REFERENCES

Banerjee, S., Chan, A.M.C., Ramanathan, N. and Yuen, P.S.L. (1978). Fast neutron scattering and attenuation technique for measurement of void fractions and phase distribution in transient flow boiling. Proceedings 6th International Heat Transfer Conference, 1, 351-355.

Banerjee, S., Hussein, E., and Menelay, D.A. (1979). Simulation of a neutron scattering method for measurement void fraction in two-phase flow. Nuclear Engineering and Design, 53, 393-405.

Banerjee, S., Yuen, P., and Vandenbroek, M.A. (1979). Calibration of a fast neutron scattering technique for measurment of void fraction in rod bundles. Journal of Heat Transfer, 101, 295-299.

Boonyanuwat, A. (2001). Steam quality measurements in a high pressure system. Thesis, Petroleum and Petrochemical College, Bangkok.

Frazzoli, F.V. and Magrini, A. (1979). Neutron gauge for measurement of high void fraction in water-steam mixture. Nuclear Technology, 45, 177-182.

Frazzoli, F.R., Magrini, A., Macini, C., and Yuen, P.S.L. (1978). Void fraction measurement in water-steam mixture by means of a Cf-252 neutron source. Journal of Applied Radiation and Isotopes, 29, 311-314.

Han, P., Hussein, E.M.A., Ingham, P.J. and Henschell, R.M. (1994). Nonintrusive measurement of transient flow boiling in rod-bundle channels using fast-neutron scattering. Nuclear Instrument and Methods in Physics Research: Section A, A353, 695-698.

Harms, A.A., Lo, S., and Hancox, W.T. (1971). Measurement of time-averaged voids by neutron diagnosis. Journal of Applied Physics, 42, 4080-4082.

Hewitt, G.F. (1982). Measurement of void fraction. In G. Hetsroni, (Eds), Handbook of multiphase systems (pp. 10-21 10-33). U.S.A.: Hemisphere Publishing Corporation.

Hussein, E.M.A. (1988). Modelling and design of a neutron scatterometer for void-fraction measurement. Nuclear Engineering and Design, 105 (1988), 333-348.

Hussein, E.M.A., and Waller, E.J. (1990). A neutron steam-quality meter for a fluidized bed plant. Applied Radiation and Isotopes, 41(10/11), 1049-1055.

Hussein, E.M.A. (1991). Optimal design of neutron scatterometer for void fraction measurement. Proceedings International Conference on Multiphase Flows, 2, 243-246.

Hussein, E.M.A. (1995). Fast-neutron techniques for volume-fraction measurement in multiphase flows. The American Society of Mechanical Engineers, HO1037, 421-428.

Hussein, E.M.A., and Han, P. (1995). Phase volume-fraction measurement in oil-water-gas flow using fast neutrons. Nuclear Geophysics, 9(3), 229-234.

Jackson, C.N., Allemann, R.T. and Spear, W.G. (1968). Neutron densitometer for measuring void fraction in steam-water flow. Transactions of the American Nuclear Society, 11, 366.

Knoll, G.F. (1989). Radiation Detection and Measurement. New York: John Wiley & Sons.

Los Alamos National Laboratory. (2000). Monte Carlo Neutron and Photon Transport Code (MCNP4C) for Personal Computers. Los Alamos. New Mexico.

Rousseau, J.C., Czerny, J., and Riegel, B. (1976). Void fraction measurement during blowdown by neutron absorption in scattering methods. OECD/NEA Specialists Meeting on Transient Two-Phase Flow, Toronto, August.

Sha, W.T. and Bonilla, C.F. (1965). Out-of-pile steam-fraction determination by neutron-beam attenuation. Nuclear Applications, 1, 69-75.

Smith, J.M., Van Ness, H.C., and Abbott, M.M. (1996). Introduction to Chemical Engineering Thermodynamics. Singapore: McGraw-Hill.

Waller, E.J. and Hussein, E.M.A. (1990). A portable neutron device for void-fraction measurement in a small-diameter pipe. Nuclear Instruments and Methods in Physics Research, A299, 670-673.

Waller, E.J. (1990). A neutron-scattering method for void-fraction measurement in a small-diameter pipe. Ph.D. Thesis, University of New Brunswick, Hamilton, Ontario.

Younis, M.H., Hoffman, T.W., and Harms, A.A. (1981). Neutron diagnosis of two-phase flow. Nuclear Instrumentation and Methods, 187, 489

Yuen, P.S.L. (1985). Devrlopment of an epithermal/fast neutron scattering technique for void fraction measurement in two-phase systems with portable neutron sources. Ph.D. Thesis, McMaster University, Hamilton, Ontario.

Yuen, P.S.L., Meneley, D.A., and Banerjee, S. (1988). Measurement of void fraction by a neutron-scattering technique with portable sources: effect of the incident energy spectrum. International Journal of Multiphase Flow, 14(4), 401-412.

APPENDIX A

EXAMPLE OF INPUT AND OUTPUT FILE FOR MCNP4C

A.1 Input File of Zero Void Fraction for Case 1 (the pipe is on x-axis, the neutron source is on z-axis and the detector is on y-axis)

```
c cell card
1 1 -0.78401 -1 -2 -3 imp:n=1 $ inside pipe
2 2 –8.02714 1 -2 imp:n=1 $ pipe
3 0 3 imp:n=0 $ outside
4 0 2 -3 1 imp:n=1 $ source
c surface
1 cx 0.501 $ inside radius
2 cx 0.62546 $ outside radius
3 cx 3
c source
sdef pos=0 0 1 erg=d1 dir=d2 vec=0 0 1
sc1 energy spectrum cf252
sp1 -3 1.025 2.926
sb2 -31 1
c material
m1  1001 0.66667 8016 0.33333
m2  26000 1
c neutron
phys:n
c detecter
fc5 flux at a point in the void
f5:n 0 -1 0 0
nps 10000000
```

A.2 Output File of Zero Void Fraction for Case 1 (the pipe is on x-axis, the neutron source is on z-axis and the detector is on y-axis)

1problem summary

run terminated when 10000000 particle histories were done.

1neutron activity in each cell   print table 126

	cell	tracks entering	population	collisions	collisions * weight (per history)	number weighted energy	flux weighted energy	average track weight (relative)	average track mfp (cm)
1	1	688855	675594	23096	5.2120E-02	1.0473E+00	2.1993E+00	2.2379E+00	4.7705E+00
2	2	1596089	907239	150081	3.1985E-02	1.2456E+00	2.2208E+00	2.1225E+00	4.2786E+00
4	4	10907239	10000005	0	0.0000E+00	1.4358E+00	2.2740E+00	1.1190E+00	0.0000E+00
	total	13192183	11582838	381045	8.4105E-02				

1tally 5   nps = 10000000

\+   flux at a point in the void

tally type 5   particle flux at a point detector.   units 1/cm**2

tally for neutrons

detector located at x,y,z = 0.00000E+00-1.00000E+00 0.00000E+00

4.24023E-02   0.0004

detector located at x,y,z = 0.00000E+00-1.00000E+00 0.00000E+00

uncollided neutron flux

3.97887E-02   0.0000

detector score diagnostics

times average score	transmissions	cumulative fraction of transmissions	tally per history	cumulative fraction of total tally
1.00000E-01	13135	0.00129	5.57308E-06	0.00013
1.00000E+01	10092507	0.99046	3.99777E-02	0.94295
2.00000E+00	38713	0.99426	2.33996E-04	0.94847
5.00000E+00	31303	0.99732	4.15251E-04	0.95826

1.00000E+01	13249	0.99862	3.94698E-04	0.96757
1.00000E+02	13814	0.99998	1.35129E-03	0.99944
1.00000E+03	47	0.99998	2.30103E-05	0.99998
1.00000E+38	0	0.99998	0.00000E+00	0.99998
1st 200 histories	201	1.00000	7.96875E-07	1.00000

average tally per history = 4.24023E-02 largest score = 7.23731E+00
(largest score)/(average tally) = 1.70682E+02 nps of largest score = 69566177
score contributions by cell

	cell	misses	hits	tally per history	weight per hit
1	1	162294	68670	1.23156E-03	1.79345E-01
2	2	15782	134299	1.38201E-03	1.02906E-01
4	4	0	10000000	3.97887E-02	3.97887E-02
	total	178076	10202969	4.24023E-02	4.15588E-02

score misses
russian roulette on pd 0
psc=0. 137516
russian roulette in transmission 40560

1analysis of the results in the tally fluctuation chart bin (tfc) for tally 5 with nps = 10000000 print table 160

normed average tally per history = 4.24023E-02
unnormed average tally per history = 4.24023E-02
estimated tally relative error = 0.0004
estimated variance of the variance = 0.0003
relative error from zero tallies =0.0000
relative error from nonzero scores = 0.0004
number of nonzero history tallies = 10000000
efficiency for the nonzero tallies = 1.0000
history number of largest tally = 5424155
largest unnormalized history tally = 8.71330E+00
(largest tally)/(average tally) = 2.05491E+02
(largest tally)/(avg nonzero tally) = 2.05491E+02
(confidence interval shift)/mean =0.0000
shifted confidence interval center = 4.24024E-02

if the largest history score sampled so far were to occur on the next history, the tfc bin quantities would change as follows:

estimated quantities	value at nps	value at nps+1	value(nps+1)/value(nps)-1.
mean	4.24023E-02	4.24032E-02	0.000020
relative error	3.71307E-04	3.71307E-04	0.001495

variance of the variance	2.92805E-04	3.00180E-04	0.025187
shifted center	4.24023E-02	4.24032E-02	0.000000
figure of merit	3.49417E+06	3.48375E+06	-0.002983

the estimated slope of the 200 largest tallies starting at 3.53855E+00 appears to be decreasing at least exponentially.
the large score tail of the empirical history score probability density function appears to have no unsampled regions.

results of 10 statistical checks for the estimated answer for the tally fluctuation chart (tfc) bin of tally 5

tfc bin behavior	--mean-- behavior	---------relative error---------- value	decrease	decrease rate	---variance of the variance---- value	decrease	decrease rate	--figure of merit-- value	behavior	-pdf- slope
desired	random	<0.05	yes	1/sqrt(nps)	<0.10	yes	1/nps	constant	random	>3.00
observed	random	0.00	yes	yes	0.00	yes	yes	constant	random	10.00
passed?	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes

this tally meets the statistical criteria used to form confidence intervals: check the tally fluctuation chart to verify.the results in other bins associated with this tally may not meet these statistical criteria.

estimated asymmetric confidence interval(1,2,3 sigma): 4.2387E-02 to 4.2418E-02; 4.2371E-02 to 4.2434E-02; 4.2355E-02 to 4.2450E-02
estimated symmetric confidence interval(1,2,3 sigma): 4.2387E-02 to 4.2418E-02; 4.2371E-02 to 4.2434E-02; 4.2355E-02 to 4.2450E-02
fom = (histories/minute)*(f(x) signal-to-noise ratio)**2 = (4.817E+06)*(8.517E-01)**2 = (4.817E+06)*(7.253E-01) = 3.494E+06
1status of the statistical checks used to form confidence intervals for the mean for each tally bin
tally result of statistical checks for the tfc bin (the first check not passed is listed) and error magnitude check for all bins
5 passed the 10 statistical checks for the tally fluctuation chart bin result
passed all bin error check: 2 tally bins all have relative errors less than 0.05 with no zero bins
the 10 statistical checks are only for the tally fluctuation chart bin and do not apply to other tally bins.
1tally fluctuation charts
run terminated when 10000000 particle histories were done.
computer time = 2.08 minutes
mcnp version 4c 01/20/00 12/24/02 06:04:29 probid = 12/24/02 06:02:15

APPENDIX B
ERROR ANALYSIS

B.1 Introduction

The estimated liquid fraction can be evaluated from the neutron counting by the relationship (Hussein, 1988):

$$\hat{\rho} = \frac{N(\rho) - N(0)}{N(1) - N(0)} \tag{B.1}$$

where:

$\hat{\rho}$ = estimated liquid fraction

$N(\rho)$ = detector responses corresponding to the test section with the actual liquid fraction

$N(1)$ = detector responses corresponding to the test section full of liquid

$N(0)$ = detector responses corresponding to the test section full of vapor

For a neutron counting measurement repeated K times from the same source for equal counting periods, the sample average N_x is as follows (Knoll, 1979).

$$\overline{N} = \sum_{i=1}^{K} \frac{N_i}{K} \tag{B.2}$$

The variance (σ^2) of N_x is defined by:

$$\sigma^2 = \frac{1}{K-1} \sum_{i=1}^{K} \left(N_i - \overline{N}\right)^2 \tag{B.3}$$

The standard deviation of the measured value $N_1, \ldots, N_K$ in the above case is σ. Therefore, the error or uncertainty in N_x can be expressed as the standard error of mean, which is given by:

$$\varepsilon = \frac{\sigma}{\sqrt{K}} \tag{B.4}$$

The precision of the measurement is usually defined using percent error of the mean:

$$\% \Delta\overline{N} = \frac{\varepsilon}{\overline{N}} \times 100 \tag{B.5}$$

For this work, each measurement was repeated ten times to ensure that the uncertainty or the standard error associated with all measurement was less than one percent. Additionally, the 68 percent of any subsequent measurements of N_i have been expected to fall in the range $\overline{N} \pm \varepsilon$

Moreover, by using the Chauvent' s criterion, if $|N_i - \overline{N}|$ exceed 1.96σ for 10 measurements, then the reading could be rejected. In that case, a new mean should be calculated without this measurement and also a new standard deviation, since the original values were unduly influenced by extreme observations.

B.2 Void Fraction Measurement

There is a propagation error in the measurement of the liquid fraction since it is a function of many values. The propagation error can be expressed as follow.

$$\Delta\hat{\rho} = \frac{\partial\hat{\rho}}{\partial N(x)}\Delta N(x)^2 + \frac{\partial\hat{\rho}}{\partial N(0)}\Delta N(0)^2 + \frac{\partial\hat{\rho}}{\partial N(1)}\Delta N(1)^2 \qquad (B.6)$$

Using a differential identity, the final form of the error can be stated as

$$\Delta\hat{\rho} = \frac{\sqrt{(N(1)-N(0))^2\Delta N(x)^2 + (N(x)-N(1))^2\Delta N(0)^2 + (N(x)-N(0))^2\Delta N(1)^2}}{(N(1)-N(0))^2} \qquad (B.7)$$

It should be noted however the counts N(0) and N(1), being reference counts, can be pre-determined so that they possess a low uncertainly. The count rate $N(\rho)$ is usually measured on-line within a short period and tends to have a relatively large variance, in comparison to the reference measurements.

The estimated volume fraction can be quoted as follows:

$$\hat{\rho} \pm \Delta\hat{\rho} \qquad (B.8)$$

APPENDIX C
DATA OF MCNP4C SIMULATION RESULTS

Table C1 Simulation results for case 1: the pipe is on x-axis, the neutron source is on z-axis and the detector is on y-axis.

Actual void fraction	Average density of mixture (g/cm^3)	Neutron flux (particle/cm^2)		The total number of neutron hit inside the pipe	Relative %Error*
		Total	Scattered		
0.0	0.78370	0.0424023	0.00123156	68670	0.0004
0.1	0.70770	0.0422902	0.00111833	61905	0.0004
0.2	0.63170	0.0421694	0.00099548	55038	0.0003
0.3	0.55570	0.0420501	0.00087654	48311	0.0003
0.4	0.47970	0.0419332	0.00075895	41502	0.0003
0.5	0.40370	0.0418149	0.00063851	34832	0.0003
0.6	0.32770	0.0417041	0.00052553	28190	0.0003
0.7	0.25170	0.0415778	0.00039978	21592	0.0003
0.8	0.17570	0.0414609	0.00028057	15173	0.0003
0.9	0.09970	0.0413423	0.00015885	8656	0.0003
1.0	0.02370	0.0412227	0.00003725	2024	0.0002

* Estimated relative error is defined to be one estimated standard deviation of the mean ($S_{\bar{x}}$) divided by the estimated mean ($\bar{x}$).

Table C2 Simulation results for case 2: the pipe is on y-axis, the neutron source is on x-axis and the detector is on z-axis.

Actual void fraction	Average density of mixture (g/cm^3)	Neutron flux (particle/cm^2)		The total number of neutron hit inside the pipe	Relative %Error
		Total	Scattered		
0.0	0.78370	0.0423952	0.00122812	68673	0.0004
0.1	0.70770	0.0422821	0.00111402	61852	0.0004
0.2	0.63170	0.0421635	0.00099488	54938	0.0003
0.3	0.55570	0.0420446	0.00087620	48150	0.0003
0.4	0.47970	0.0419307	0.00076037	41338	0.0003
0.5	0.40370	0.0418149	0.00064126	34809	0.0003
0.6	0.32770	0.0417021	0.00052606	28184	0.0003
0.7	0.25170	0.0415786	0.00040251	21637	0.0003
0.8	0.17570	0.0414614	0.00028174	15116	0.0003
0.9	0.09970	0.0413421	0.00015938	8676	0.0003
1.0	0.02370	0.0412218	0.00003687	2027	0.0002

* Estimated relative error is defined to be one estimated standard deviation of the mean ($S_{\bar{x}}$) divided by the estimated mean ($\bar{x}$).

Table C3 Simulation results for case 3: the pipe is on z-axis, the neutron source is on y-axis and the detector is on x-axis.

Actual void fraction	Average density of mixture (g/cm³)	Neutron flux (particle/cm²)		The total number of neutron hit inside the pipe	Relative %Error*
		Total	Scattered		
0.0	0.78370	0.0424302	0.00125078	68652	0.0004
0.1	0.70770	0.0423142	0.00113387	61771	0.0004
0.2	0.63170	0.0421921	0.00100899	54939	0.0004
0.3	0.55570	0.0420722	0.00088791	48094	0.0003
0.4	0.47970	0.0419545	0.00077011	41471	0.0003
0.5	0.40370	0.0418362	0.00065173	34834	0.0003
0.6	0.32770	0.0417175	0.00053127	28318	0.0003
0.7	0.25170	0.0416009	0.00041432	21749	0.0003
0.8	0.17570	0.0414839	0.00029457	15172	0.0003
0.9	0.09970	0.0413494	0.00015610	17806	0.0002
1.0	0.02370	0.0412367	0.00004150	2068	0.0003

* Estimated relative error is defined to be one estimated standard deviation of the mean ($S_{\bar{x}}$) divided by the estimated mean ($\bar{x}$).

APPENDIX D

DATA OF STATIC AIR-LUCITE EXPERIMENTAL RESULTS

Table D1 Neutron count rate for 2 minutes of the test section at different Lucite fraction.

Experiment	Zero	0.086	0.173	0.259
1	1490	1449	1457	1483
2	1453	1449	1489	1501
3	1458	1477	1440	1469
4	1425	1488	1467	1467
5	1469	1481	1467	1495
6	1497	1435	1500	1477
7	1448	1443	1474	1471
8	1464	1488	1490	1495
9	1439	1469	1461	1448
10	1458	1481	1478	1489
Mean	1460.10	1466.00	1472.30	1479.50
%standard error	0.47	0.43	0.38	0.35
Variance	470.32	401.78	317.34	264.72
Standard error	6.86	6.34	5.63	5.15

Table D1 Neutron count rate for 2 minutes of the test section at different Lucite fraction (continued).

Experiment	0.345	0.432	0.518	0.604	1.00
1	1473	1485	1495	1496	1529
2	1470	1511	1486	1494	1554
3	1480	1478	1507	1502	1512
4	1486	1491	1486	1492	1520
5	1473	1498	1477	1462	1550
6	1486	1477	1492	1541	1527
7	1490	1484	1515	1522	1522
8	1494	1489	1484	1473	1563
9	1490	1484	1502	1533	1515
10	1480	1499	1483	1501	1545
Mean	1482.20	1489.60	1492.70	1501.60	1533.70
%standard error	0.18	0.22	0.25	0.52	0.37
Variance	68.62	110.71	144.46	613.60	319.57
Standard error	2.62	3.33	3.80	7.83	5.65

APPENDIX E
DATA OF DYNAMIC NITROGEN-WATER EXPERIMENTAL RESULTS

E.1 Fast Neutron Scattering Technique

E.1.1 Case 1: without filter

Table E1.1 Neutron count rate at different nitrogen flow rates for 50 seconds.

Experiment	Full of water	2 scfh	3.2 scfh
1	1585	1611	1537
2	1605	1580	1560
3	1492	1536	1480
4	1612	1557	1486
5	1541	1510	1552
6	1565	1462	1532
7	1543	1462	1604
8	1498	1549	1499
9	1536	1542	1539
10	1569	1546	1507
11	1427	1576	1512
12	1661	1504	1550
13	1549	1548	1490
14	1556	1570	1543
15	1539	1579	1493
16	1504	1555	1575
17	1611	1559	1519
18	1514	1521	1509
19	1559	1519	1525
20	1469	1537	1538
Mean	1546.75	1541.15	1527.50
Variance	2960.30	1399.08	1017.53
Standard error	12.17	8.36	7.13
%standard error	0.79	0.54	0.47

Table E1.1 Neutron count rate at different nitrogen flow rates for 50 seconds (continued).

Experiment	4.5 scfh	7 scfh	9.2 scfh
1	1479	1497	1476
2	1523	1450	1508
3	1560	1432	1478
4	1543	1487	1450
5	1508	1545	1556
6	1510	1472	1491
7	1482	1404	1555
8	1492	1511	1445
9	1543	1524	1431
10	1469	1501	1397
11	1533	1489	1520
12	1481	1485	1429
13	1611	1459	1423
14	1525	1463	1475
15	1573	1454	1555
16	1530	1476	1464
17	1500	1405	1450
18	1481	1448	1448
19	1520	1521	1432
20	1494	1530	1455
Mean	1517.85	1477.65	1471.90
Variance	1306.87	1536.45	2138.83
Standard error	8.08	8.76	10.34
%standard error	0.53	0.59	0.70

Table E1.1 Neutron count rate at different nitrogen flow rates for 50 seconds (continued).

Experiment	14 scfh	18.8 scfh	Full of vapor
1	1473	1355	1179
2	1432	1473	1121
3	1423	1443	1225
4	1451	1413	1238
5	1511	1403	1157
6	1459	1404	1219
7	1450	1379	1162
8	1450	1375	1199
9	1406	1454	1208
10	1418	1523	1242
11	1457	1360	1255
12	1438	1382	1193
13	1445	1443	1194
14	1459	1378	1255
15	1401	1382	1248
16	1441	1374	1205
17	1428	1371	1158
18	1488	1345	1196
19	1470	1424	1194
20	1514	1494	1182
Mean	1450.70	1408.75	1201.50
Variance	923.17	2395.36	1304.89
Standard error	6.79	10.94	8.08
%standard error	0.47	0.78	0.67

E.1.2 Case 2: with 60 μm filter

Table E1.2 Neutron count rate at different nitrogen flow rates for 50 seconds

Experiment	Full of water	2 scfh	3.2 scfh
1	1560	1556	1603
2	1542	1535	1583
3	1613	1526	1569
4	1519	1606	1471
5	1558	1551	1496
6	1541	1556	1504
7	1508	1602	1554
8	1536	1545	1517
9	1543	1560	1560
10	1561	1606	1552
11	1548	1559	1603
12	1570	1547	1473
13	1605	1609	1545
14	1542	1495	1552
15	1593	1517	1520
16	1551	1570	1548
17	1613	1559	1544
18	1533	1535	1519
19	1523	1537	1543
20	1560	1504	1531
Mean	1555.95	1553.75	1539.35
Variance	899.52	1072.09	1344.77
Standard error	6.71	7.32	8.20
%standard error	0.43	0.47	0.53

Table E1.2 Neutron count rate at different nitrogen flow rates for 50 seconds (continued).

Experiment	4.5 scfh	7 scfh	9.2 scfh
1	1628	1512	1456
2	1498	1534	1417
3	1597	1460	1495
4	1484	1426	1371
5	1539	1569	1464
6	1553	1443	1431
7	1555	1487	1440
8	1555	1478	1534
9	1491	1461	1476
10	1466	1512	1544
11	1533	1590	1468
12	1516	1566	1526
13	1529	1531	1552
14	1526	1439	1437
15	1569	1518	1476
16	1521	1505	1479
17	1572	1499	1508
18	1509	1435	1488
19	1497	1495	1544
20	1553	1548	1461
Mean	1534.55	1500.40	1478.35
Variance	1575.94	2249.62	2236.66
Standard error	8.88	10.61	10.58
%standard error	0.58	0.71	0.72

Table E1.2 Neutron count rate at different nitrogen flow rates for 50 seconds (continued).

Experiment	14 scfh	18.8 scfh	Full of vapor
1	1475	1400	1191
2	1395	1384	1191
3	1509	1452	1184
4	1497	1339	1200
5	1572	1456	1214
6	1456	1502	1220
7	1376	1474	1179
8	1499	1419	1215
9	1479	1453	1199
10	1476	1391	1209
11	1475	1442	1219
12	1490	1441	1216
13	1458	1368	1198
14	1402	1460	1181
15	1459	1400	1180
16	1475	1414	1214
17	1461	1404	1212
18	1502	1451	1280
19	1441	1387	1212
20	1503	1371	1169
Mean	1470.00	1420.40	1204.15
Variance	1929.89	1711.41	560.24
Standard error	9.82	9.25	5.29
%standard error	0.67	0.65	0.44

E.1.3 Case 3: with 15 micron filter.

Table E1.3 Neutron count rate at different nitrogen flow rates for 50 seconds.

Experiment	Full of water	2 scfh	3.2 scfh
1	1674	-	1755
2	1746	-	1736
3	1658	-	1742
4	1725	-	1781
5	1821	-	1681
6	1726	-	1786
7	1712	-	1776
8	1713	-	1784
9	1725	-	1760
10	1729	-	1629
11	1745	-	1655
12	1768	-	1739
13	1751	-	1711
14	1742	-	1774
15	1692	-	1731
16	1733	-	1715
17	1774	-	1721
18	1744	-	1754
19	1734	-	1691
20	1727	-	1684
Mean	1731.95	-	1730.25
Variance	1227.63	-	1978.83
Standard error	7.83	-	9.95
%standard error	0.45	-	0.57

Table E1.3 Neutron count rate at different nitrogen flow rates for 50 seconds (continued).

Experiment	4.5 scfh	7 scfh	9.2 scfh
1	1677	1720	1692
2	1745	1722	1715
3	1683	1737	1733
4	1754	1682	1721
5	1781	1758	1679
6	1752	1698	1717
7	1735	1704	1755
8	1787	1768	1837
9	1742	1736	1706
10	1742	1725	1656
11	1778	1781	1714
12	1732	1759	1738
13	1706	1786	1663
14	1673	1729	1800
15	1707	1706	1695
16	1728	1697	1703
17	1705	1664	1709
18	1695	1653	1751
19	1743	1675	1730
20	1723	1722	1592
Mean	1729.40	1721.10	1715.30
Variance	1115.41	1396.83	2627.48
Standard error	7.47	8.36	11.46
%standard error	0.43	0.49	0.67

Table E1.3 Neutron count rate at different nitrogen flow rates for 50 seconds (continued).

Experiment	14 scfh	18.8 scfh	Full of vapor
1	1646	1579	1262
2	1661	1678	1320
3	1640	1630	1334
4	1759	1615	1382
5	1656	1674	1323
6	1739	1683	1382
7	1668	1638	1404
8	1664	1649	1320
9	1657	1641	1389
10	1645	1669	1384
11	1660	1623	1415
12	1720	1593	1293
13	1685	1675	1275
14	1656	1690	1415
15	1754	1665	1341
16	1707	1622	1426
17	1657	1667	1329
18	1608	1741	1341
19	1738	1716	1385
20	1637	1685	1382
Mean	1677.85	1656.65	1355.10
Variance	1853.08	1588.45	2294.83
Standard error	9.63	8.91	10.71
%standard error	0.57	0.54	0.79

E.2 Fast Neutron Transmission Technique

Case 3 with 15 μm filter was the only case that was experimented.

Table E2 Neutron count rate at different nitrogen flow rates for 50 seconds.

Experiment	Full of water	2 scfh	3.2 scfh	4.5 scfh
1	2424	-	2351	2281
2	2264	-	2384	2344
3	2254	-	2343	2304
4	2287	-	2368	2381
5	2388	-	2391	2320
6	2428	-	2355	2334
7	2239	-	2392	2380
8	2468	-	2297	2382
9	2367	-	2382	2358
10	2434	-	2381	2444
11	2395	-	2325	2344
12	2472	-	2331	2306
13	2370	-	2346	2402
14	2397	-	2377	2340
15	2317	-	2311	2360
16	2486	-	2428	2412
17	2484	-	2448	2271
18	2320	-	2385	2439
19	2292	-	2369	2389
20	2280	-	2325	2406
Mean	2368.30	-	2364.45	2359.85
Variance	6668.43	-	1408.89	2392.24
Standard error	18.26	-	8.39	10.94
%standard error	0.77	-	0.35	0.46

Table E2 Neutron count rate at different nitrogen flow rates for 50 seconds (continued).

Experiment	7 scfh	9.2 scfh	14 scfh	18.8 scfh	Full of vapor
1	2331	2346	2206	2173	1811
2	2301	2341	2277	2206	1909
3	2374	2278	2270	2262	1978
4	2396	2330	2305	2257	1815
5	2289	2238	2215	2193	1889
6	2309	2331	2264	2301	1853
7	2294	2287	2214	2170	1961
8	2340	2303	2237	2220	1872
9	2392	2317	2300	2221	1885
10	2402	2261	2276	2241	1922
11	2340	2269	2202	2168	1860
12	2330	2299	2232	2270	1893
13	2370	2276	2219	2231	1875
14	2334	2272	2239	2240	1926
15	2398	2351	2221	2243	1971
16	2325	2357	2133	2255	2002
17	2306	2303	2276	2244	1933
18	2398	2281	2208	2170	1982
19	2331	2247	2214	2210	1883
20	2298	2315	2230	2208	1927
Mean	2342.90	2300.10	2236.90	2224.15	1907.35
Variance	1523.25	1239.46	1636.62	1380.24	2894.77
Standard error	8.73	7.87	9.05	8.31	12.03
%standard error	0.37	0.34	0.40	0.37	0.63

APPENDIX F
DATA OF DYNAMIC STEAM-WATER EXPERIMENTAL RESULTS

F.1 Study of Temperature Effects

Table F1 Neutron count rates at various temperature and pressure 5 MPa for 10 seconds.

Experiment	50°C	80°C	100°C	150°C	200°C
1	90161	88136	88886	86984	85286
2	89919	88378	88758	87141	85422
3	89838	88607	87684	87129	85190
4	89886	88951	88310	86407	85109
5	90574	88332	88093	86360	85420
6	90166	88725	87762	86815	85423
7	89406	88060	88341	86808	85656
8	89993	88681	87792	86117	85794
9	89802	88639	87782	86390	85320
10	90031	90114	87539	86210	85418
11	90685	86467	88106	86738	85327
12	89917	89679	87851	86808	85667
13	90516	90038	87866	87309	85422
14	90281	89621	88504	86994	85554
15	90026	89445	88282	87167	85289
16	89789	90548	88134	86432	85284
17	90142	90463	87954	86954	85460
18	90211	91186	87888	86792	85930
19	90296	90835	88558	87108	85090
20	90072	90564	88367	87118	85750
Mean	90085.55	89273.45	88122.85	86789.05	85440.55
Variance	89444.26	1386320.47	136955.71	125132.26	50920.79
Standard error	66.87	263.28	82.75	79.10	50.46
%standard error	0.07	0.29	0.09	0.09	0.06

F.2 Steam Quality Measurements

Table F2.1 Neutron count rates at 150°C for 10 seconds for series1.

Experiment	100%	75%	50%	25%	0%
1	110545	112579	114263	115260	116208
2	110716	112205	113803	115256	117513
3	110782	113112	114948	115639	116226
4	110081	112685	114776	115226	115164
5	109045	112864	114420	115118	115750
6	109189	113522	113987	115705	116452
7	109177	112698	113545	115602	117049
8	110566	113309	113268	115381	116516
9	110993	113245	114288	116435	116827
10	110872	112578	114312	116345	115647
11	111514	112811	114265	115313	115730
12	111213	113175	113365	114820	116641
13	110907	113047	114398	115308	116014
14	111010	113398	113792	116195	116400
15	111499	112866	113727	116821	115894
16	110058	111860	113395	115174	116792
17	111743	113004	114647	114719	115627
18	111219	112632	113794	115675	116862
19	110559	113305	115401	115390	115804
20	110915	112761	114072	115382	116952
Mean	110630.15	112882.80	114123.30	115538.20	116303.40
Variance	596328.66	168010.17	313116.22	290436.69	357512.78
Standard error	172.67	91.65	125.12	120.51	133.70
%standard error	0.16	0.08	0.11	0.10	0.11

Table F2.2 Neutron count rates at 150°C for 10 seconds for series2.

Experiment	100%	75%	50%	25%	0%
1	106933	108464	111522	111897	114888
2	107759	108289	109702	113615	114881
3	106402	108697	110043	113518	114882
4	107380	108396	110109	111685	114160
5	107470	109453	111081	112031	114790
6	107352	108625	110589	112462	114543
7	107061	108140	110377	111836	114669
8	107499	108162	110291	112136	114178
9	106783	108096	110074	112031	114137
10	106834	108690	109734	113506	113064
11	106596	108656	109996	112627	113626
12	107742	109129	110047	112688	114113
13	106596	108941	110140	112371	113328
14	107283	108207	109624	112499	114033
15	107124	109160	109993	112385	114351
16	107272	109126	111710	112391	114940
17	106874	108003	110144	112736	113188
18	107904	109092	110283	112701	113495
19	107406	108430	110130	112032	113065
20	107477	109281	110016	112554	113172
Mean	107187.35	108651.85	110280.25	112485.05	114075.15
Variance	174981.40	196914.98	309056.41	302156.05	454454.45
Standard error	93.54	99.23	124.31	122.91	150.74
%standard error	0.09	0.09	0.11	0.11	0.13

Table F2.3 Neutron count rates at 200°C for 10 seconds for series1.

Experiment	100%	75%	50%	25%	0%
1	109186	112637	113511	114976	115940
2	109950	112312	113399	114991	115587
3	109791	111791	114214	114775	115607
4	109913	112166	114448	115092	116035
5	109695	112075	113191	114339	115442
6	110052	112227	113652	114441	115732
7	109958	111872	114259	115115	115397
8	110496	112843	113950	114806	115404
9	110630	112052	113921	114441	115267
10	110368	112500	113367	114008	115385
11	110480	112291	114020	115286	116007
12	110950	111891	113821	114412	115776
13	110421	111921	113889	114614	115267
14	110423	112507	113943	114898	115307
15	109964	113221	113791	114000	115385
16	110357	112343	114903	114872	115440
17	110238	112701	114590	114728	115397
18	110092	112972	114272	114804	115537
19	110883	112331	114072	114663	115262
20	110957	112939	114855	114833	115789
Mean	110240.20	111932.15	113751.20	114704.70	115548.15
Variance	200879.96	172772.56	149372.59	119457.59	62670.13
Standard error	100.22	92.94	86.42	77.28	55.98
%standard error	0.09	0.08	0.08	0.07	0.05

Table F2.4 Neutron count rates at 200°C for 10 seconds for series2.

Experiment	100%	75%	50%	25%	0%
1	110041	112728	114868	116388	117932
2	110437	113258	114510	116309	117518
3	109544	112914	114743	116375	117925
4	109347	112924	114869	116217	117872
5	110256	113539	113953	115200	117560
6	110447	112825	114490	115596	118402
7	109532	112882	114451	115647	117680
8	110212	112624	114822	115878	118505
9	110237	112729	114786	115879	117590
10	110771	112850	114533	115796	118094
11	110078	113063	115092	116465	118208
12	110190	112917	115581	115873	117614
13	110241	112859	115539	115875	118202
14	110528	113107	115749	116489	117844
15	110837	113108	115917	116623	117946
16	110601	113854	114226	116321	117842
17	109991	113460	114671	115772	117293
18	110123	113119	114877	116659	118175
19	110373	113150	115316	116676	117142
20	109884	113815	114360	116279	117916
Mean	110183.50	113086.25	114867.65	116115.85	117863.00
Variance	154846.68	119630.51	274422.13	166506.98	122742.95
Standard error	87.99	77.34	117.14	91.24	78.34
%standard error	0.08	0.07	0.10	0.08	0.07

Table F2.5 Neutron count rates at 250°C for 10 seconds for series1.

Experiment	100%	75%	50%	25%	0%
1	112646	114208	114943	115840	116891
2	112368	112708	115140	116760	117096
3	112147	113020	114747	116569	116889
4	112381	113624	114743	116373	116831
5	112185	113185	114752	117248	116838
6	112298	112976	114354	116143	116654
7	112113	113582	115509	116478	117477
8	112835	113632	114166	116475	117238
9	112294	113489	114370	116536	117216
10	112760	113022	115077	116861	117591
11	112495	113044	115828	116366	117480
12	112855	113819	114725	116945	117856
13	112542	113491	114860	116816	117396
14	112331	113722	114824	116661	116823
15	112095	113732	115224	116320	116939
16	112238	113810	114513	116329	117319
17	112612	112941	114423	116789	117090
18	112326	113742	114171	117020	116839
19	112756	113508	115022	117357	116953
20	112629	113123	114066	116427	116918
Mean	112445.30	113418.90	114772.85	116615.65	117116.70
Variance	60198.33	152186.20	207862.66	135440.45	100809.91
Standard error	54.86	87.23	101.95	82.29	71.00
%standard error	0.05	0.08	0.09	0.07	0.06

Table F2.6 Neutron count rates at 250°C for 10 seconds for series2.

Experiment	100%	75%	50%	25%	0%
1	113563	115017	114938	116423	116386
2	113621	114732	115225	115945	117045
3	113181	114614	115007	116285	116407
4	112647	114855	115692	116403	117346
5	112552	113742	115943	115601	116676
6	112770	114472	115168	115656	116827
7	112741	114515	115917	116599	116337
8	112672	114860	115139	115839	116493
9	113149	114288	115728	116443	116383
10	113923	115309	115571	116580	117264
11	113628	115040	115786	116519	117149
12	113920	115086	115674	116387	116511
13	113345	114358	115808	116393	116720
14	113782	114755	115347	115872	116528
15	113283	114511	115035	115773	116686
16	113445	114836	116111	116669	117143
17	113125	115316	115412	116072	116149
18	112936	114536	115586	116231	117049
19	114007	113737	115926	116280	116601
20	112851	114489	115347	115820	116778
Mean	113257.05	114653.40	115518.00	116189.50	116723.90
Variance	218226.47	182986.57	124869.79	113720.47	117068.83
Standard error	104.46	95.65	79.02	75.41	76.51
%standard error	0.09	0.08	0.07	0.06	0.07

APPENDIX G
STEAM QUALITY CALCULATION

The system is shown in Figure G1. The heated water from the preheater is entering the autoclave at saturated condition of 150°C and the corresponding pressure of 475.9 kPa. The volumetric flow rate of water is measured at the end and it is quite stable at 260 cc/min. The power of the heater is 50% of maximum capacity, which is 500 W.

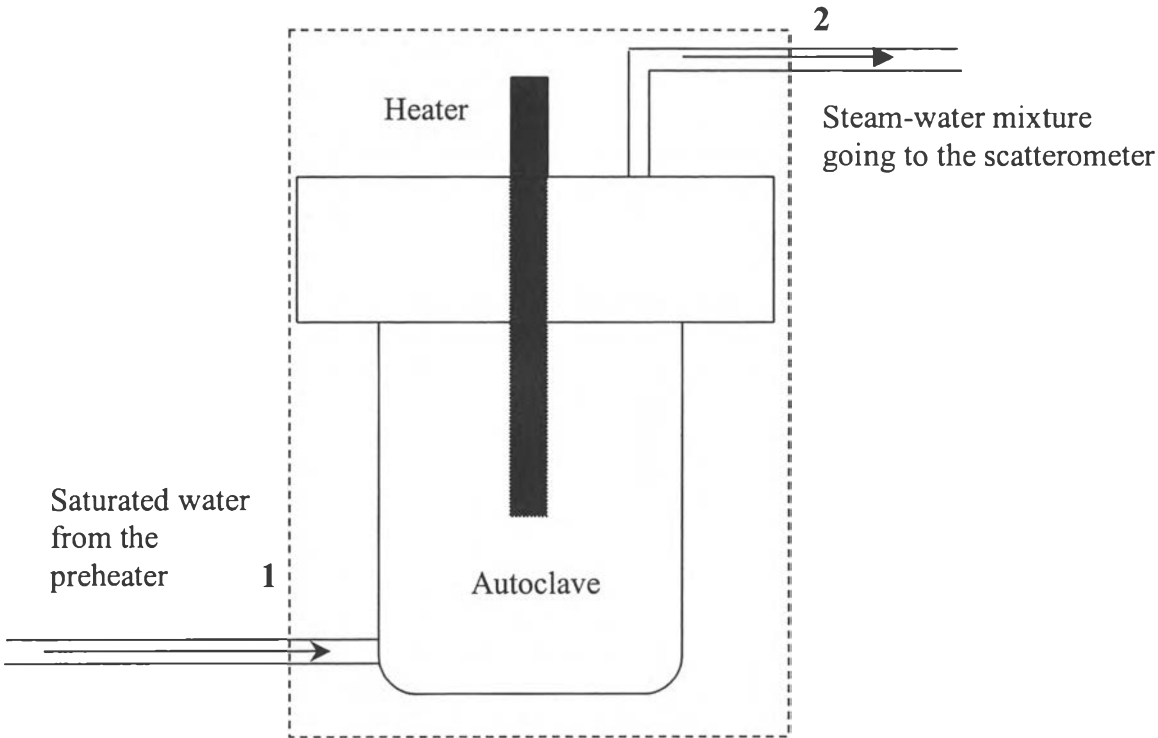

Figure G1 System for thermodynamic calculation.

Assumption: 1. The heated water entering to the autoclave is saturated water.

2. The heat loss from the heater is negligible because the heater is installed inside the autoclave.

Energy balance equation for steady state flow system around the autoclave:

$$\dot{m}\left[\Delta h + \left(\frac{\Delta u^2}{2}\right) + g\Delta z\right] = Q + W_s \qquad \text{(G.1)}$$

Assumption: 1. There is no shaft work produced from system.

2. There is no change in velocity of saturated water.

Therefore, equation (G.1) is reduced to;

$$\dot{m}(\Delta h + g\Delta z) = Q \tag{G.2}$$

The potential energy is small compared to the change in enthalpy and the heat added to the system. So, this term can be neglected.

$$\dot{m}(\Delta h) = Q \tag{G.3}$$

It is assumed that the heated water is saturated water and that enthalpy of saturated water entering through the autoclave at point 1 (h_1) is equal to the enthalpy of saturated water at the exit of the autoclave (h_2) can be calculated from this equation.

$$\dot{m}(h_2 - h_f) = Q \tag{G.4}$$

where h_f = 632.18 J/g

$Q = (0.50 \times 500) = 250$ J/s

For the mass flow rate of saturated water ($\dot{m}$) is estimated from equation G.5)

$$\dot{m} = V\rho \tag{G.5}$$

where V is the volumetric flow rate of saturated water

ρ is the density of water at 25 °C

Therefore,

$$\dot{m} = \left[278\left(\frac{cc}{min}\right) \times 0.997\left(\frac{g}{cm^3}\right)\right] \times \left(\frac{1\,min}{60\,sec}\right)$$

$$\dot{m} = 4.62\frac{g}{s}$$

Then

$$h_2 = \left(\frac{Q}{\dot{m}}\right) + h_f$$

$$h_2 = \left(\frac{250}{4.32}\right) + 632.18$$

$$h_2 = 686.30\frac{J}{s}$$

From the steam quality calculation, the flow of saturated water is assumed to be homogeneous in order to calculate steam quality (x) from this equation.

$$x = \frac{h_2 - h_f}{h_g - h_f} \tag{G.6}$$

where h_g is the enthalpy of saturated vapor equal to 2746.77 J/g.

$$x = \frac{686.30 - 632.18}{2746.44 - 632.18}$$

$$x = 0.026$$

Therefore, steam quality at saturated temperature of 150°C and 50% of maximum capacity of heater is 0.026.

CURRICULUM VITAE

Name: Ms. Bhurisa Thitakamol

Date of Birth: April 4, 1979

Nationality: Thai

University Education:

1997-2001 Bachelor Degree of Engineering in Chemical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand. (Second class honors)

Industrial Trainings:

1. Department of Industrial Chemistry, School of Engineering Tokai University for the period of April 19 – May 19, 2000
2. Research assistance for Master thesis in the topic of Development of a Neutron Device to Measure Steam Quality in a High Pressure, Department of Chemical Engineering, Faculty of Engineering, University of New Brunswick, Canada from April 1, 2002 – March 21, 2003.
3. Radiation Protection training course – level II, Fredericton, Canada, from June 24 – 25, 2002

Publications:

1. Lothongkum, A.W., Chinsutthi, R., and Thitakamol, B., (2001). Energy conservation in the designated buildings and factories. Rangsit University Journal of Engineering and Technology, 5(1), 5-12.
2. Lothongkum, A.W., Chinsutthi, R., and Thitakamol, B., (2001). Energy auditing at Khao Leam hydro power plant. Rangsit University Journal of Engineering and Technology, 5(1), 63-72.

Proceedings:

1. Steam Quality Measurement in a High Pressure System, 11th Annual Conference on Student Research, University of New Brunswick, February 14-15, 2003.

Extracurricular Activities:

1. AFS exchange student for annual program in Italy, 1996
2. Member of Northern Club, King Mongkut's Institute of Technology Ladkrabang, 1999-2000
3. Member of Thai Student Association, University of New Brunswick, 2002-2003