

TASK CLOSE OUT DOCUMENT

Task Scope Evaluate The Effect of Non-Condensable
IN the REFLUX BOILING MODE

To: M. Levenson
S. Levy
E. Zebroski

Task No. 10C

Date Complete 4/17/79

Reason felt task is complete:

More detailed analysis should be performed
with a complete system model. A scaled test
must be performed to confirm the conclusions.

Members of Committee

D.C. Dittmore

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Abstract

Having addressed earlier the "Behavior of RCS with Steam Generators In Condensing Mode", C. Solbrig, et. al., April 10, 1979, the IAG was asked to further investigate the possible effect of non-condensibles under the mode of decay heat removal in which the primary system loses natural circulation and goes into a boiling (in the pressure vessel)/condensing (in the steam generator) mode.

Summary

Based upon a review of the available information and the competing phenomena the following is concluded:

- (a) It is possible that a volume of evolved non-condensable gases might reach a size wherein it might temporarily effectively seal the top of the candy cane and limit the flow of steam to the steam generator.
- (b) This condition would not be expected to occur unless the system lost natural circulation and boiled at or near atmospheric pressure with the pressurizer relief valve (and block valve) open for a considerable period; i.e., 24 - 60 hours or longer depending on the actual radiolysis rate.
- (c) If this condition did occur it should be possible to break this seal by raising system pressure to the range of 10 to 20 atmospheres. This pressurization might occur either by; (a) via pressure relief through the pressurizer relief valve which under choked conditions would require ~200 psia back pressure to vent the steam generated in the core, or (b) by closing the pressurizer relief valve if that were still possible. In either case, pressurization should occur via steaming in the core and continued evolution of non-condensibles, although this may be a very slow process.
- (d) During steady state operation in a boiling mode, with or without the relief valve open, an equilibrium condition would be expected to be attained where the gases released by radiolysis during boiling should equal those which go back into solution at the condensation surface, and/or out the pressurizer relief valve if it remains open.
- (e) Once the system has stabilized, the heat removal from the primary system will either be via the pressurizer relief valve, condensation in the steam generator, or a combination of both. Some combination which yields a system pressure somewhere between atmospheric and ~200 psia is most likely, although it is likely that steam flow to, and condensation in, the steam generator will ultimately predominate.

An important premise for these conclusions is that the volume of non-condensable gases which might be expected to be present even after boiling at atmospheric pressure for a considerable period; i.e., ~2000 SCF after 12 to 24 hours, would be relatively small when the pressure increases to the range ~200 psia. Under these conditions the non-condensibles would either become co-mingled with the steam or in the worst case, if there was stratification they would be compressed (by the steam acting as a piston) to a much smaller volume above the water level in the steam generator. Condensation in the

steam generator should in either event be re-established in the steam generator. Another important factor is that long before stable conditions could be achieved, percolation of steam/oscillation of water levels should be expected. Such percolation should also encourage good mixing of the steam and non-condensibles, if they are not already well mixed.

Discussion

If natural circulation without boiling were somehow lost and could not be re-established, the stagnant liquid in the reactor vessel would eventually be brought to saturation and bulk boiling could begin. Ostensibly the pressurizer relief valve would be opened to allow displacement of the relatively cold pressurizer water out of the primary system for some period to be able to make volume provision for the generated steam in the top of the system. During this period of initial boiling non-condensable gases would be given off by radiolysis and would pass with the steam over to the steam generator, where the steam would condense and at least initially hydrogen could begin to buildup. If this condition were to allow to continue at low pressure it is possible that hydrogen would build up in the steam generator and ultimately over into the candy cane. Assuming no re-resolution in the generator, which is very conservative, and maximum evolution of hydrogen in the core during boiling a volume of ~1050 SCF, could build up after a considerable period of boiling at atmospheric pressure. Conservative estimates for the time to do this range from 24 to 60 hours with extensive core damage (See Appendix I). The measured level of dissolved non-condensable gases remaining in the primary system as of 4/16/79 was ~800 SCF*. Therefore, boiling at atmospheric pressure for 24 to 60 hours could result in a volume of non-condensibles on the order ~2000 SCF assuming no re-resolution. This volume of gas built up above the water level in the steam generator and into the candy cane could conceivably form a seal which would block or limit steam flow to the steam generator. Since mass diffusion of steam through hydrogen is quite low (See Appendix 2) one could argue that such a condition could prevent reflux boiling. However, the volumes of non-condensable gases are still relatively low and if raised to a pressure of 10 to 20 atmospheres would represent a partial volume of ~1% of the primary system volume and ~10% of the steam generator volume on the primary side. Thus raising the system pressure to 10 to 20 atmospheres by closing the pressurizer relief valve and/or block valve, or allowing it to achieve a pressure of 175 - 200 psig naturally by steaming thru the pressurizer relief, if it is completely open, would provide a means of breaking the postulated seal of non-condensable gases. Once the system is pressurized in this fashion the steam should begin condensing in the secondary heat exchanger, if it wasn't already doing so, on the cold tubes and/or at the water surface depending on the level of water being maintained in the heat exchanger.

One potentially important consideration is the effect of non-condensibles in the heat exchanger on the heat transfer coefficients for condensation.

*water samples indicate ~68 cc/ml ~800 SCF with a primary system volume of ~12000 ft³.

Normal condensation heat transfer coefficients on the order of 800 BTU/hr ft.² F can be expected without non-condensibles. The effect of non-condensibles is expected to reduce this coefficient by approximately an order of magnitude reduction. However, even if one conservatively assumes a coefficient reduction of two orders of magnitude there is still ample heat transfer rate to condense all steam generated. This is true because of the large amount of heat transfer area, even if only the top 5 - 10% of the heat exchanger tube length is available for condensation.

Once the path for condensation has been established, a stable equilibrium condition should eventually be attained at these pressures where the steam and hydrogen would be evolved in the core, remain co-mingled, and pass to the heat exchanger and partially vent out the pressurizer if the relief valve remained open, and resolution would occur at the same rates should be sufficient to remove available hydrogen. With or without the relief valve open the system will stabilize at a pressure above 1 atm and probably below 200 psi, an equilibrium which will be determined by the rate of resolution of H₂/O₂ which will equilibrate with the core radiolysis. Appendix 4 analysis demonstrates that equilibrium could be established at or above 2 atm. If the relief valve remains open pressures on this order are more likely, if closed they will be higher. In either case it is likely the secondary heat exchanger will be the predominant point of heat removal in the system, as opposed to the relief valve on the pressurizer. However, with the relief valve open, some makeup would be desirable over the long-term.

The higher pressures proposed to assure no problems with non-condensibles are conducive to both high solubility of H₂ and low radiolysis. It is coincidentally true that the reflux boiling/condensation thermal hydraulics should also be more stable at these pressures since the specific volume differences of gas and liquid are much smaller than at atmospheric pressure.

Recommendations

The evaluations described are of necessity somewhat qualitative and idealized. As a consequence it is considered imperative that:

- (a) A scaled test of some sort be performed as soon as possible to confirm the conclusion that a non-condensable gas seal can be broken under varying system conditions.
- (b) Someone at B&W or in the working group should be assigned the responsibility to perform more detailed system-unique analyses for TMI -II to investigate the various boiling modes, and
- (c) Operating procedures should be developed to assure that appropriate actions are taken to come to a stable boiling condition at a predetermined pressure, with appropriate attention to question of non-condensibles, should natural circulation be lost.

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APPENDIX I

Non-Condensibles Currently in Primary Water

Water sample measurement as of 4/16/79 indicates 68 cc. at STP per Kg of water. This represents a volume fraction of $68 \text{ cc} \frac{(1 \text{ gm/cc})}{(1000 \text{ gm})} = .068$

Total Primary System Volume $\approx 12000 \text{ Ft}^3$

Total Volume of Non-Condensibles at STP in primary system $\approx 12000 \times .068 = 816 \text{ SCF} \approx 800 \text{ SCF}$

Non-Condensibles Evolution During Boiling At Atmospheric Pressure

Under boiling conditions in the core, with decay heat, radiolysis will result in the evolution of both H_2 and O_2 .

The attached letter, P. W. Marriott to D. Rockwell, of April 9, 1979, indicates an upper bound on H_2 evolution would be 73 SCF/hr using Reg. Guide 1.7 assumptions and a core thermal power of 5 mw. Adjusting this to the current SM level yields 43.8 SCF/hr at atmospheric pressure.

$43.8 \text{ SCF} \times 24 \text{ hrs} = 1051 \text{ SCF } \text{H}_2$
With O_2 this would become 1576 SCF.

Total if all currently dissolved gases come out of solution $= 1576 + 816 = 2392 \approx 2400 \text{ SCF}$. This is very conservative. More realistic rates on the order of 300 to 600 SCF/day are more likely, particularly as the steam/hydrogen pressure above the core increases. At more realistic rates it could take 2 to 5 days to achieve levels as high as $\approx 2400 \text{ SCF}$ with no resolution and complete release of all currently dissolved gases.

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19.01 (Q)
64-64-79

TO:

D.A. Rockwell

April 9, 1971

SUBJECT: RESPONSES TO GFD QUESTIONS ON HYDROGEN

This memo summarizes our comments on several hydrogen-related subjects requested by GFD over the past two days.

I. Reduction of Coolant Temperature to Maximize Net Degassing.

MIT consultants report that a) for 515 psia of H_2 pressure at 200°F the amount of H_2 dissolved in the water is 0.63 ml/gm (we get 0.64 ml/gm).

b) for 500 psia of H_2 pressure at 140°F the amount of H_2 dissolved in the water is 0.63 ml/gm (we get 0.57 ml/gm).

c) the amount of H_2 dissolved in water at 20 psia of H_2 and a temperature of 200°F is 0.02 (we get 0.025 ml/gm).

d) the amount of H_2 dissolved in water at 20 psia of H_2 and a temperature of 140°F is 0.01 (we get 0.022).

The practical conclusions are:

- 1) We agree as high a pressure as practical will get the maximum amount of H_2 dissolved in the water, and therefore, the maximum release on the let down.
- 2) We believe, based on GE experience in de-supersaturation of H_2 in water, that the temperature is not important in the range of 150 to 200°F.
- 3) There is a possibility that flashing from 280°F (but not from 200°F) could interfere with flow in the let down line. Therefore, 200°F would be better than 280°F for net degassing.

II. Hydrogen Generation Rate Long-Term

Input: Thermal Power 5 MW

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Case 1. Without any boiling in the core, and with an overpressure of H_2 in the let down tank at T=120°F of 1 atm of H_2 the radiolysis should be zero = 0.

Case 2. Without any boiling in the core, and with an intact core, the rate based on RML6562 pg. 8 and comparison with E/R data should be

$$S(H_2) \times 0.03 \left(\frac{\text{scfh}}{\text{MW}_T} \right) \times 60 \left(\frac{\text{min}}{\text{hr}} \right) \times 0.03 \left(\frac{\text{non boiling}}{\text{boiling}} \right)$$

Case 3. Using AS 1.3 and 1.7 assumptions on fission product release, boiling where radiolysis is occurring, for a degraded core, (G=0.5 for γ s and β s). The generation rate of a mature 2700 MW_T core at 10 days is 73 scfh of H_2 .

60 scfh

April 9, 1979

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Case 4. Experience data from GE BWRs on shut down at 5 RM, (as in 2 above) 9 scfh

Case 5. The most likely value is case 3 with the SRS-565 non boiling correction factor of 0.03: $73 \text{ (scfh)} \times 0.03 \text{ (non boiling)}$ 2.2 scfh

H_2 removal rate by solubility based on 515 psia and 200°F, we can remove 100 scfh.

Conclusion: Even in the worst case at 515 psia the radiolysis H_2 can be removed even at 10 gpm with a factor of safety greater than 10 (based on non boiling).

As per 1300 PST this date we have data from plant that shows possibility of some boiling in core - if we use BWR Boiling data our rates would be 10-20 scfh.

III. Potassium Permanganate as a Hydrogen Getter

We have considered what problems might be encountered. In using $KMnO_4$ to remove H_2 . Assume a 2 literated loop at 500 psia 220°F: this would require the addition of 1.6×10^6 kg of saturated $KMnO_4$ water solution - about 65 of the total primary loop volume or about 1400 minutes at 3 gpm.

This would add about 1000 kg of $KMnO_4$ and yield about 600 kg MnO_2 sludge if all the H_2 were reacted. This much sludge could interfere with the letdown flow. KOH is an end product of the reaction, so the coolant could become quite basic (pH ~ 12). Materials properties are still being studied. A better additive might be H_2O_2 because the reaction product is H_2O . The major question is the decomposition of H_2O_2 to form O_2 (free) which could lead to $H_2 + O_2$ and the possibility of rapid reaction. The decomposition would be less troublesome with slow injection so that the H_2O_2 could immediately react with ample H_2 in the vicinity of the injection point.

Allegretto

P. W. Harriott, Chairman
Three Mile Island Task Force

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APPENDIX 2

Diffusion of Steam Through H₂ Gas

$$J = -AD \frac{\partial x}{\partial z}$$

$$A = 36 \text{ in.}^2 \approx 1 \text{ m}^2 \quad D \approx 1 \frac{\text{cm}^2}{\text{sec}} \quad \angle 230^\circ - 10^\circ$$

$$J = -10^4 \text{ cm}^2 \cdot 1 \frac{\text{cm}^2}{\text{sec}} \cdot \frac{0 - 1.0}{1000 \text{ cm}} = +10 \frac{\text{cm}^3}{\text{sec}} \times \frac{1 \text{ ft}^3}{(30.24 \text{ cm})^3} = \frac{10}{2.77 \times 10^3} \frac{\text{ft}^3}{\text{sec}}$$

$$J = 0.36 \times 10^{-2} \text{ ft}^3/\text{sec}$$

Need for steam generation rate

$$\dot{m} = \frac{(3 \text{ mw}) (3.413 \times 10^6) \text{ BTU/Hr mw} \times 26.8 \text{ ft}^3}{970.3 \text{ BTU/lb} \left(\frac{3600 \text{ sec}}{\text{hr}} \right) \text{ lb}} = .0723 \times 10^3 \frac{\text{ft}^3}{\text{sec}}$$

$$\dot{m} \text{ at 1 atm} = 72.3 \text{ ft}^3/\text{sec}$$

This says straight diffusion through a hydrogen slug is not practical at 1 atm. Hydrogen will tend to pile up more and more if the mechanism relied totally on mass diffusion through a slug of gas in the pipe.

If gas is compressed into secondary Hx due to increased pressure to a depth of ~/hr, and A_{crosssection} = 25.2 ft² ≈ 2.3 m²

$$J = -10^4 \times 2.3 \times 1 \frac{\text{cm}^2}{\text{sec}} \cdot \frac{0 - 1.0}{100} \frac{1}{(30.24)^3} = \frac{2.3 \times 10^2}{2.77 \times 10^3} = .8310^{-1} \text{ ft}^3/\text{sec}$$

Still is too low for diffusion through the H₂. However, by the time the steam reached the top of the Hx it would begin to condense on the tubes and run down through the hydrogen plug.

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APPENDIX 3

Flowrate Through Pressurizer Relief Valve

Valve throat area $\sim 1.05 \text{ in}^2$

Critical Isentropic Flow through a Nozzle

$G \sim 53 \text{ lb/hr in}^2 \text{ psi}$ at 1 atm $h_g = 1150 \text{ BTU/lb}$
 $G \sim 52 \text{ lb/hr in}^2 \text{ psi}$ at 15 atm $h_g = 1200 \text{ BTU/lb}$

$$\dot{m}_{\text{steam}} = \frac{(3\text{mw}) (3.413 \times 10^6 \text{ BTU/mw hr})}{833.6 \text{ BTU/lb}} = 12.28 \times 10^3 \text{ lb/hr at 15 atm}$$

$$\dot{m}_{\text{steam}} = 12.28 \frac{(833.6)}{970.3} \times 10^3 = 10.55 \times 10^3 \text{ lb/hr at 1 atm}$$

$$P_{\text{psi}} = \frac{10.55 \times 10^3 \text{ lb/hr}}{1.05 \text{ in}^2} \frac{1}{52 \text{ lb/hr in}^2 \text{ psi}} = 193.2 \text{ psi}$$

$$P_{\text{psi}} = \frac{12.28 \times 10^3}{1.05} \frac{1}{53} = 220.6 \text{ psi}$$

This says that to vent through the relief valve on the pressurizer will require about 200 psi back-pressure. In other words the system will tend to pressurize it self when venting through the pressurizer relief valve.

APPENDIX 4

To: D. C. Ditmore - Industry
Advisory
Group

From: P. W. Marriott
L. Nesbitt
M. Siegler

4/17/79

Subject: Hydrogen Solubility Evaluations

TMI - Gas Removal/Mass Transfer

$$\text{Power} = 3\text{mw} = (3 \times 10^3 \text{ kw}) \times 3413 \frac{\text{BTU}}{\text{kw.hr}} = 10.2 \times 10^6 \frac{\text{BTU}}{\text{hr}}$$

Assume: 212°F, 1 atmosphere pressure

$$h_{fg} = 970.3 \frac{\text{BTU}}{\text{lb}}$$

$$\therefore \text{Steam Generation Rate of Saturation Conditions} = \frac{10.2 \times 10^6}{970.3} = 1.05 \times 10^4 \frac{\text{lb}}{\text{hr}}$$

$$\text{Solubility of H}_2 \text{ at 1 atm, 212°F} = 1.69 \times 10^{-6} \frac{\text{lb H}_2}{\text{lb water (atm)}} \left(\frac{1}{1} \right)$$

(Note that the solubility is proportional to the number of atmospheres of pressure. Higher pressure improve the solubility).

Solubility in the available in condensing steam is:

$$\therefore (1.05 \times 10^4 \frac{\text{lb}}{\text{hr}}) (1.69 \times 10^{-6} \text{ .atm}) (359 \text{ ft}^3 \text{H}_2 \text{ at STP})$$

$$= 319 \times 10^{-2} \text{ ft}^3/\text{hr at STP} \sim 3 \text{ ft}^3/\text{hr H}_2 \text{ solubility in the condensing steam.}$$

This limits the amount of H₂ which can be transferred. (If the rate of evolution of H₂ by radiolysis in the core during boiling exceeds this rate then H₂ will build up in the system in the secondary steam generator.)

As an alternate case, if you assume 120°F instead of 212°F, the result is approximately the same.

$$\text{Solubility of H}_2 \text{ at 120°F} = 1.48 \times 10^{-6} \frac{\text{lb}}{\text{lb atm}}$$

Solubility Rate in Available Condensing Steam is,

$$= 3.19 \frac{(1.48 \times 10^{-6})}{1.69 \times 10^{-6}} = 2.8 \text{ ft}^3/\text{hr}$$

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Now, if you look at the case of 15 atmospheres total pressure t=392°F,

$$\text{H}_2 \text{ Solubility} = 3.36 \times 10^{-6} \frac{\text{lb}}{\text{lb atm}}$$

APPENDIX 4 (Cont.)

If you then take into account the 15 atm pressure, the H_2 transport into the condensing steam would be

$$(1.05 \times 10^4 \frac{\text{lb steam}}{\text{hr}}) \frac{(970.3)}{833.6} (3.36 \times 10^{-6} \frac{\text{lb}}{\text{lb atm}}) \frac{(\text{mole})}{2 \text{ lb}} \frac{(359 \text{ ft}^3 \text{ at STP})}{\text{mole}} (15 \text{ atm})$$

$$= 11087.6 \times 10^{-2} = 110.9 \text{ ft}^3/\text{hr}$$

As an alternate case if you look at 120°F the result is:

$$(110.9) \frac{(1.48)}{3.36} = 48.8 \text{ ft}^3/\text{hr} \quad (\text{STP})$$

The actual solubility during condensation probably falls in the ranges of:

$$2.8 - 3 \text{ ft}^3/\text{hr at 1 atm, and} \\ 48.8 - 110.9 \text{ ft}^3/\text{hr at 15 atm}$$

But, what really helps at the higher pressure is that the radiolysis should be suppressed because of the dissolved H_2 . 15 atm would probably work, (since very conservative estimates indicate H_2 evolution due to radiolysis when boiling at 1 atm in the postulated core condition for TMI - II is no greater than 43.8 SCF/hr*. In fact some pressure below 15 atm but above 1 atm would probably have sufficient solubility rates compared to radiolysis evolution rates for H_2 .)

Quick Look At Oxygen Solubility

$$\text{at } 212^\circ\text{F } O_2 \text{ Solubility} = 25.2 \times 10^{-6} \frac{\text{lb}}{\text{lb.atm}}$$

$$O_2 \text{ Transport (To Condensing Steam)} = (25.2 \times 10^{-6})(1.05 \times 10^4) \left(1 \frac{\text{mol}}{32 \text{ lb}}\right) \frac{(359 \text{ ft}^3 \text{ STP})}{\text{mole}}$$

$$= 296.8 \times 10^{-2} \sim 3 \text{ ft}^3/\text{hr at STP and 1 atm}$$

$$\text{at } 392^\circ\text{F } O_2 \text{ Solubility} = 45.1 \times 10^{-6} \frac{\text{lb}}{\text{lb.atm}}$$

$$O_2 \text{ Transport} = (45.1 \times 10^{-6})(1.05 \times 10^4) \frac{(970.3)}{833.6} \left(\frac{1}{32}\right) (359) \\ = 9242 \times 10^{-2} \sim 92 \text{ ft}^3/\text{hr}$$

O_2 numbers are quite similar to H_2 numbers on a volumetric basis.

Note: All transports are based on either 1 atm or 15 atm available gas pressure.

O_2 generation rate should be $\sim 1/2 H_2$ and $\sim 1/2 (43.8 \text{ ft}^3/\text{hr}) \sim 21.9 \text{ ft}^3/\text{hr}$ at the most at 1 atm. So again at 1 atm you can't remove all generated gas, but at 15 atm considering the decrease expected in radiolysis you should be able to remove all evolved H_2 and O_2 , based on full equilibrium being reached in H_2O for each gas. (In fact sufficient solubility rates compared to radiolysis evolution rates for O_2)

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APPENDIX 4 (Cont.)

Try 2 Atm Pressure

Let's assume that 2 ppm by weight of H_2 = sufficient to suppress radiolysis

$$\therefore 2 \times 10^{-6} \frac{\partial H_2}{\partial H_2O}$$

Assume ~ 2 atm total pressure

$$t_{sat} = 252^\circ F \quad h_{fg} = 944.2$$

$$\therefore \text{Steam Rate at 3 mw} = (1.05 \times 10^4 \frac{lb}{hr}) \frac{(970.3)}{944.2} = 1.08 \times 10^4 \frac{lb}{hr}$$

$$\therefore 2 \times 10^{-6} \frac{lb H_2}{lb H_2O} \times 10.8 \times 10^3 \frac{lb}{hr} \times \frac{359 ft^3}{2 lb H_2}$$

= $3877 \times 10^{-3} ft^3/hr$ H_2 required to be transported to maintain 2 ppm is condensed steam.

$$H_2 \text{ solubility at } 252^\circ F \text{ and } 2 \text{ atm total pressure} = 1.91 \times 10^{-6} \frac{lb}{lb.atm}$$

Mass Transport

$$\text{into Condensing Steam} = (10.8 \times 10^3 \frac{lb}{hr}) (1.91 \times 10^{-6} \frac{lb}{lb.atm}) (2 \text{ atm}) (359 \frac{SCF}{2 lb}) = 7405 \times 10^{-3} = 7.4 \frac{ft^3}{hr}$$

\therefore at 2 ppm H_2 and 2 atm the rate of resolution possible during condensation is $>$ than the rate of evolution due to radiolysis.

Conclusions

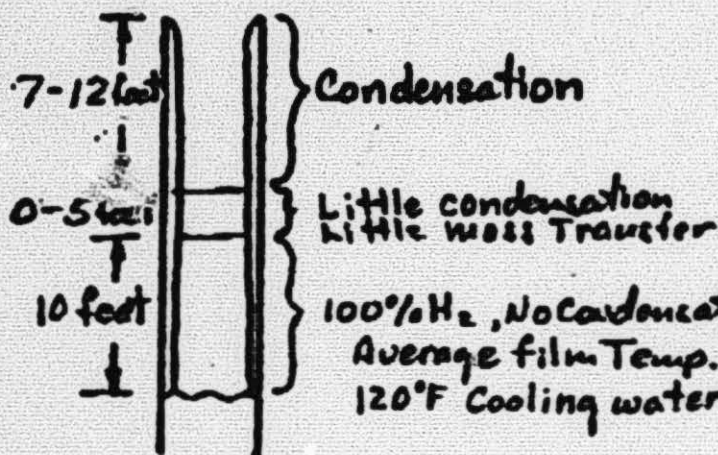
Mass transfer calculations yielded $\sim 255 ft^3/hr$ capable of being transferred if H_2O film reaches equilibrium saturation valve. But at 2 ppm concentration you only need about $4 ft^3/hr$.

\therefore System will probably seek a higher liquid level than the level assumed
 \therefore in mass transfer calculation of $\sim 25'$.

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DATE 4/17/79
 BY R. LAW SHEET 1 of 2

Mass Transfer



Conditions: steam 250°F
 P 2 atm

Adsorbing film 200°F

width of exposed Tubes
 $W = 2500 \frac{\text{ft}^2}{\text{ft}}$ (wetted perimeter)

film surface velocity = $10 \frac{\text{ft}}{\text{min}}$

Steam & water Rate
 $10,000 \frac{\text{lbm}}{\text{hr}}$
 1 steam generator in service

From Bird-Stewart-Lightfoot p. 540

$$w \frac{\text{lbmoles}}{\text{min}} = W \cdot L \cdot \chi \sqrt{\frac{4 \cdot D_L \cdot v_{max}}{\pi L}}$$

$$w = 2.5 \times 10^3 \cdot 10 \cdot 1.02 \times 10^{-4} \sqrt{\frac{4 \cdot 1.7 \times 10^{-5} \times 10}{\pi \cdot 10}} \quad L = 10 \text{ feet}$$

$$D_{L, H_2O} = 1.7 \times 10^{-5} \frac{\text{ft}^2}{\text{min}}$$

where $\chi = S p_{H_2}$ Solubility $S @ 200^\circ\text{F} = 1.7 \times 10^{-5} \frac{\text{lbmoles } H_2}{\text{lbmoles } H_2O \cdot \text{Atm}}$

$$\chi = 1.7 \times 10^{-5} \frac{\text{lbmoles } H_2}{\text{lbmoles } H_2O \cdot \text{Atm}} \times 2 \text{ Atm} \times \frac{60 \text{ lbmoles } H_2O}{1 \text{ ft}^3} \times \frac{1 \text{ lbmole } H_2}{2 \text{ lbmoles } H_2}$$

$$= 1.02 \times 10^{-4} \frac{\text{lbmoles } H_2}{\text{cuft } H_2O}$$

$p_{H_2} = 2 \text{ atm}$

$$w = 2.5 \times 1.02 \times 4.65 \times 10^{-3} = .012 \frac{\text{lbmoles}}{\text{min}} = 255 \frac{\text{ft}^3 H_2}{\text{hr}}$$

or L.B. value of $17 \frac{\text{ft}^3}{\text{min}}$

v_{max} comes from falling film solution B.S.L. p. 37

$$Q = \frac{\rho g W \delta^3}{3\mu} \quad v_{max} = \frac{\rho g \delta^2}{2\mu}$$

$$Q = 10,000 \frac{\text{lbm}}{\text{hr}} \frac{\text{ft}^3}{60 \text{ min}} \frac{\text{hr}}{60 \text{ min}} = 2.78 \frac{\text{ft}^3}{\text{min}}$$

$$\rho = 60 \frac{\text{lbm}}{\text{ft}^3}$$

$$\mu = .25 \text{ cp}$$

$$g = 32.2 \frac{\text{ft}}{\text{sec}^2}$$

$$W = 2500 \text{ ft}$$

$$T = 200^\circ \text{F}$$

$$\text{fc} = 6.719 \times 10^{-4} \frac{\text{lbm}}{\text{ft-sec}}$$

$$\delta^3 = \frac{3 \times .25 \text{ cp} \times 2.78 \frac{\text{ft}^3}{\text{min}} \times 6.72 \times 10^{-4} \frac{\text{lbm}}{\text{ft-sec-cp}}}{\frac{60 \frac{\text{lbm}}{\text{ft}^3} \times 32.2 \frac{\text{ft}}{\text{sec}^2} \times 2500 \text{ ft} \times \frac{60 \text{ sec}}{\text{min}}}}$$

$$= \frac{14 \times 10^{-4}}{2.9 \times 10^7} = .48 \times 10^{-11}$$

$$= 4.8 \times 10^{-12} \text{ ft}^3$$

$$\delta = 1.69 \times 10^{-4} \text{ ft}$$

$$v_{max} = \frac{60 \frac{\text{lbm}}{\text{ft}^3} \times 32.2 \frac{\text{ft}}{\text{sec}^2} (1.69 \times 10^{-4} \text{ ft})^2}{2 \times .25 \text{ cp} \times 6.72 \times 10^{-4} \frac{\text{lbm}}{\text{ft-sec-cp}}} \times \frac{60 \text{ sec}}{\text{min}}$$

$$= \frac{3.3 \times 10^5 \times 10^{-8} \frac{\text{ft}}{\text{min}}}{3.4 \times 10^{-4}} = 9.7 \frac{\text{ft}}{\text{min}}$$

at L.B. Nelson 17 Apr 79

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