer design. Strainers on the HPCI and RCIC systems are the original basket strainer design, where the suction line entering the side-wall of the suppression pool is connected to the side branch of a piping tee, and basket strainers are attached to each end of the tee. The Cooper suppression pool is shown in Figure 1, which also shows the SRV discharge quenchers and locations of the ECCS suction strainers in the suppression pool. Every other bay in the Cooper pool contains a quencher. The RHR and CS suction strainers are located in alternate bays, where there are no quenchers. The HPCI and RCIC strainers are located in suppression pool bays that contain an SRV quencher, but these suction strainers are located below the quencher.

3.1 Bulk Pool Velocity

An important assumption in the steam ingestion analysis is that the water in the pool near the quencher is at saturated conditions. The mixing provided by even one RHR loop in operation makes that condition unlikely. In Figure 1, the direction of discharge of the RHR jets is shown. This RHR discharge will force clockwise circulation of the pool. To estimate bulk pool velocity, the momentum imparted to the pool by the RHR jets is balanced against the irreversible losses for flow in the pool. There are several contributors to the pressure loss including wall friction, the contraction/expansion of the flow passing over the ring girders connecting the torus bays, and the drag on the LOCA downcomers and other hardware in the pool. Assuming that major losses for pool flow come from flow over the ring girders and the drag on the LOCA downcomers, the bulk pool velocity for one RHR pump in operation was calculated to be 0.9 ft/s. For both RHR loops in operation, each loop with one pump, the bulk pool velocity was 1.3 ft/s and with all four RHR pumps, two pumps per loop and assuming two pumps deliver twice the flow of one pump, the bulk velocity was calculated to be 2.5 ft/s.

It can be seen in Figure 1 that the direction of bulk pool motion is towards the strainers and away from the quenchers for the CS strainer in Bay 15 and for the two RHR strainers in Bay 7. Only these strainers would be affected by bulk pool motion, since pool motion will tend to sweep steam bubbles away from the other RHR and CS strainers. Note that the RHR discharge nozzles are located in the next bay upstream from these two quenchers, which should provide even greater mixing than at other quencher locations. The mixing provided by the bulk pool motion, nearly 1 ft/s with only one RHR, and the close proximity to the RHR discharge nozzles should prevent locally saturated conditions from developing in the pool near the quenchers. Therefore, the effects of bulk pool motion need not be considered.

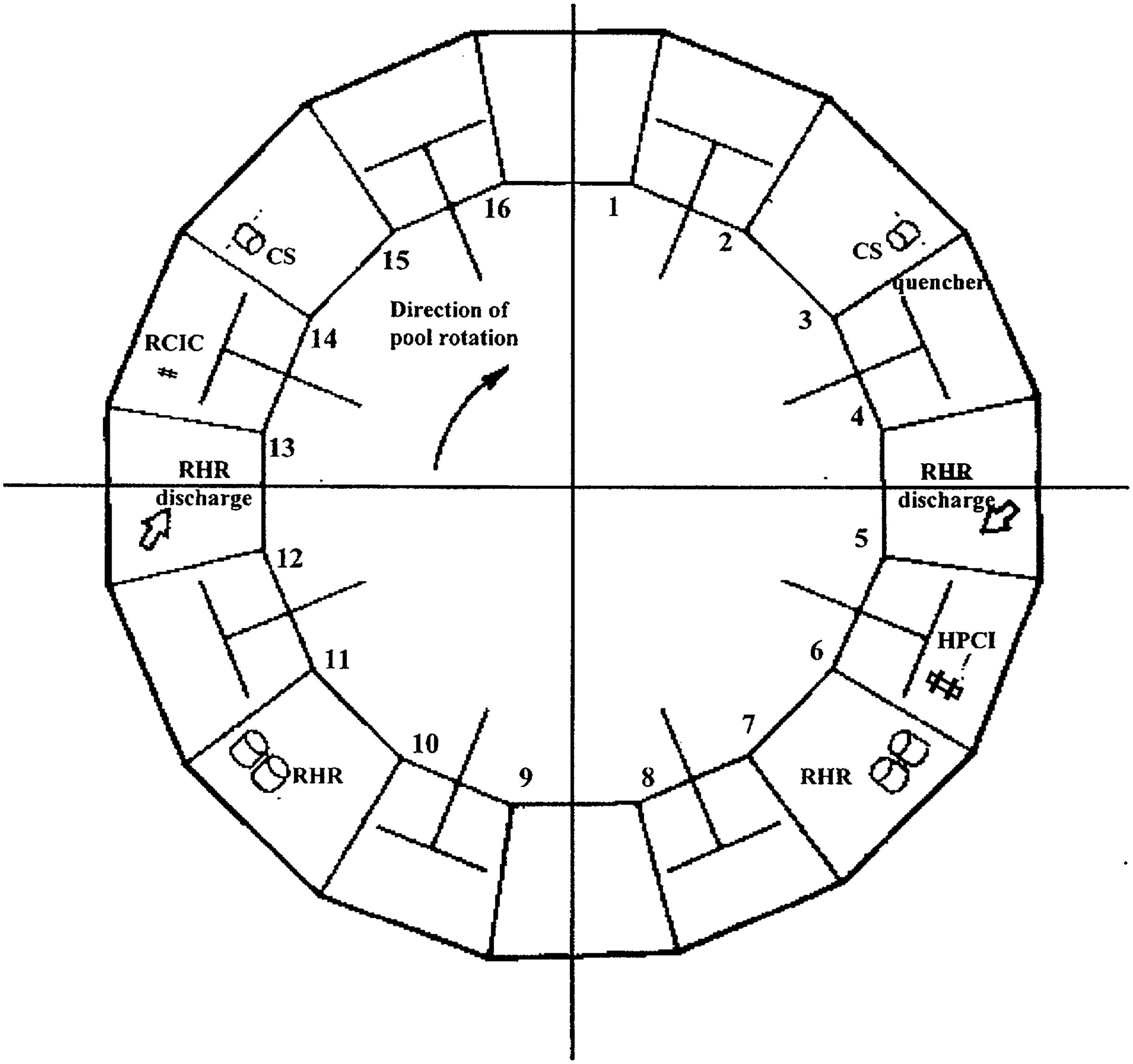

Figure 1 - Plan View of the Cooper Torus Showing Quencher and Suction Strainer Locations (from Reference 9)

3.2 SRV Quencher Steam Plume

The size and lateral extent of the steam plume formed above the SRV quencher arm is a function of the SRV flow. For the steam ingestion analysis, the quencher flow is based on the technical specification maximum set-point limit pressure for the SRVs, 1133 psig. Due to the varying distribution of holes along the quencher arm, the flow of steam exiting the end of the T-quencher arm is greater than the flow from the middle. Consistent with earlier steam ingestion analysis [5], the steam from each arm of the quencher is assumed to form a circular plume over the end of the arm [5]. While there will likely be some flow distribution along the arm, the circular plume model should conservatively maximize the calculated plume size and the lateral extent of the plume in the direction of the strainer.

The SRV flow is calculated from the reactor pressure using the reference flow and pressure. This is the same approach used in Appendix C of Reference 10 to calculate the SRV flow during reactor depressurization. The SRV flow is given by the following expression:

Note that the SRV reference flow is the flow expected at 103% of the SRV reference pressure. As noted above, the SRV flow is based on at the technical specification maximum set-point pressure for the valves of 1133 psig.

The plume boundary is defined by the plume radius, which is given by:

$$r_p = (A_p / \pi)^{1/2}$$

The steam plume, for maximum reactor pressure, is plotted in Figure 2 below.

Figure 2 – Quencher Plume for Maximum Reactor Pressure

Figure 3 shows the plume radius versus reactor pressure at 6.044 feet above the torus bottom. This corresponds to the elevation of the nearest edge of the RHR strainer disk. Note the plume radius is about three feet at the maximum reactor pressure.

Figure 3 – Quencher Plume Radius at 6.044 ft Elevation vs. Reactor Pressure

3.3 Suction Strainer Entrainment Envelope

The entrainment envelope around the ECCS suction strainer represents the boundary of the flow ingested by the strainer. The size and shape of the envelope is a function of the volumetric flow rate into the strainer, the strainer length, and conditions in the flow field near the strainer. Steam bubbles near the strainer, which are most likely to be entrained, are those which are rising slowly, with the rise velocity of a single bubble. For this reason, the rise velocity of a single bubble is used to define the flow into the strainer. This provides a boundary for single bubbles, escaping the steam plume, which could be entrained by the suction strainer.

Figures 4 and 5 shows the X-Y envelopes for the RHR and CS strainers. The up-flow to the strainer is at the bubble rise velocity, which is very low, and a large envelope is required to carry flow to the strainer at this low flow rate. Low inflow provides a conservative estimate of the entrainment envelope size.

Figure 4 – X–Y Entrainment Envelope for the RHR Strainer

Figure 5 –X-Y Entrainment Envelope for the CS Strainer

The entrainment envelope at the end of the suction strainer is also modeled as a line sink in a uniform flow with vertical and horizontal velocity components of the uniform flow the components of the bubble rise velocity which are normal and parallel to the strainer. If the plane parallel to the axis of the strainer is named the Z-Y plane, the same equations apply. The sink location is adjusted to insure the top of the Z-Y envelope is consistent with the top of the envelope in the X-Y plane.

3.4 Evaluation of Steam Ingestion

As noted earlier, steam ingestion is predicted if the quencher steam plume intersects any part of the ECCS suction strainer or the entrainment envelope surrounding the suction strainer. Figures 6, 7 and 8 show the relative location of the quencher plume, the suction strainer and entrainment envelope for the HPCI, the RHR and the CS suction strainers.

Figure 6 shows the HPCI strainer, its entrainment envelope along with the quencher and steam plume. The entrainment envelope is sufficiently far from the steam plume that entrainment is not expected. The smaller RCIC strainer, with a flow of 55.6 lbm/s (≈ 440 gpm), is located in the same relative position on the torus wall. This strainer will have an even smaller entrainment envelope and will also not be at risk for steam entrainment.

Figure 6 - End View of the Steam Plume and the HPCI Entrainment Envelope

Figure 7 shows the RHR suction strainer, this strainer is the most limiting geometry of the strainers at Cooper. Shown are the entrainment envelope, and the quencher and steam plume. The figure shows an end view of the torus bay. Note that the quencher arm does not lie on the bay centerline. This is because the figure shows the bay containing the strainer. The quencher is in the adjacent bay and set back from the bay end, so when viewed from the bay containing the strainer, the quencher arm appears off-set from the bay centerline. The strainer entrainment envelope is shown with a dashed line.

Figure 7 – End View of the Steam Plume and Entrainment Envelope for the RHR Strainer

Figure 8 shows the CS suction strainer, the entrainment envelope and the quencher and steam plume. As noted earlier for Figure 7, the quencher arm does not lie on the torus centerline because the quencher is in the adjacent bay and set back from the bay end, so when viewed from the strainer bay it appears off-set from the centerline. The strainer entrainment envelope is shown by a dashed line.

Figure 8 – End View of the Steam Plume and Entrainment Envelope for the CS Strainer

4.0 CONCLUSIONS

An analysis has been performed to determine if there will be ingestion of SRV steam by the ECCS suction strainers in the Cooper Nuclear Station. Steam ingestion would be predicted if the steam plume formed by SRV discharge intersected any part of the suction strainer or the entrainment envelope for flow entering the suction strainer. The analysis was performed assuming a saturated suppression pool around the quencher and maximum SRV flow to obtain the most conservative steam volumetric flow to the pool.

The steam discharge to the pool was modeled as a circular plume. The steam plume radius was conservatively calculated to be about 3 feet beyond the centerline of the quencher arm for a reactor pressure of 1133 psig.

The entrainment envelope for flow into the individual strainers was conservatively calculated assuming up-flow to the strainer at the rise velocity of an individual bubble. For the RHR suction strainer, the most limiting geometry, the clearance between the entrainment envelope and the steam plume was about 8 inches. Clearance between the steam plume and the CS suction strainer was greater, more than one foot. The entrainment envelope for the HPCI suction strainer was analyzed and was found to have several feet of clearance from the steam plume. The RCIC strainer, located in a similar position as the HPCI strainer and with an even smaller flow, was also concluded to not be at risk.

These results, based on conservative modeling assumptions, show no overlap between the quencher steam plume and either the strainer or the entrainment envelope for flow into the strainers for any of the ECC systems. Thus, the predictions show no ingestion of steam by the suction strainers at the Cooper Nuclear Station.

5.0 REFERENCES

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2. Containment Analysis Input Parameters (Form OPL-4A) for CNS February 13, 2001.
3. Transient Protection Parameters Verification for Reload Licensing Analyses (Form OPL-3) for Cooper, Reload 19, Cycle 20.
4. Nebraska Public Power District Calculation NEDC 97-088, Rev. 2, February 16, 1999.
5. Rhee, J., Healzer, J., Moody, F., Post, J., "James A. Fitzpatrick Nuclear Power Plant: Evaluation of Steam Ingestion in Emergency Core Cooling System (ECCS) Suction Strainers." GE-NE-E12-00168-00-01. May 2000.
6. White, F.M., "Fluid Mechanics," 2nd ed., Wiley, New York, 1986, Sect. 8.3-8.
7. Blevins, R.D., "Applied Fluid Dynamics Handbook," Van Nostrand Reinhold Co., 1984, p. 250.
8. Technical Paper No. 410, "Flow of Fluids through Valves. Fittings, and Pipes," Crane Co., 1985.
9. "Cooper Nuclear Station Suppression Pool Temperature Response," GE Report NEDC-24360-P, August, 1981.
10. "BWR Owners' Group Severe Accident and Emergency Procedures Guidelines," Appendix C: Calculations, Revision 2, March 2001.

APPENDIX A – Input Parameters

Table A-1 Key Input Parameter Values for Cooper

Input Parameter	Value	Source
LPCI/RHR pump flow rate (1 pumps)	8800 gpm	Ref. 2, Item 6n, no.2
CS pump flow rate	6500 gpm	Ref. 2, Item 7b, no.2a
RCIC pump flow rate	55.6 lbm/s	Ref. 2, Item 8c
HPCI pump flow rate	4250 gpm	Ref. 2, Item 5g
RHR stacked-disk strainer geom.: inlet pipe OD		GE dwg. 105E2200, Rev.1
outside diameter		
strainer length		
wall-to-strainer offset (1)		Ref. 4, Sect. 3.11
strainer angle		GE dwg. 105E2322, Rev. 1
penetration closest to quencher		B&R dwg. 4260, Sheet 2B
penetration off set from bay center		B&R dwg. 4260, Sheet 2A
CS stacked-disk strainer geom.: inlet pipe OD		GE dwg. 105E2199, Rev.1
outside diameter		
strainer length		
wall-to-strainer offset (1)		Ref. 4, Sect. 3.11
strainer angle		GE dwg. 105E2322, Rev. 1
penetration closest to quencher		B&R dwg. 4260, Sheet 2B
penetration off set from bay center		B&R dwg. 4260, Sheet 2A
HPCI basket strainer geometry: inlet pipe OD	16 in	CBI dwg. 69, Rev. 5
strainer tee outside diameter	16 in	Ref. 8, App. B (16" NPS)
strainer length, incl. Basket (2)	5.459 ft	Ref. 4, Sect 3.11
wall-to-strainer centerline offset (3)	1.419 ft	Ref. 4, Sect 3.11
strainer angle (4)	30° from vert.	B&R Dwg. 4260, Sheet 2A&B
penetration number	226	B&R dwg. 4260, Sheet 2B
penetration off set from bay center	4 ft – 0 in	B&R dwg. 4260, Sheet 2A
RCIC basket strainer geometry: inlet pipe OD	6.625 in	CBI dwg. 69, Rev. 5
strainer outside diameter	6.625 in	Ref. 8, App. B (6" NPS)
strainer length, incl. Basket (2)	3.145 ft	Ref. 4, Sect 3.11
wall-to-strainer centerline offset (3)	0.888 ft	Ref. 4, Sect 3.11
strainer angle (4)	30° from vert.	B&R dwg. 4260, Sheet 2A&B
penetration number	224	B&R dwg. 4260, Sheet 2B
penetration off set from bay center	9 ft – 6 in	B&R dwg. 4260, Sheet 2A
SRV reference pressure	1090 psig	Ref. 3, page 10, Item 6 – 8
SRV technical specifications pressure	1133 psig	
SRV flow rate at reference pressure	870,000 lbm/hr	Ref. 3, page 10, Item 6 – 8
Suppression chamber pressure	0.0 psig	Ref. 2, Item 3d, no. 3

Table A-1 (Cont.) Key Input Parameter Values for Cooper

Input Parameter	Value	Source
SRV quencher end-to-end length		EDS dwg. VR-P-WW71A-H,
Quencher arm outside diameter		GE dwgs. 112D2562,794E828
Quencher arm length to end of hole pattern		Ref. 8, App. B (12" NPS)
LOCA vent header centerline elevation	880.917 ft	Ref. 2, Item 2k, no. 8
number of downcomers	80	Ref. 2, Item 2e
header centerline to downcomer exit	9.084 ft	Ref. 2, Item 2k, no. 7
downcomer diameter	1.958 ft	Ref. 2, Item 2f
downcomer submergence at low water level	3.0 ft	Ref. 2, Item 2i, no. 1
quencher centerline elevation	867 ft – 9 in	Kaiser dwg. S-1002, Rev. 1
torus centerline elevation	876.625 ft	Ref. 2, Item 2k, no. 9
torus major radius	50.875 ft	Ref. 2, Item 3h
torus minor radius (cross section radius)	14.375 ft	Ref. 2. Item 3i
radius to inside of torus ring girder	12 ft – 7 in	CBI dwg. 52, Rev. 6
LWL elevation	874.833 ft	calc. from above
quencher submergence at LWL	7.083 ft	calc from above
RHR discharge diameter	14 in	Kaiser dwg. 112.01, Rev. 0
RHR discharge angle w/ vertical	67° 30'	
RHR discharge angle w/bay centerline(X210A)	29° 36'	
RHR discharge angle w/bay centerline(X210B)	36° 52'	

Notes: 1. The off-set distance for both CS and RHR strainers referred to here is the distance from the torus wall to the bottom of the strainer. This is given as dimension "d" in Reference 4.

2. The RCIC and HPCI strainer lengths have been calculated using the length of the tee component branch, given as dimension "y" in Reference 4, plus the length of both baskets, from CBI dwg. 67, Rev.1.

3. The RCIC and HPCI off-set distances have been taken as dimension "x" in Reference 4, the distance from where the strainer pipe enters the torus to the centerline of the through branch of the strainer tee.

4. The angles of the RCIC and HPCI penetrations are shown in B&R dwg. 4260 Sheet 2A, while the penetration identification numbers are related to the strainers in Sheet 2B.