CONTAINMENT SUMP CHANNEL FLOW MODELLING

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1. Introduction

In the event of a loss of coolant accident (LOCA) within containment of a pressurised water reactor (PWR) there is the potential for the generation of debris with the attendant concern of containment sump screen blockage. The debris, consisting piping or equipment insulation, protective coatings or paints, concrete dust or general containment housekeeping materials, may be transported to the containment sump during the recirculation phase of emergency core cooling system (ECCS) and containment spray system (CSS) operations.

Unresolved Safety Issue (USI) A-43, “Containment emergency sump performance” had been previously evaluated and declared as resolved by the NRC in 1985. The NRC concluded from the results of research on boiling water reactor (BWR) ECCS suction strainer blockage that newly identified phenomena and failure modes were not considered in the resolution of Issue A-43. In addition, operating experience identified new contributors to debris and possible blockage of PWR sumps, such as degraded or failed containment paint coatings. NRC identified concerns regarding these new contributors to post accident sump performance as Generic Safety Issue (GSI)-191, “Assessment of Debris Accumulation on PWR Sump Performance” and initiated a research effort to address these new concerns.

The NRC subsequently issued Bulletin 2003-01, “Potential Impact of Debris Blockage on Emergency Sump Recirculation at Pressurized-Water Reactors”, to address near-term interim measures. The purpose of the bulletin was to request information from the PWR licensees describing:

1. compliance with existing requirements; or
2. the implementation of interim compensatory measures.

The NRC has issued a Temporary Instruction with the primary purposes to:

1. ensure that licensee actions are consistent with bulletin responses and the bulletin’s intent; and
2. verify PWR licensees are performing containment condition assessments to ensure that they are prepared to perform sump evaluations soon after guidance is issued.

Further, the NRC intends to issue a Generic Letter which will likely request the following information from licensees:

1. the guidance/methodology used to perform post-accident sump performance evaluation;
2. an implementation schedule for any modifications the evaluation demonstrates to be necessary;
3. a description of interim compensatory measures to be taken until necessary modifications can be performed;
4. a basis for concluding that the debris blockage concerns associated with GSI-191 do not adversely impact sump performance once any necessary modifications are complete; and
5. a description of any controls in place to ensure material brought into containment would not degrade sump performance.

The regulatory focus on this issue will ultimately require licensees to evaluate containment sump performance with a focus on the generation and transport of debris to the sump screens. The method presented here provides licensees with a method to analyse post accident fluid velocities on the containment floor without the complexity and manpower investment required to perform a computational fluid dynamics (CFD) calculation.

2. Analysis approaches

2.1 Computational fluid dynamics approach

Los Alamos National Lab (LANL) Nuclear Design and Risk Analysis Group developed a computational fluid dynamics (CFD) model of a volunteer plant. This volunteer plant provided the necessary information to LANL to develop a CFD model of their containment. The simulation model was formulated to evaluate fluid movement within the volunteer plant’s flooded containment floor region following a loss of coolant accident.

The objective of the programme was to determine the expected water velocities in the containment pool following a postulated LOCA scenario and determine the potential for debris transport. The model developed and cases investigated utilised a commercial CFD code. Among the scenarios considered were a large break LOCA with maximum pool depths and safeguards flow rates. The model was used to perform a three dimensional steady state simulation of the fluid flow on the volunteer plant’s containment floor and included nearly 500 000 cells. The boundary conditions were provide by the volunteer plant and included flow input points and magnitudes to the containment pool, safeguard pumped flow rates, the containment flood levels and the containment structural configuration. Much of the data provided to LANL had been previously developed by the volunteer plant to support other analyses related to sump debris issues at the plant.

2.2 Nodal Network approach

Westinghouse, under sponsorship of the Westinghouse Owners Group (WOG), undertook an effort approximate the results of the LANL CFD calculation results by utilising a conservative but less complex approach in an attempt to support evaluations by members of the WOG that are expected to be required to support closure of GSI-191. Specifically, the simplified approach taken was to consider the flow about the containment floor as a network of open channel flows.

An open channel flow network model was developed for the volunteer plant and evaluated with network analysis software tool. The results of the Nodal Network calculations were compared to the LANL CFD results. The results compared favourably with the LANL benchmark and are discussed in detail in Section 4.

3. Open channel flow network development

3.1 Purpose

It is fully expected that the licensees will be required to provide an analytical evaluation of the containment sump performance in light of the GSI-191 and the anticipated NRC Generic Letter. By necessity, an integral part of that evaluation will be the transport of event-generated and other debris to the containment sump to ascertain the potential for ECCS sump blockage. Deposition of that debris on the containment sump screen is a concern, as it may result in an unacceptable increase in differential pressure across the screen during operation of the ECCS and CSS as they recirculate fluid from the containment sump.

Integral to debris transport is the fluid velocity from the cooling water sources following the accident scenario to the containment sump. One method of evaluating fluid transport velocities is to develop a CFD model and simulate break and spray flows to determine local velocities. Although the CFD analysis provides a detailed prediction of local flow velocities and turbulence levels in the flow field, manpower requirements in generating the CFD model presents economic basis for pursuing other approaches. Under WOG sponsorship, Westinghouse undertook an effort to evaluate other potential means of predicting flow velocities within containment flooded regions. The efforts focused on a channel flow network analysis of the volunteer plant containment floor. The results of the CFD analysis assisted in developing an appreciation of containment channel flow and also served as a benchmark against which the analysis results could be compared.

3.2 Model inputs

The prerequisites for successful open channel flow network modelling of the post accident ECCS sump include the following inputs. For the Westinghouse effort, the inputs were provided by the identified sources.

3.2.1 Containment configuration

Floor plan and elevation configuration: It is essential that an accurate configuration of containment flooded region be well defined, including obstacles to flow. For the volunteer plant work, plant personnel provided structural and architectural drawings that gave the necessary depiction of the containment sump and flooded plane. Both plan and elevation views are required.

3.2.2 Containment water definition

Water sources: The sources of post accident water into the containment flood plane that were used as the boundary conditions for the LANL CFD analysis modelling were provided by volunteer plant personnel. A total of 24 water sources to the containment floor had been defined for previous containment debris analysis work. The water sources (magnitudes and physical locations) used in the

LANL CFD model were also used as inputs to the Westinghouse Nodal Network model to assure any comparison to the CFD results were valid.

Flood plane: The flooding level on the containment floor is an important parameter in addressing the potential for debris transport to the containment sump. The flooding level used in the Westinghouse Nodal Network calculations was based on the value used by LANL as supplied by volunteer plant personnel. This was done to provide a basis for consistent comparison of the Nodal Network calculations to the CFD calculations.

Post accident flow rates: The post accident containment sump flow rates (including ECCS and CSS flows) are necessary in the determination of velocities in the pool on the containment floor. To provide for a consistent basis of comparison between the Nodal Network calculations and the CFD calculations, the Nodal Network calculations used the same values as were used in the LANL CFD calculations. Flow rates were provided to LANL by volunteer plant personnel.

3.3 Model development

3.3.1 Channel definition

The open channel specification was based on identifying major flow areas from the various sources to the final destination, i.e. the sump. In the case of the volunteer plant containment, the basic channel model definition is a ring of channels around the containment floor with sources defined along the ring header and a destination of the containment sumps. Although most containments are expected to be a similar contiguous ring from sources to destinations, this feature is not essential to the modelling.

The boundaries of the individual channels are defined based on either major structural or flow changes. Essentially, at any point there is a significant change in flow area (increase or decrease) the channel should be terminated and new one defined until the next structural or flow change. The same approach is taken at points of significant flow input to the network. If less than major changes in flow are introduced along the defined channel it conservatively assumed to occur at the beginning of the channel.

Depiction of the volunteer plant channel network definition is illustrated in Figure 1.

Finally, the results of the LANL were used to enhance the understanding of fluid motion on the flooded containment floor and influence the definition of channel boundaries. The visual representation of the CFD results proved valuable in the understanding of flow movement. Figure 2 provides the channel definition superimposed over the velocity vector field.

3.3.2 Flow resistance calculations

Form and channel frictional losses were included in channel resistance to flow. Form losses were primarily based on the reduction or increase in flow areas and were calculated based on hydraulic diameters. K factors were taken from Crane Technical Paper 410 [1].

Frictional losses were calculated based on Altsul’s Formula [2] and then verified with the Colebrook-White formula (also given in [2]).

Altsul's Formula:

$$f = 0.1\left[1.46\frac{k_S}{D_H} + \frac{100}{R_e}\right]^{\frac{1}{4}}$$

Colebrook-White Formula:

$$\frac{1}{\sqrt{f}} = -2.0\log_{10}\left[\frac{k_S}{3.71D_H} + \frac{2.51}{R_e\sqrt{f}}\right]$$

where:

f is the Darcy friction factor coefficient;

R_e is the Reynolds number;

D_h is the hydraulic diameter;

k_s is the roughness height.

Figure 1 provides schematic diagram of the Nodal Network channel definition developed for the Volunteer Plant. Included in the schematic are the calculated friction and form resistances, flow area and hydraulic diameter for each channel. Figure 2 then superimposes the channel network defined on the above basis onto a Cartesian plot of the LANL CFD model results. The figure is a composite of the results presented by LANL personnel at an NRC sponsored public meeting on GSI-191 on 5 March 2003 in Albuquerque, NM [3].

4. Evaluation of Nodal Network method results

4.1 Comparison of Nodal Network and CFD velocities

LANL provided electronic files containing the results of their CFD code simulation at a specific containment elevation. The data was reduced and used to calculate the channel flow velocities at locations corresponding to locations within the Nodal Network developed by Westinghouse. These velocity values were then compared to the velocity values calculated with the Nodal Network to ascertain the success in replicating the calculated flow results. Table 1 provides a tabulation of the comparison of the flow velocities calculated using the Nodal Network described above and those calculated at corresponding locations with the LANL CFD model. This comparison is for a large break LOCA in the lower left loop compartment with maximum ECCS and containment spray flow rates and a maximum flooding level.

The results compare very favourably with the network analysis providing slightly higher flow velocities. This result should be expected since typically the width of the channel is not the full width of the flow area but represents only the major flow area. The exception to the comparable comparison occurs in junction between nodes 10 to 7. At this junction, the calculated flow rate from the CFD data reduction appears to be inconsistent with the specified boundary condition of 1021 gpm flow out of the lower left compartment of the containment that contains the postulated RCS break. Using a revised flow rate that is consistent with the calculated velocities from the loop compartment, the velocity comparison is more acceptable for all channels. This comparison of these revised calculated flow rates is shown in Table 2.

4.2 Discussion of advantages, limitations and cautions

The Nodal Network approach does have limitations with respect to the application of CFD. Two specific examples are:

- The Nodal Network approach does not allow for the calculation of local velocity effects, such as flow around objects in the flow stream.
- The Nodal Network approach does not calculate the turbulence level in the flow field.

In the first case, "dead zones" of stagnant fluid that are predicted by CFD models will not be predicted by Nodal Network models. In the second case, turbulence predicted by CFD models that might cause degradation of certain insulation and debris types is not predicted by Nodal Network models.

The Nodal Network approach may also have some benefits over the application of CFD. For example:

- Since Nodal Network approach is based on basic engineering principles, the model may be developed by plant engineering personnel. It follows that the model development may be accomplished more quickly, perhaps less expensively, and without specialised computer software (the equations may be solved by in a spreadsheet).
- Even with the limitations noted above, a Nodal Network may be used to gain quick insights to debris transport.
- Nodal Network results might indicate that a containment has sufficient amount of transportable debris that further refinement of flow calculations (use of CFD models) is not warranted.
- A Nodal Network may also be used parametrically to assess the sensitivity of various parameters, such as the amount of a type of debris in a specific location, on the amount of debris transported to the containment sump.

It is also noted that the Nodal Network and CFD approaches have similar data needs. Thus, much of the data to be identified and collected to develop a Nodal Network model is also needed to develop a CFD model. Thus, if the application a Nodal Network model suggests that the development of a CFD model is warranted, much of the data collection to support the Nodal Network is applicable to the development of the CFD model.

Table 1. Comparison of Nodal Network and CFD fluid velocities for volunteer plant, maximum flood level and maximum ECCS and CSS flow rates

Connected nodes		**Nodal Network model fluid velocity**	**CFD model fluid velocity**
From	**To**	(ft/sec)	(ft/sec)
2	3	0.042	0.057
3	4	0.135	0.120
4	5	0.381	0.296
5	6	0.449	0.400
6	7	0.594	0.457
8	9	0.053	0.034
9	10	0.158	0.084
10	7	0.315	0.660

Table 2. Comparison of Nodal Network and CFD fluid velocities for volunteer plant, revised flow rates for based on loop compartment velocities

Connected nodes		**Nodal Network model fluid velocity**	**CFD model fluid velocity**
From	**To**	**(ft/sec)**	**(ft/sec)**
2	3	0.084	0.057
3	4	0.165	0.120
4	5	0.438	0.296
5	6	0.490	0.400
6	7	0.642	0.457
8	9	0.015	0.034
9	10	0.080	0.084
10	7	0.682	0.660

5. Summary

5.1 Conclusions

Based on the comparison of channel flow Nodal Network calculations to CFD calculations presented in this paper, it is concluded that the Nodal Network technique may be applied to the determination of post-accident fluid velocities in the flooded containment regions. Given accurate input and boundary conditions, the network analysis approach can be used to provide reasonable, conservative fluid velocities in the fluid pool formed post-accident on the containment floor.

A Nodal Network tool, similar to the one described in this paper, may be developed, maintained and used by the plant engineering staff without specialised codes or training. Sensitivity calculations performed using a Nodal Network model may be used to identify when further, more detailed fluid analyses may not be warranted; that is, debris loading on the sump screens estimated from the Nodal Network model are sufficiently large such that additional refined analyses would not be beneficial. Furthermore, much of the effort to develop the input for a CFD model is common to that required for a Nodal Network model; both models use much of the same data.

Given the above, it is suggested that the use of a Nodal Network approach is a reasonable tool that may be used to evaluate both the bulk fluid movement and bulk debris movement in the containment pool post accident. Furthermore, a Nodal Network approach may also be used to support and guide the application of a more detailed CFD approach.

5.2 Guidance for future application

As a minimum, the following information and guidance is provided for the analyst to support the successful application of a Nodal Network approach. The model definition data is also considered necessary to support the successful application of a CFD approach.

Model definition data (see Section 3.2 for additional clarification):

- accurate physical configuration of containment flooded region;
- sources of post accident water flowing into the flood plane;
- definition of the flooding elevation;
- ECCS and containment sump flow rates.

Channel definition guidance:

- Channels should be defined at every major restriction and expansion of flow area.
- Significant portions of the containment floor are not active in the transport of debris (the construction of smooth velocity vectors assist in the definition major active flow paths and therefore channel definition).
- The velocity vector profiles provided by the LANL illustrate the active flow areas versus pooling regions.

REFERENCES

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Figure 1. Schematic of Nodal Network for volunteer plant

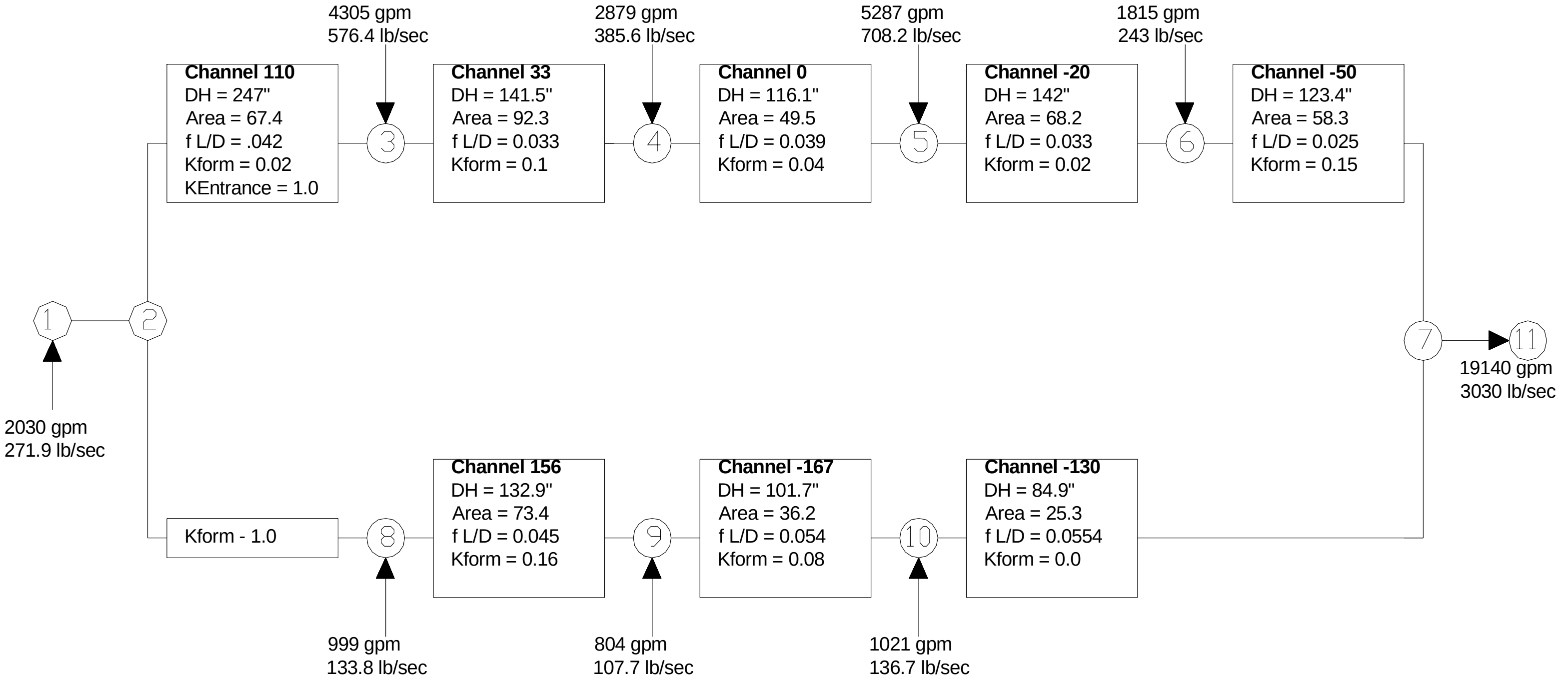
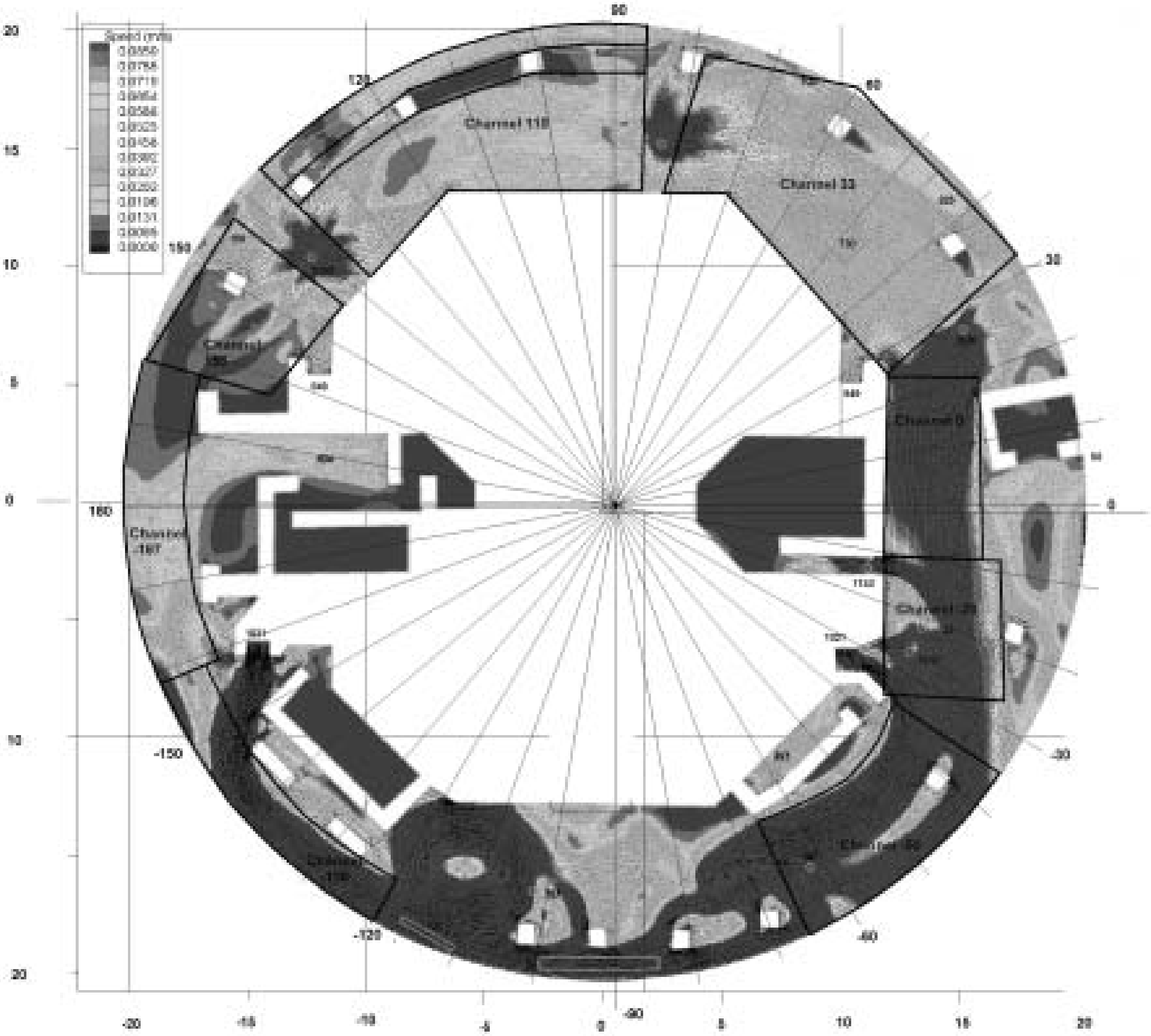


Figure 2. Nodal Network overlay onto CFD model of volunteer plant [3]



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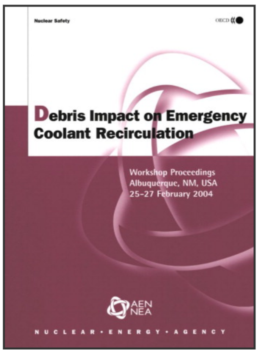

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