Proceedings of the ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting and 8th International Conference on Nanochannels, Microchannels, and Minichannels
FEDSM-ICNMM2010
August 1-5, 2010, Montreal, Canada

FEDSM-ICNMM2010-31283

BETTER ESTIMATE ANALYSIS FOR USE IN EMERGENCY OPERATING PROCEDURE DURING A LOSS OF COOLANT ACCIDENT

Daniel M. Speyer, Ph.D.

The Cooper Union for the Advancement of Science and Art
Cooper Square
New York, NY 10003, USA
Phone: 1-212-874-1172
E-mail: speyer@cooper.edu

Jong E. Chang, Ph.D.

Entergy Nuclear
440 Hamilton Avenue
White Plains, NY 10601, USA
Phone: 1-914-734-6766
Fax: 1-914-827-7779
E-mail: jchang@entergy.com

Ardesar Irani

Entergy Nuclear
440 Hamilton Avenue
White Plains, NY 10601, USA
Phone: 1-914-272-3236
E-mail: airani@entergy.com

ABSTRACT

Emergency Operating Procedures (EOPs) [1] provide prioritized response strategies that guide the operator in management of emergency transients. A desirable attribute of EOPs is optimal recovery from the transient. To achieve this, it is necessary to develop more realistic criteria rather than criteria based on traditional licensing analysis methods. One such application is evaluating measured core makeup flow during the recirculation phase of a Loss of Coolant Accident (LOCA) with adverse containment environment.

During the recirculation phase of a LOCA, the adequacy of the internal recirculated water flow (from the containment sump) is confirmed by individual loop measured injection flows satisfying EOP criteria. Of particular concern is the flow split in the loop emergency cooling injection lines and the potentially large instrument uncertainty associated with measuring low flow rates. In the event one of the injection lines spills to containment (and possibly without a line spilling), traditional analysis methods based criteria would suggest adequate makeup flow may not be confirmed, and consequently the EOPs would prescribe external recirculation, which is not the preferred mode.

In the present paper the EOP criteria for post LOCA core cooling flow is developed – using better estimate methods. Several (significantly) less restrictive analysis assumptions were identified and a new/materially different approach from that used in the past was taken. As result a more robust flow criterion was obtained – simpler and permitting about 0.019 m^3/s [300 gpm] less flow.

NOMENCLATURE

Greek Letter

σ : standard deviation

Symbols

$fL(i)$: flow fraction of loop number i

X_{wgt} : weighting factor

c_1 : orifice (flow meter) constant [$\mathbf{L}^4\boldsymbol{\tau}^{-1}\mathbf{F}^{-1/2}$]

dP : differential pressure [$\mathbf{F}\mathbf{L}^{-2}$, % of span]

$\dot{V}$: volumetric flow rate [$\mathbf{L}^3\boldsymbol{\tau}^{-1}$: m^3/sec, gpm; % of span]

$\Delta\dot{V}$: unweighted flow error [$\mathbf{L}^3\boldsymbol{\tau}^{-1}$, % of span]

$\dot{V}_i$: weighted flow error [$\mathbf{L}^3\boldsymbol{\tau}^{-1}$, % of span]

where i = unc, EA, or bias

(above dimensions: **F** = force, **L** = length, **τ** = time)

Subscripts

act: actual
bias: bias
core: core
EA: environmental allowance
obs: observed

unc: uncertainty

Acronyms

EA:	Environmental Allowance
ECCS:	Emergency Core Cooling System
EOP:	Emergency Operating Procedure
LOCA:	Loss of Coolant Accident
NSS:	Nuclear Seam Supply System
RCS:	Reactor Coolant System
SRSS:	Square Root of Sum of Squares

1. INTRODUCTION AND STATEMENT OF THE PROBLEM

During the recirculation phase of a (large break) LOCA, the Emergency Core Cooling System (ECCS) flow from the containment sump should be greater than boil off – to ensure the core water level recovers.

The earliest time for recirculation to begin is 20 minutes (when the refueling water storage tank is exhausted); and at that time the calculated minimum core makeup flow is 0.0341 m^3/s [540 gpm].[1]

The recirculation flow is measured by four orifice flow meters of a typical 4 loop plant one for each Reactor Coolant System (RCS) loop and since one of the injection lines may be broken the highest flow reading is not credited. (It is assumed to be bypassing the RCS, and spilling directly to containment.)

Given the large flow uncertainties and spilling assumption it was evident better estimate assumptions could be a benefit in the development of a revised EOP flow criterion; however, the EOP flow criterion also must be workable (sufficiently simple) for use during the evolving accident.

2. USE OF BETTER ESTIMATE ANALYSIS

The flow meter indication's uncertainty (instrument error), and the spilling assumption (and the resulting flow split in the intact injection lines), are the two effects that have a major impact on the EOP.[2]

In the present context (for this particular plant) the EOP core cooling flow criteria is developed using what is believed to be a novel approach – taking credit for existing (vendor) hydraulic analysis results for the flow distribution in the ECCS injection lines (based on actual piping layout/components). This is termed better estimate analysis, as the analysis uses traditional licensing assumptions as well (e.g., reduced pump head-flow curve). From knowledge of the hydraulic analysis loop flow split it is possible to (effectively) credit flow in loop(s) where flow indication is either unavailable or not used.

Given the approach used – most notably that all (4) loop indicated flows may not be available/may not be used and thus some ECCS flow(s) may be inferred – it is relevant that a "back up indication" for core makeup flow exists. If the flow was inadequate rising core exit thermocouple temperatures would prompt the operator to switch to external recirculation.

In addition the analysis uses scenario specific modifications to the uncertainty analysis to significantly reduce the resulting instrument errors. Basically use of SRSS method (square root of sum of squares) to statistically combine multiple loop flow indications.[3] Finally to assess the EOP flow criteria that was developed, one standard deviation (1σ) uncertainty values were used. Again it can be characterized as a better estimate approach.

2.1. Indicated Flow Uncertainty, Environmental Allowance, Bias and Total Error

Previously developed loop total flow error analyses/results (see Annex B) were revised. Instead of total flow error ($\sum \dot{V}_i$), the flow uncertainty ($\dot{V}_{unc}$), environmental allowance EA ($\dot{V}_{EA}$), and bias ($\dot{V}_{bias}$) were calculated. This permits the use of the SRSS method, when summing flow uncertainty and summing EA's, for multiple loop flow indications.

The equations are developed in Annex A, and the results (2σ values) are summarized in Table 1 versus actual loop flow ($\dot{V}_{act}$).

2.2. Use of Flow Split Information to Augment Indicator Values

Vendor hydraulic calculations (described below) for the individual loop flows (at 20 minutes) were used, as follows.

For the case of one injection line spilling: 0.134 m^3/s [2123 gpm] (spilling line), and 0.0209, 0.0102, and 0.0021 m^3/s [331, 162 and 34 gpm]. The three intact loop flows total 0.0332 m^3/s [527 gpm][4] and the loop flow fractions $fL(i)$ to the core are:

---

[1] The times of interest are 20 and 30 minutes (containment spray may be taken from the sump as early as 30 minutes); and only 20 minutes cases are provided. The 30 minute analysis methods are identical, and numerical results and conclusions are similar.

[2] Calorimetric (operating power) error, decay heat calculation uncertainty, and deposition rate of vessel stored energy to the sump, are also significant factors – accounting for 12 to 14% of the required flow.

[3] Use of SRSS method is neither new nor novel; however, the design calculations for error (unfortunately) may not tabulate separately uncertainty, environmental allowance, and bias (contrast Table 1 and Table B-1), and as such may inhibit extensive reformulation or require extensive recalculations.

[4] The total ECCS flow in this vendor hydraulic calculation is 2.6% below the required core makeup flow (0.0332 versus 0.0341 m^3/s [527 versus 540 gpm]). This small difference is (presumably) attributable to minor differences in calculation models and assumptions. (In the context of these calculations/application these are the same number!)

$fL(1)$ = 0.0

$fL(2)$ = 331/527 = 0.63

$fL(3)$ = 162/527 = 0.31

$fL(4)$ = 34/527 = 0.06

(If no spillage is assumed the flows are as follows: 0.0457, 0.0418, 0.0328 and 0.0328 m^3/s [724, 663, 521 and 520 gpm].)

We shall now apply these results – and develop the EOP flow criterion.

Requiring the minimum core makeup flow of 0.0341 m^3/s [540 gpm] (in the 3 intact lines), and applying the above flow split (fractions of the 0.0341 m^3/s [540 gpm]), yields "known" values of 0.0214, 0.0105 and 0.0022 m^3/s [339, 166, and 35 gpm], in the respective loops.

Notice, here we speak of "known" values – they are not actually known but rather are a conservative representation, as opposed to a best estimate value. But a best estimate analysis would not be particularly useful because we could not pick a conservative flow split, and thus not know what loop flow errors to use. In principle we (perhaps) could use the actual flow indications, but in reality this is impractical/impossible. The operator will be unable to collect and use the information while dealing with the early phase of a serious accident. (This is discussed more in Annex B.)

$\dot{V}_{act}$	$\dot{V}_{unc}$	$\dot{V}_{EA}$	$\dot{V}_{bias}$	$\sum \dot{V}_i$
0.0	12.7	15.7	8.8	37.2
3.5	11.6	14.8	7.5	33.9
10.0	9.7	13.1	5.6	28.4
16.6	8.2	11.4	4.4	24.0
20.0	7.6	10.7	4.0	22.3
33.9	5.7	8.1	2.8	16.6
50.0	4.5	6.1	2.0	12.6
70.0	4.1	4.6	1.5	10.2

Notes:

- 100% span is 0.0631 m^3/s [1000 gpm]
- multiply table values by 10 to obtain gpm
- no adverse environmental high radiation

Table 1. Indicated Flow Uncertainty, Environment Allowance (EA), Bias, and Total Error versus Actual Flow (in Percent of Span)

2.3. Flow Criteria and Number of (Loop) Flow Indications Available/Used

Assuming various failures, there can be anywhere from 2 to (all) 4 flow indications available. And even if all flow indications are available, it is advantageous if a flow criterion can more quickly allow a "go decision" by using only the two or three highest flow indications.

The (20 minute) flow criteria developed are as follows.

<u>0.0341 m^3/s [540 gpm] minimum core makeup flow is confirmed if:</u>

2nd highest flow (indication)	≥ 0.0318 m^3/s [505 gpm]
sum 2nd & 3rd highest	≥ 0.0515 m^3/s [817 gpm]
sum 2nd, 3rd & 4th highest	≥ 0.0658 m^3/s [1043 gpm]

As an example, the calculation for 3 loop flow indications follows (i.e., sum 2nd and 3rd highest flows).

The flow uncertainty, EA, and bias, at the various loop flows are provided in Table 1 including values at the 2nd and 3rd highest flow indications (33.9 and 16.6% of span).

The two lower flows are algebraically summed (the highest flow is assumed to be spilling), as are the associated flow biases. However, the 2 flow indications are subject to separate (random) flow uncertainties – and these are added using the SRSS method; and the same applies to the EA values. The total is 0.0515 m^3/s [817 gpm].

$$[339+166]+[28+44]+\sqrt{57^2+82^2}+\sqrt{81^2+114^2}\ gpm$$
$$= 817\ gpm.$$

The symbolic representation for the EOP flow criteria ($\dot{V}_{EOP}$) follows. Here the summation is over 1 loop (i=1), over two loops (i=1, 2) or 3 loops (i=1, 2, 3). The various flow errors: flow uncertainty, environmental allowance, and bias, are $\dot{V}_{unc}$, $\dot{V}_{EA}$ and $\dot{V}_{bias}$, respectively.

$$\dot{V}_{EOP} = \sum fL(i)\dot{V}_{core} + \sum \dot{V}_{bias}(i) + \sqrt{\sum \dot{V}^2_{unc}(i)} + \sqrt{\sum \dot{V}^2_{EA}(i)} \qquad (1)$$

2.4. Additional/Other Better Estimate Assumptions

To further reduce the EOP flow criterion it is possible to use (for example) 1σ uncertainty and EA values – similar to what was done below in testing the effectiveness of the flow criteria.

While this is technically sound, it deviates from traditional licensing methods, but is a satisfactory approach for an EOP.

2.5. Description of Vendor Hydraulic Calculations Used

All ECC System hydraulic calculations used in this study were previously performed by the Nuclear Steam Supply System (NSSS) vendor as part of LOCA analyses. These calculations utilize containment sump water level and pressure, and containment and RCS pressures, as upstream and downstream boundary conditions, respectively, to calculate the flows in the flow network (series/parallel flow paths). Included were measured ECCS pump head-flow performance curves and line losses based on the as-built piping configuration.

Basically results of two calculations are used: analysis with the lowest resistance line spilling to containment pressure and 3 intact lines injecting to the higher RCS pressure; and analysis with all 4 lines intact. In order to maximize the adverse flow spilt, and minimize the total flow delivered to the RCS, these analyses have minor differences in the assumptions – including the assumed pump head versus flow.

3. EFFECTIVENESS OF EOP FLOW CRITERIA FOR LARGE LOCA

3.1. Assessment for Case of Large LOCA without Spillage

In order to assess the adequacy of the EOP flow criteria developed above, analysis was carried out for the LOCA without spilling.

The vendor hydraulic analysis loop flow results were provided above. This is a minimum ECCS case (minimum core flow), and using the vendor calculated loop flows as the "known" flows, one can adjust the values by better estimate (1σ) flow uncertainty and EA values. Except now the minus uncertainty and EA values are used,[5] and the bias values (strictly positive) were not used.

i.e., the question is: does the result pass the EOP flow criterion? To the extent it takes all the errors as minus (not random) and uses the "known" loop flows (as discussed earlier in section 2.2) this is a conservative approach, but using the 1σ values tends to offset this.

The resulting flows are 0.0393, 0.0708 and 0.1025 m^3/s [623, 1122 and 1625 gpm] – for 2, 3, and 4 indicators, respectively.[6] These are considerably above the EOP flow criterion of 0.0318, 0.0515 and 0.0658 m^3/s [505, 817, and 1043 gpm], and the EOP flow criterion is satisfactory.

3.2. Assessment for Case of Large LOCA with Spillage

As noted earlier even with zero flow error the flow criterion cannot successfully pass the vendor hydraulic analysis spillage case, as the total ECCS flow was slightly less than the 0.0341 m^3/s [540 gpm] required core makeup flow. With better estimate methods the minimum loop flow (the 2 indicator criterion) is 0.0318 m^3/s [505 gpm] – while the highest flow non-spilling line carried 0.0214 m^3/s [339 gpm] in the vendor analysis.

Although we have not performed revised hydraulic (flow split) analysis, the likely flow in the non-spilling lines will be significantly greater. Two reasons were vendor analysis used a degraded (minimum) pump head-flow curve, and the broken injection line was the line with the lowest losses (as opposed to one of the other 3 lines).

As a limiting case – given the disparity between the flow fractions in the 4 loops (see above – the spilling line carries more than 6 times the flow in the second highest flow rate line), placing the break on any other line will make a substantial difference. Thus even if we assume the vendor analysis case will not (in actuality) meet the EOP criterion, that represents 1 of the 4 possible spilling lines, and the EOP would still probably pass the other three cases, or a success rate of 75%.

In any event (below) comparing the better estimate and traditional licensing approach with line spilling we find the difference in flows (in order to pass the EOP criteria) are greater than 0.019 m^3/s [300 gpm].

[5] At 0.0418 m^3/s [663 gpm] the uncertainty and EA values are -0.0014 m^3/s [-22 gpm] and -0.0011 m^3/s [-17 gpm]. At 0.0328 m^3/s [520 gpm] they are -0.0016 m^3/s [-26 gpm] and -0.0015 m^3/s [-23 gpm], respectively.

[6] Although the analysis is without spillage the operator (procedure) cannot discount the possibility, and the highest flow indicator is always discounted.

4. COMPARE EOP FLOW CRITERIA USING TRADITIONAL LICENSING AND BETTER ESITIMATE METHODS

The following Table 2 summarizes the EOP criteria – obtained using the traditional licensing and better estimate methods.

Flow Indications	EOP criteria	
	Traditional Method[7]	Better Estimate
2^{nd} highest	≥ 0.0530 m^3/s [840 gpm]	≥ 0.0318 m^3/s [505 gpm]
or (if 3^{rd} highest > #) then sum 2^{nd} & 3^{rd} highest	(if > 0.0252 m^3/s [400 gpm]) sum ≥ 0.0719 m^3/s [1140 gpm]	(N/A) sum ≥ 0.0515 m^3/s [817 gpm]
or (if 4^{th} highest > #) then sum 2^{nd} thru 4^{th} highest	(if > 0.0252 m^3/s [400 gpm]) sum ≥ 0.0908 m^3/s [1440 gpm]	(N/A) sum ≥ 0.0658 m^3/s [1043 gpm]

Table 2. Comparison of Better Estimate and Traditional Licensing Method EOP Flow Criteria Methods – to Verify Minimum Core Makeup Flow of 0.03451 m^3/s [540 gpm]

5. QUANTIFY BENEFIT (IN ECCS FLOW SPACE) IN BETTER ESTIMATE EOP FLOW CRITERIA

In order to compare the two methods: traditional licensing method (Annex B) versus better estimate, consider two limiting cases – symmetric flow split and most asymmetric split, and an intermediate flow split.

In order to make these comparisons it is assumed the actual flows are also the indicator values (or that the indicators' errors have nullified each other).

5.1. Symmetric Flow Split and No Spilling Line

This is the most optimistic situation in which each of the 4 indicated flows are 25% of the total. As we assumed the actual flows are also the indicated flows this provides an estimate[8] of the total required ECCS flow. Comparing with the actual flows (to pass the flow criterion) to one measure of the total flow, the ECCS pump design flow, the Table 3 results are obtained.

Number Flow Indicators Available	Total ECCS Flow to Satisfy EOP Flow Criterion (in percent of design flow)	
	Traditional Licensing	Better Estimate
2	112 (fails)	67 (passes)
3	76 (marginal)[9]	55 (passes)
4	64 (passes)	46 (passes)

Note: ECCS pump design flow is 0.189 m^3/s [3000 gpm]

Table 3. Estimate of ECCS Flow Required to Satisfy the EOP Flow Criteria for Symmetric Flow Split in All 4 Lines

From Table 3 results the traditional licensing method fails in the 2 indicator case; and the 3 indicator case marginally passes, as the vendor hydraulic analysis flow was 81% of the design compared to Table 3 value of 76%. All the better estimate cases have considerable margin.

Since some flow asymmetry will be present, and we ignore the highest flow loop, roughly 50% of the time things will be worse than Table 3 suggests. But it is a good indication of the flow difference between the better estimate and traditional licensing method. The better estimate method has "recovered" about 15 to 40% pump flow.

5.2. Most Asymmetric Flow Split and 1 Line Spilling

This is the most pessimistic situation – an extreme flow split asymmetry – with intact lines at {63%, 31%, 6%}.

In neither of the asymmetric flow split cases can the required total ECCS flow be so neatly calculated (as above). Instead we have the total ECCS flow in the 3 injection lines – which are a relatively small fraction of the total ECCS flow. However, this and the following intermediate flow split case,

[7] This is (C) in Annex B. Variation (A), which is probably unworkable in an EOP, gives improved values – but still considerably below the better estimate approach. (e.g., see subsequent footnote relevant to Table 3 results.)

[8] The Tables 3 (and Table 4) results are termed "an estimate" because of the assumption that indicated flow equals actual flow – not that the calculations was numerically imprecise.

[9] e.g., using traditional licensing method in the 3 indicators case, the lowest two (of the three) must total at least 0.0719 m^3/s [1140 gpm] (from Table 2). Or 0.0360 m^3/s [570 gpm] per loop, or for all 4 loops 0.1438 m^3/s [2280 gpm]. This is 76% of the ECCS pump design flow. However, the ECCS pump design flow of 0.189 m^3/s [3000 gpm] is (approximately) an upper bound, while the vendor hydraulic analysis minimum flow of 0.153 m^3/s [2428 gpm] is a lower bound, for the total no spilling large break LOCA ECCS flow; and in Table 3 the former is used (expressed as percent of ECCS pump design flow). Had the latter normalization been used the table value would be 94% (i.e., passes but marginally).

provide an indication of the margins recovered using the better estimate method.[10]

The results are shown in Table 4.

5.3. Intermediate Asymmetric Flow Split and 1 Line Spilling

An intermediate flow split asymmetry in which the flow split in the intact lines is {48%, 32%, 20%}. i.e., average of the above two cases ({63%, 31%, 6%} and {33%, 33%, 33%}).

The results are also shown in Table 4.

Flow Indications	Actual Flow (in m^3/s [gpm])	
	Traditional Licensing	Better Estimate
2^{nd} highest line	0.0530 [840]	0.0318 [505]
<u>total all 3 intact lines:</u>		
most (asymmetric)	0.0842 [1335]	0.0506 [802]
intermediate	0.1104 [1750]	0.0662 [1050]
2^{nd} & 3^{rd} highest	0.0719 [1140]	0.0515 [817]
<u>total all 3 intact lines:</u>		
most	0.0859 [1373][11]	0.0549 [870]
intermediate	0.0977 [1563]	0.0643 [1020]
2^{nd} thru 4^{th} highest	0.0908 [1440]	0.0658 [1043]
<u>total all 3 intact lines:</u>		
most	0.5212 [8330]	0.0658 [1043]
intermediate	0.1564 [2500]	0.0658 [1043]

Table 4. Estimate of Intact Injection Line(s) Flow that Satisfy EOP Flow Criteria: "Most" and "Intermediate" Asymmetry Flow Splits of {63%, 31%, 6%} and {48%, 32%, 20%}

6. CONCLUSION

A better estimate method of developing emergency operating procedure (EOP) core makeup flow criteria was developed – taking credit for a priori knowledge of worst case flow split in the 4 ECCS lines, and using statistical combination of the random errors in the flow indications.

Comparing the better estimate EOP flow criteria to those developed using traditional licensing methods, the better estimate had very significant advantages – as follows.

(1) 0.019 m^3/s [300 gpm] less indicated flow required.

This was the case comparing the 2^{nd} highest flow to the flow criteria, or the sum of the 2^{nd} and 3^{rd} highest flows, or the sum of the 2^{nd}, 3^{rd}, and 4^{th} highest flows. (The highest flow indication cannot be used – as it may be bypassing the RCS and spilling to the containment.)

(2) Implementation of EOP flow criteria was divorced from explicit tabulation/graph of flow error versus indicated flow, or use of a conservative flow error.

Even using such a table or graph, the traditional licensing approach led to significantly larger required flows. Such a table or figure would probably be unworkable (too complex/too time consuming) by an operator – at about 20 minutes into the LOCA.

(3) The criteria will, in all likelihood, avoid external recirculation of containment water – for large break LOCA.

The traditional licensing method generated EOP will have a significant risk of requiring external recirculation when the core makeup flow is in fact adequate. This is clearly undesirable.

ACKNOWLEDGMENTS

The authors would like to acknowledge the effort of Louis F. Liberatori in providing meaningful insight and direction during the completion of this work.

REFERENCES

[1] Westinghouse Electric Corporation, 2005, Westinghouse Owners Group Emergency Response Guidelines, HP/LP-Rev. 2.

[2] Soffer, L., et al., 1995, *Accident Source Terms for Light-Water Nuclear Power Plants*, NUREG-1465, U.S. Nuclear Regulatory Commission, Washington, DC.

[10] This case is somewhat non-physical as increased flow in the intact lines (greater than the hydraulic analysis value of 0.0332 m^3/s [527 gpm]) cannot occur without a concurrent reduction in flow split. This was one reason for including the intermediate case!

[11] The following example illustrates the calculation using the traditional licensing criterion for the sum of the 2^{nd} and 3^{rd} highest (indicated) flows totaling <u>at least</u> 0.0713 m^3/s [1140 gpm], e.g., for the most asymmetric flow split of 0.63, 0.31 and 0.06, the 3^{rd} highest flow is 0.0221 m^3/s [353 gpm]. This is 13% less than the criterion minimum of 0.0252 m^3/s [400 gpm] – thus the flow (0.0719 m^3/s [1140 gpm]) is increased by 13% to satisfy this criterion, and still keep the same flow split; and finally the total is increased to account for the 6% of flow in the 4^{th} loop.

ANNEX A

DEVELOPMENT OF FLOW ERRORS FOR ORIFICE METER

A.1. Total (Flow) Error and the Uncertainty, Environmental Allowance and Bias – Development of Weighting Factors

For the flow indicators the observed differential pressure (dP) is the sum of the actual flow induced dP, and the uncertainty, environmental allowance, and bias dP's ($dP_{act} + dP_{unc} + dP_{EA} + dP_{bias}$). The values of the dP's (as percent of span) were obtained from the error calculations for the orifice flow meter.

The relationship of volumetric flow and dP is,

$$\dot{V} = c_1 \sqrt{dP} \quad \text{(A.1)}$$

At a particular (actual) flow the actual dP is

$$dP_{act} = (\dot{V}_{act} / c_1)^2 \quad \text{(A.2)}$$

and the difference between the observed and actual flow (the flow error) is given by,

$$\begin{aligned} \Delta\dot{V} &= \dot{V}_{obs} - \dot{V}_{act} \\ &= c_1\sqrt{dP_{act} + dP_{unc} + dP_{EA} + dP_{bias}} - c_1\sqrt{dP_{act}} \end{aligned} \quad \text{(A.3)}$$

But, in order to use the SRSS method to statistically combine uncertainties and environmental allowances in multiple loops (indicators) the individual uncertainty, environmental allowance, and bias values are required.

The (unweighted) flow "uncertainty" ($\Delta\dot{V}_{unc}$), flow "environmental allowance" ($\Delta\dot{V}_{EA}$), and flow "bias" ($\Delta\dot{V}_{bias}$), are each calculated at the actual flow as though the other two were not present; and since the relationship between dP and flow are non-linear (and the changes are not small) the total flow error is (substantially) unequal to their sum ($\Delta\dot{V}_{unc} + \Delta\dot{V}_{EA} + \Delta\dot{V}_{bias}$).

Thus a weighing factor (X_{wtg}) is introduced, and for flow uncertainty, flow environmental allowance, and flow bias, the following adjusted (weighted) values $\dot{V}_{unc}$, $\dot{V}_{EA}$ and $\dot{V}_{bias}$ are used.

$$\dot{V}_i = X_{wtg}\,\Delta\dot{V}_i \quad \text{(A.4)}$$

where i = unc, EA, or bias

$$\begin{aligned} \Delta\dot{V} &= \dot{V}_{obs} - \dot{V}_{act} \\ &= \sum\dot{V}_i = \dot{V}_{unc} + \dot{V}_{EA} + \dot{V}_{bias} \end{aligned} \quad \text{(A.5)}$$

which allows calculation of the weighting factor.

$$X_{wtg} = \frac{\Delta\dot{V}}{\sum\Delta\dot{V}_i} = \frac{\Delta\dot{V}}{\Delta\dot{V}_{unc} + \Delta\dot{V}_{EA} + \Delta\dot{V}_{bias}} \quad \text{(A.6)}$$

$$\Delta\dot{V}_i = c_1\sqrt{dP_{act} + dP_i} - c_1\sqrt{dP_{act}} \quad \text{(A.7)}$$

A.2. Environmental Allowance (EA): High Radiation, High Pressure, High Temperature, and High Humidity Effects

The high radiation, high pressure, high temperature, and high humidity effects are combined in the environmental allowance (EA). However, for the post LOCA times of 30 minutes or less, high containment radiation is not present. [2]

As these components (of the EA term) were originally combined using SRSS, it is the justification for combining multiple indicator EA's by the SRSS method. However, for each indicated flow that loop bias is not random and cannot be statistically combined with uncertainty.

ANNEX B

TRADITIONAL LICENSING METHOD EOP FLOW CRITERION DEVELOPMENT

The following develops an alternate EOP flow criterion using more traditional licensing methods. It is based on the observed individual loop flows, adjusted for the loop total flow error, but without use of the SRSS method; and without use of the calculated flow split.

The total flow errors are summarized in Table B-1.

$\dot{V}_{act}$	$\sum \dot{V}_i$ (total error)	$\dot{V}_{act} + \sum \dot{V}_i$
0	38	38
10	30	40
20	23	43
30	19	49
50	14	64
70	11	81

Notes:

- 100% span is 0.0631 m^3/s [1000 gpm]
- multiply table values by 10 to obtain gpm
- includes adverse environmental high radiation

Table B-1. Total Flow Error and Indicated Flow (Actual Flow Plus Flow Error), versus Actual Flow (in Percent of Span)

There are actually three possible approaches considered here. In each case it is assumed the highest flow is in a spilling line, and is not used. In each case the flows are summed and compared to the minimum required core makeup flow of 0.0341 m^3/s [540 gpm].

(A) After discarding highest flow, for all flows above 38% of span, the actual flow is (to be) obtained from plot of actual flow versus indicated flow (from Table B-1) and actual flows are added.

To require an operator to do something this complex in the 20 to 30 minutes post LOCA time frame is potentially problematic.

(B) After discarding highest flow, for all flows above 38% of span the margins to 38% are added.

This method (B) uses the largest error – namely at actual flow of zero [Since method (A) is probably too difficult for the EOP]. But in this case even with no line spilling, only the case of 4 indicators passes – and only barely: 55% versus 54% (of span).

(C) After discarding highest flow, for all flows above 40% of span, the margins to 30% are added.

There are any numbers of versions of (C) – and by inspection this version (40% of span cutoff) seemed reasonable.