The New Equation of Steam Quality and the Evaluation of Nonradioactive Tracer Method in PWR Steam Generators

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ABSTRACT

The performance of steam turbines is tested as ANSI/ASME-PTC 6. This code provides rules for the accurate testing of steam turbines for the purpose of obtaining the level of performance with a minimum uncertainty. Only the relevant portion of this code needs to process any individual case, In some case the procedure is simple. However, in complex turbines or complex operation modes, more procedures are required to test the involved provisions. Anyway, to measure the steam quality in the Wolsong PHWR with 4 SGs in Korea by the methods in the section "Measure of steam quality methods" of ANSI/ASME PTC 6, the result was not good though the steam generators are efficient. So, the new testing method was developed and the sophisticated equation of steam quality was introduced and uses the nonradioactive chemical tracer, Lithium hydroxide(LiOH) instead of the radioactive tracer, Na-24.

In the ASME-PTC 6, there are several steam quality measuring methods like radioactive tracer, Dilution technique, Condensing method and Throttle-steam methods. The typical steam quality $(1-\chi)$ or the moisture carryover ratio (χ) equation in the re-circulation type steam generators is as following.

$$\chi = \frac{(1-R)C_{ms}}{C_b} \qquad \text{(A)}$$

where, $R = w_{ms} / w_e$, Inverse of circulation ratio,

C_{ms}, Tracer concentration in the sample of main steam

C_b, Tracer concentration in the sample of SG blowdown

By the way, we derived a general steam quality equation as following

$$\chi_T = \frac{R'^2 \, C_{fw}}{(R'+L)\,(R'+L+M\,(1-L))\dfrac{\sum C_b \, w_{fwi}}{\sum w_{fwi}} - (R'+L)\,(L+M\,(1-L)+R'L)\,C_{fw}} \quad \text{.. (B)}$$

where, $R' = w_r / w_{ms}$, Recirculation ratio L,M are SG's geometric factors

in case of the steady state, w_{ms} would be replaced with w_{fw}

The steam quality is 99.59% with the equation (A) in the specification limit value of 99.75%. But the new calculation result with the equation (B) is 99.98%.

1. INTRODUCTION

Generally, the steam supply system in Nuclear Power Plants consists in 2, 3 or 4 steam generators and one turbine. The steam generator is tested in the initial test step or in service inspection to verify the performance of heat balance and to check the electric output efficiency. The test procedures are well documented in ANSI/ASME PTC 6-series. In PWR or PHWR, the steam generators are producing saturated steam by the moisture separator systems which are installed inside the SG. The moisture separators are blocking the carryover of droplet by lower than 0.25% steam quality because the droplets are the main causes of erosion of the turbine blades. So, quality is a very important test item and an acceptance criteria in the saturated steam turbine cycles in case of the construction NPP or the replacement.

The entire performance of steam turbines are carried out by the code of ANSI/ ASME PTC 6-1996. The methods of determining steam quality is described in section 4.19. The following is stated the methods briefly to enhance the situations.

2. MEASUREMENT OF STEAM QUALITY IN ANSI/ASME PTC 6

The following methods are used to determine the steam quality of any steam turbines.

(1) Radioactive-tracer technique (throttle steam and extraction steam).
(2) Heater-drain-flow measurement (extraction steam only) and heat balance.
(3) Calorimeter for direct determination of quality (throttle-steam only).

2.1 Radioactive-Tracer Technique

Radioactive tracers have been used for determining steam quality of throttle and extraction steam of steam turbines operating predominately within the moisture region with nuclear-steam supply. Although excellent results have been obtained, the techniques of the method had not been sufficiently developed, at the time PTC 19.11-1970 was published, to include them in that

Supplement. Therefore, a complete description of the tracer technique is included in the following paragraphs.

Selection of one of these methods for determining steam quality must be based upon the conditions peculiar to a particular steam-supply system, since each method has limitations which govern its use.

Steam sampling, with respect to the type of probe, its location and method of withdrawing the sample, shall be performed in accordance with the ASTM "Method of Sampling Steam." D-1066. Inherent limitations in the probe-sample technique make it extremely difficult to obtain a representative streamline sample. (Also see PTC 19.11-1970.) The tracer technique has the advantage that it does not require a representative sample of the water steam mixture. Only a sample of the water phase is required.

2.2 Dilution Technique.

The dilution technique is the most accurate for determining either the water-phase or the moisture fraction of a two-phase vapor-water flow. The dilution technique is based on the measurement of a tracer concentration in water sample and is well suited because it does not rely on geometric or hydraulic quantities. Dilution can be accomplished in either of two ways, applicable to determining both throttle and extraction enthalpy.

2.3 Condensing Method.

An appropriate tracer, dissolved in the water-phase of wet steam at a concentration C_w, will be diluted by condensation of vapor. After the steams is totally condensed, the tracer concentration in the condensate will be C_c.

The concentrations are related by the balance

$$C_w w = C_c w_c \qquad (2\text{-}1)$$

where:

w = amount of water in steam

w_c = amount of condensate from wet steam

With the tracer concentrations known from test measurements before and after condensation, steam-wetness (moisture) fraction(χ) is represented by the ratio:

$$\chi = w / w_c = C_c / C_w \qquad (2\text{-}2)$$

2.3.1 Throttle-Steam Quality.

Throttle-steam quality can be calculated from the quality and pressure of the steam leaving the steam generator and throttle-steam pressure, using a constant-enthalpy process since radiation losses from the connecting steam piping are generally negligible. The moisture in the steam leaving the steam generator is the result of water-carry-over. Thus, a tracer present in the SG water will also be found in the steam leaving the SG.

The condensing method may also be used to determine wet-extraction steam enthalpy. This method is particularly attractive if a suitable tracer is already present in the steam path. However, error analysis shows that accurate results can only be obtained on heaters without cascading drains.

With this method extraction enthalpy is evaluated from an energy balance and a tracer balance around the heaters. For the tracer balance the concentration of the tracer in all flows to and from the shell side of each heater are needed. Sampling the heater drains for concentration measurement of the tracer is fairly easy, as this is only single-phase flow. Sampling water out of the extraction line requires the same precautions as in the case of the injection method.

2.3.2 Constant-Rate Injection Method.

A water-soluble tracer of concentration C_{inj} is injected at a constant rate w_{inj} into the vapor-water flow where moisture is to be measured. The concentration C_w is measured in the water phase downstream of the injection point after adequate mixing has taken place. For this condition the following material can be written :

$$C_o w + w_{inj} C_{inj} = (w + w_{inj} + \Delta w) C_w \quad \text{(2-3)}$$

Or

$$w = \frac{w_{inj}(C_{inj} - C_w) - \Delta_w C_w}{C_w - C_o} \quad \text{(2-4)}$$

where :

w = mass-flow rate of water in vapor-water mixture

C_o = initial concentration in the water-phase at the sampling point, before injection starts, due to natural amounts of tracer (background concentration)

3. Example of the Moisture Calculation with ANSI/ASME PTC 6

To measure the steam quality of Wolsong PHWR with 4 SGs in 1999 by the methods described in the section "measurement of steam quality" with equation (3-1), the results are no good as shown in table 1. The main reason is sampling error because the steam sample probes are no good. Generally, the wet steam flows along piping wall. The principal disadvantage of the moisture sampling tubes is that their accuracy is directly affected by the extent to which the steam sample represents the average condition of the steam flowing in the pipe. Although a moisture sampling tube which is designed so that the average velocity through the eight(8) sampling holes is approximately equal to the average steam velocity in the pipe. In large pipes, there is evidence that the moisture in the steam tends to collect along the pipe wall thus escaping isokinetic sampling. So, the entire steam quality is derived after the steam was condensing. But the equation of(3-1) hasn't the condensate term. Anyway, the moisture qualities of Wolsong are over the specification, 0.25%

$$\chi = \frac{(1-R)C_{ms}}{C_b} \quad \text{......} \quad (3\text{-}1)$$

where, R = w_{ms} / w_e, Inverse of circulation ratio

Table 3.1 Moisture quality(%) in steam at Wolsong unit 4, calculated with equation (3-1)

Rx. power \ SG	SG #1	SG #2	SG #3	SG #4	Average	Date
75%	0.132	0.227	0.156	0.666	0.296	'99.5.31
85%	0.296	0.405	0.171	0.740	0.403	'99.6. 2
90%	0.293	0.346	0.175	0.695	0.377	'99.6. 2
95%	0.309	0.366	0.212	0.777	0.416	'99.6. 2
100%	0.271	0.455	0.232	0.632	0.397	'99.6. 8

4. New Equation of Steam Quality in Steam Generator with Preheater

The equation of steam quality is derived from the mass balance of water and tracer. Accurate water flow and tracer concentrations are also necessary. For the typical steam generators with preheater illustrated in Figure 2.

4.1 Moisture Carryover

From the definition of moisture carryover, the moisture carryover equation is obtained as follows

$$\chi = \frac{w_{moisture}}{w_{steam+moisture}} \quad \text{......} \quad (4\text{-}1)$$

Under steady-state of steam turbine systems water-steam flow, the entry feedwater flow is equal to the main steam flow with moistures.

$$w_{fw} = w_{ms} = w_{steam} + w_{moisture} \quad \text{......} \quad (4\text{-}2)$$

In downcomer regions, the total flow of downward is the sum of recirculating water and the feedwater to enter in upper feeding.

$$w_{dc} = R'w_{fw} + Lw_{fw} = (R'+L)w_{fw} \quad \text{......} \quad (4\text{-}3)$$

where, R' is recirculating ratio

L is feeding ratio of upper region.

In blowdown regions, the water flow balance is as follows,

$$w_{bd} = R'w_{fw} + Lw_{fw} + (1-L)w_{fw} = (R'+1)w_{fw} \quad \text{......} \quad (4\text{-}4)$$

and from the tracer flow balance,

$$C_w w_{moisture} = C_{ms} w_{ms} = C_{fw} w_{fw}$$

and

$$w_{moisture} = \frac{C_{ms}}{C_w} w_{ms} = \frac{C_{fw}}{C_w} w_{fw} \qquad (4\text{-}5)$$

from equation (4-1) and (4-5), and the concentration of tracer in main steam sample and feedwater sample is equal. $C_{ms} = C_{fw}$ (under the steady state conditions)

$$\chi = \frac{w_{moisture}}{w_{steam+moisture}} = \frac{\frac{C_{ms}}{C_w} w_{ms}}{w_{steam+moisture}} = \frac{C_{ms}}{C_w} = \frac{C_{fw}}{C_w} \qquad (4\text{-}6)$$

4.2. In Downcomer Region(after mixing the downcomer flow and feedwater flow)

If the water steam interface sampling is impossible, the equation (4-6) should be expressed with the tracer concentration in downcomer. The downcomer water is mixing with the downward flow and the partially entered feedwater flow. By the same method, the moisture quality equation is expressed as tracer concentration of blowdown from the mass balance flow and tracer.
In the downcomer region, the mass balance of tracer is expressed as follows.

$$w_{dc} C_{dc} = R' w_{fw} C_w + L w_{fw} C_{fw} = (R'+L) C_w w_{fw} \qquad (4\text{-}7)$$

and $(R'+L) C_{dc} = R' C_w + L C_{fw}$

$$\therefore\ C_w = \frac{(R'+L) C_{dc} - L C_{fw}}{R'} \qquad (4\text{-}8)$$

finally, we get one equation from (4-6) and (4-8)

$$\chi = \frac{C_{fw}}{\frac{(R'+L) C_{dc} - L C_{fw}}{R'}} = \frac{R' C_{fw}}{(R'+L) C_{dc} - L C_{fw}} \qquad (4\text{-}9)$$

If there is no feedwater flow in downcomer regions(L=0), the equation (4-8) is simply expressed as following.

$$\chi = \frac{R' C_{fw}}{(R'+0) C_{dc} - 0 \times C_{fw}} = \frac{R' C_{fw}}{R' C_{dc}} = \frac{C_{fw}}{C_{dc}}$$

4.3 In Blowdown Region

If the sampling is possible only in the blowdown flow, the equation (4-9) should be expressed with the tracer concentration in blowdown. The water is mixing with entire feedwater and downcomer flow in blowdown region.
In the blowdown region, the mass balance of tracer is expressed as follows.

$$\chi = \frac{R' C_{fw}}{(R'+L)C_{dc} - LC_{fw}}$$

from the water flow balance,

$$w_b = R' w_{fw} + Lw_{fw} + (1-L)w_{fw} = (R'+1)w_{fw} \quad \text{.......} (4\text{-}10)$$

and from the tracer mass balance, the downcomer tracer concentration is got

$$C_b w_b = R' C_{dc} w_{dc} + LC_{fw} w_{fw} + (1-L)C_{fw} w_{fw} = R' C_{dc} w_{fw} + C_{fw} w_{fw}$$
$$C_b (R'+1) w_{fw} = R' C_{dc} w_{fw} + C_{fw} w_{fw}$$
$$C_b (R'+1) = R' C_{dc} + C_{fw}$$

So,

$$C_{dc} = \frac{(R'+1)C_b - C_{fw}}{R'} \quad \text{.......} (4\text{-}11)$$

from (4-9) and (4-11), We can get an equation of moisture quality.

$$\chi = \frac{R' C_{fw}}{(R'+L)(\frac{(R'+1)C_b - C_{fw}}{R'}) - LC_{fw}} = \frac{R'^2 C_{fw}}{(R'+L)(R'+1)C_b - (R'+L+R'L)C_{fw}} \quad \text{.......} (4\text{-}12)$$

If there is no downcomer feedwater flow is none(L=0), then the above equation is expressed as following.

$$\chi = \frac{R'^2 C_{fw}}{(R'+0)(R'+1)C_b - (R'+0+R\times 0)\, C_{fw}} = \frac{R'^2 C_{fw}}{R'(R'+1)C_b - R' C_{fw}}$$
$$= \frac{R' C_{fw}}{(R'+1)C_b - C_{fw}} = \frac{C_{fw}}{(1+\frac{1}{R'})C_b - \frac{1}{R'} C_{fw}} \quad \text{.......} (4\text{-}13)$$

Let us prove the ANSI/ASME PTC 6 equation from the equation (4-13)
If the tracer concentration in feedwater is negligible, then $c_{fw} = 0$, and

$$\chi = \frac{R' C_{fw}}{(R'+1)C_b} = \frac{(R''-1)C_{fw}}{R'' C_b} = \frac{(1/R-1)\, C_{fw}}{(1/R)\, C_b}$$

$$= \frac{(1-R)C_{fw}}{C_b} \quad \text{.......... (ANSI/ASME PTC 6 EQUATION)}$$

where, R" is circulation ratio and R is inverse of circulation ratio (R" = 1/R)

4.4 In case of Partially Mixed flow in Downcomer region

Generally, the blowdown flow water and feedwater are not completely mixed by the flow barrier. In that case, the same method is available. If the mixing ratio is M, the tracer of concentration in downcomer and blowdown is expressed as following.

$$C_{dc} = \frac{(R'+L+M(1-L))C_b - (L+M(1-L))C_{fw}}{R'} \quad \text{.......... (4-14)}$$

So, the final equation is derived as following.

$$\chi = \frac{R'C_{fw}}{(R'+L)(\frac{(R'+L+M(1-L))C_b - (L+M(1-L))C_{fw}}{R'}) - LC_{fw}} \quad \text{.......... (4-15)}$$

General Equation of Moisture Quality in Steam Generators is,

$$\chi = \frac{R'^2 C_{fw}}{(R'+L)(R'+L+M(1-L))C_b - (R'+L)(L+M(1-L)+R'L)C_{fw}} \quad \text{.......... (4-16)}$$

4.5 Multi Loop Steam generators General Equation of Moisture Quality

In PWR, there are loops with two or three team gernerators. Especially, PHWR have four steam generaors. In that case, the total steam generator system's performance is got by the below equation that considers each steam gernerator's tracer concentration and steam flow capacity factors

$$\chi_T = \frac{R'^2 C_{fw}}{(R'+L)(R'+L+M(1-L))\frac{1}{\sum w_{fw_i}}\sum C_{bi} w_{fw_i} - (R'+L)(L+M(1-L)+R'L)C_{fw}} \quad \text{.... (4-17)}$$

and each steam generators' performance are get by the below equation that is considered each steam gernerator's capacity factor

$$\chi_i = \frac{R'^2 C_{fw}(C_{ms_i}/\sum C_{ms_i})(\sum C_b / C_{b_i})}{(R'+L)(R'+L+M(1-L))\frac{1}{\sum w_{fw_i}}\sum C_{b_i} w_{fw_i} - (R'+L)(L+M(1-L)+R'L)C_{fw}} \quad \text{. (4-18)}$$

4.6 SAMPLE Equation of three(3) loops type steam generator (Westinghouse type)

Westinghouse model's steam generator has downcomer region sample taps. In that case,

$$\chi = \frac{R'C_{fw}}{(R'+L)C_{dc} - LC_{fw}}$$

and the downcomer sample is taken before mixing with the auxiliary feedwater flow. so, L=0 .

then $$\chi = \frac{R'C_{fw}}{(R'+0)C_{dc} - 0 \times C_{fw}} = \frac{C_{fw}}{C_{dc}}$$

and for all steam generators

$$\chi_T = \frac{C_{fw}}{\frac{1}{\sum w_{fw_i}} \sum C_{dc_i} w_{fw_i}}$$

So, $$\chi_T = \frac{C_{fw}(w_{fw1} + w_{fw2} + w_{fw3})}{C_{cd_1} w_{fw_i} + C_{cd_2} w_{fw_2} + C_{cd_3} w_{fw_3}} \qquad (4\text{-}19)$$

And for steam generator # 1 equation is,

$$\chi_{SG1} = C_{fw} \frac{w_{fw1} + w_{fw2} + w_{fw3}}{C_{cd_1} w_{fw_i} + C_{cd_2} w_{fw_2} + C_{cd_3} w_{fw_3}} \frac{C_{ms_1}}{C_{ms_1} + C_{ms_2} + C_{ms_3}} \frac{C_{dc_1} + C_{dc_2} + C_{dc_3}}{C_{dc_1}} \qquad (4\text{-}20)$$

4.7 <u>SAMPLE Calculation in Wolsong NPP</u>

In Wolsong, there is no feed water in down comer region, the SG is only feeded by the preheater region(L=0), and the mixing ratio in blowdown region is about 25%(M=0.25).
Then the general equation is,

$$\chi = \frac{R'^2 C_{fw}}{(R')(R'+0.25)C_b - (R'(0.25(1-0) + R \times 0)C_{fw}} = \frac{R'C_{fw}}{(R'+0.25)\, C_b - 0.25\, C_{fw}} \qquad (4\text{-}21)$$

also, the entire moisture quality equation is as following,

$$\chi_T = \frac{R'C_{fw}}{(R'+0.25)\frac{1}{\sum w_{fw}} \sum C_{b_i} w_{fw} - 0.25 C_{fw}} \qquad (4\text{-}22)$$

And for the each steam generator,

$$\chi_i = \frac{R'C_{fw}(C_{ms_i} / \sum C_{ms_i})(\sum C_{bi} / C_{b_i})}{(R'+0.25)\frac{1}{\sum w_{fw_i}} \sum C_{b_i} w_{fw_i} - 0.25 C_{fw}} \qquad (4\text{-}23)$$

Table 4.7 The two calculation results of moisture quality(%) in SG of Wolsong NPP

SG / Equation	SG 1	SG 2	SG 3	SG 4	Average
ANSI/ASME PTC 6	0.340	0.391	0.251	0.663	0.411
New Equation	0.016	0.017	0.011	0.028	0.018

5. The Evaluation of nonradioactive tracer

The uncertainty in flows or qualities measured with radioactive tracers is dependent on the uncertainty in the individual measurements that are made. These measurements are counting, injection rate, background, and other similar measurements. The radiation that is emitted from the tracer is a random decay and follows a Poisson's distribution. The uncertainty is dependent on the size of the sample.

Radiation background is also a possible source of error. There are two types of background which must be considered. The first is natural about 1% correction and the resulting uncertainty is about 0.5%. This second is radiation in the cycle due to the tracer. This can range from 0% to 10% depending on reactor carryover, demineralizers, and other similar sources. The latter uncertainties are usually larger that those due to natural radiation.

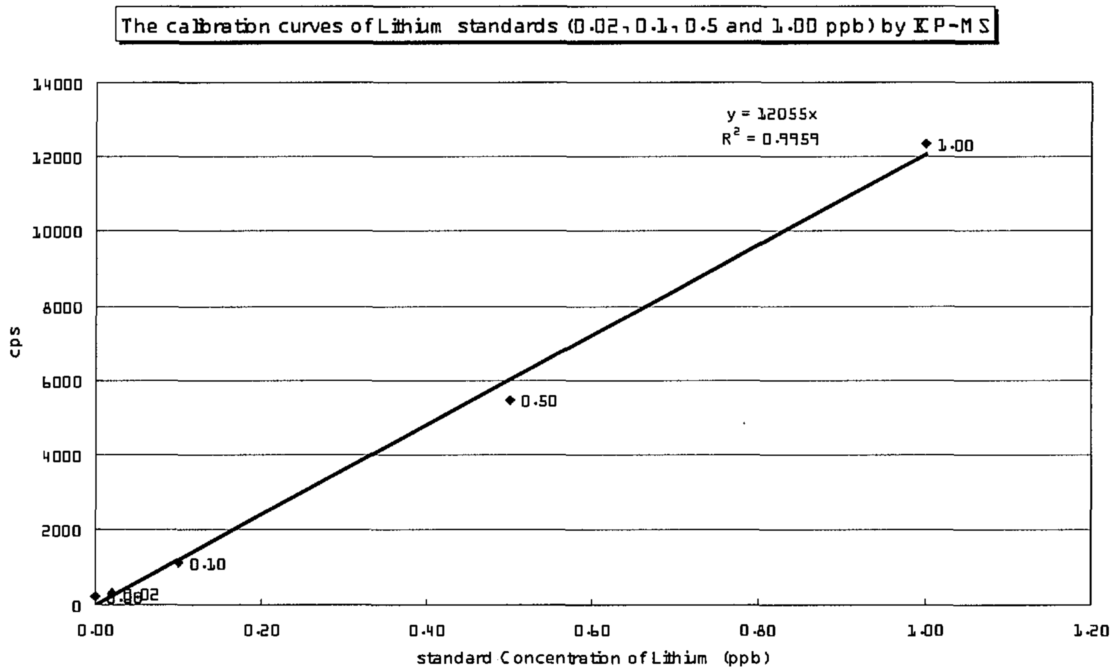
Listed below are Code test expected uncertainties :

(a) Standards - ± 0.5%
(b) Counting - ± 1.0%
(c) Injection rate - ± 1.0%
(d) Natural background - ± 0.5%
(e) Cycle background - ± 1.0%

The sampling technique of nonradioactive tracers has several advantages that make this method more adaptable for use at nonnuclear installations, where the licensing and personnel required for using radioactive tracers may not be available. However, uncertainties from the following sources can be introduced and might be expected during a Code test;

(a) preparation of standards;
(b) variation in injection rate;
(c) contamination of samples;
(d) sampling and analysis.

Anyway, the lithium is a good nonradioactive tracer because it is distributed in water phase, its background is negligible and especially, the analysis methods has been developed to achieve sufficient accuracy as shown below by the analysis data.



6. CONCLUSION

In nuclear power plants, the performance of steam turbines is tested as ANSI/ASME-PTC 6. This code provides rules for the accurate testing of steam turbines for the purpose of obtaining the level of performance with a minimum uncertainty. But this code provides a simplified equation to test the steam generators. So, we deducted a general equation of steam quality in complex turbines or complex operation modes to measure the steam quality of multi steam generators. And the new method are overcome the pipe wall flow effect. To measure the steam quality in the Wolsong PHWR with 4 SGs in Korea by the methods in the section "Measure of steam quality" of ANSI/ASME PTC 6, the result was not good though the steam generators are effiecient. So, the new testing method was developed and the sophisticated equation of steam quality was introduced.

7. REFERENCES

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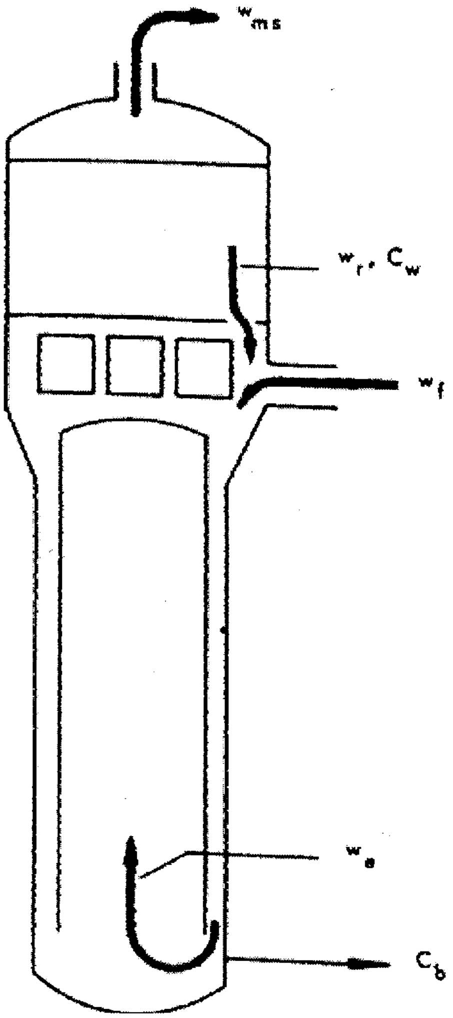
Figure 1. Throttle Steam-quality Calculations for Pressurized Water Reactor



Nomenclature

w = Flow Rate

C = Concentration

w_{ms} = Main steam flow

w_{fw} = Feedwater Flow : Under Steady-State ,

w_r = Recirculation Flow

w_e = Entry Flow = $w_r + w_{ms}$

C_b = Blowdown-Tracer Concentration

C_w = Tracer Concentration at Water Steam Interface

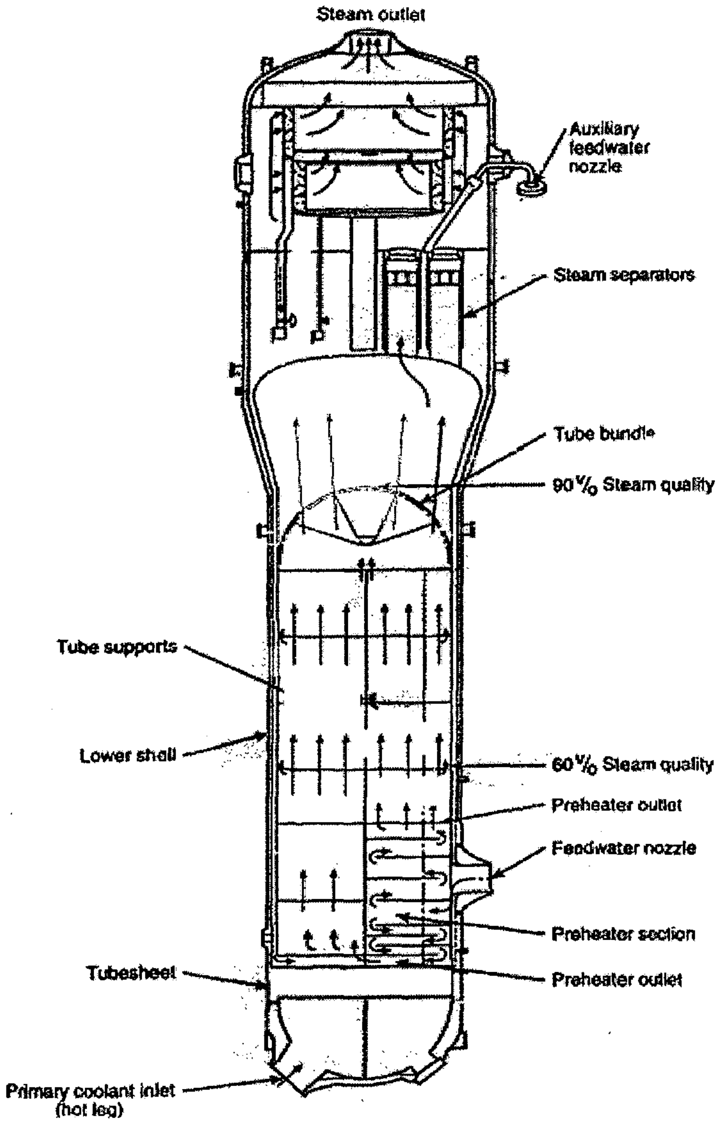
R = w_{ms} / w_e, (Inverse of Circulation Ratio)

$w_e = w_{ms}$/R

$w_r = w_e - w_{ms} = w_{ms}$/R - w_{ms} = (1-R) w_{ms}/R

$C_w = C_b\ w_e / w_r = C_b$/(1-R)

Figure 2. Typical Steam Generator with Preheater.



R' = Recirculation ratio = Circulation -1 = R"-1 = 1/R-1 = (1-R)/R
L = Aux feedwater ratio of entry feedwater

$$w_b = R' w_{fw} + L w_{fw} + (1-L) w_{fw} = (R'+1) w_{fw}$$

$$C_b w_b = R' C_{dc} w_{dc} + L C_{fw} w_{fw} + (1-L) C_{fw} w_{fw} = R' C_{dc} w_{fw} + C_{fw} w_{fw}$$