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SUMMARY

Transient effects of making step changes of the core dump tank concentration are studied for single-region operation of the HRT. It is assumed that the feed and the letdown streams are only between the core high pressure system and the core dump tanks, and that transfer of fuel to or from the blanket can only be made through the core high pressure system.

Transfer rates between the HRT high pressure systems of 75 to 100 lbs/min will give reasonable mixing times, about 4 hours, without peaking of fuel concentration which may cause premature critical conditions in the core. Lower transfer rates could be used for lower feed rates, but the mixing time will be longer. Transfer rates greater than 100 lbs/min would not shorten the mixing time appreciably and, therefore, they need not be considered.

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MIXING RATES BETWEEN THE HRT HIGH PRESSURE SYSTEMS

Introduction

Consideration of operating the HRT as a single region reactor leads to interest in the rate of mixing of the fuel between the two high pressure systems for various flow rates.

In the situation being studied here, the feed and letdown streams are only from and to the core dump tanks, as shown in Figure 1. Step changes are made in the core dump tank concentrations and their effects on the high pressure system concentrations are then calculated.

A variation of this problem is being studied by P. N. Haubenreich⁽¹⁾. Instead of a letdown stream from the core high pressure system to the core dump tanks, as being considered here, a letdown stream from the blanket high pressure system to the core dump tanks is assumed.

Procedure

Time-dependent fuel material balances are written for each of the high pressure systems and the core dump tanks, as shown in Appendix A. Solution of these simultaneous equations yield the time behavior of the fuel concentration in each of the three systems following a step change of concentration in one or more of the systems. In writing and solving these equations, the following assumptions are made:

1. Uniform U-235 concentration in each of the three systems.
2. Constant mass in each of the three systems.
3. Transfer rates are constant.

The resulting solutions are shown in Appendix A.

For comparison purposes, equations are derived for infinite mixing between the two high pressure systems, as shown in Appendix B.

Table 1 shows the flow rates and the fuel concentrations for the various cases studied. The temperature of the high pressure systems is assumed to be 270°C and that of the low pressure system is assumed to be 100°C. Steady state U-235 concentration in the core high pressure system is assumed to be 3 g/liter of 1.599 g/lb solution except for case VI⁽²⁾. Purge rates are assumed to be 2 lbs/min. for each of high pressure systems, which is the minimum with the present purge pumps⁽¹⁾. Feed rates are 8 lbs/min. and 12 lbs/min., which are respectively the normal feed rate, and the maximum feed rate⁽¹⁾. The core and blanket high pressure systems contain 884 lbs and 3280 lbs of solution, respectively, and it is assumed that the core dump tanks contain 478 lbs of solution.

Table 1

SUMMARY OF FLOW RATES AND FUEL CONCENTRATIONS FOR VARIOUS MIXING CASES

Case	Feed Rate f lb/min.	Letdown Rate ℓ lb/min.	Transfer Rate from Core to Blanket R_1 lb/min.	Transfer Rate from Blanket to Core R_2 lb/min.	Steady State Concentrations			Initial Concentrations		
					Core Conc. C_c g/lb	Blanket Conc. C_b g/lb	Dump Tank Conc. C_c g/lb	Core Conc. C_c^0 g/lb	Blanket Conc. C_b^0 g/lb	Dump Tank Conc. C_c^0 g/lb
I	8	12	25	27	1.599	1.481	2.399	0	0	15.519
II	8	12	50	52	1.599	1.538	2.399	0	0	15.910
III	8	12	75	77	1.599	1.557	2.399	0	0	16.040
IV	8	12	100	102	1.599	1.568	2.399	0	0	16.115
V	12	16	100	102	1.599	1.568	2.132	0	0	15.849
VI	0*	12	100	102	0	0	16.115	1.599	1.599	2.399
VII	8	12	∞	∞	1.599	1.599	2.339	0	0	16.328
VIII	12	16	∞	∞	1.599	1.599	2.132	0	0	16.061

* No feed directly from the dump tanks, but it is assumed that the feed pumps are feeding 8 lbs/min. of pure D_2O from the condensate tanks to the core high pressure system.

Initial and final steady state concentrations for Cases IV and VI are reversed. Case VI considers the U-235 concentration behavior in the HRT following a change of the feed source from the core dump tanks to the condensate tanks. (The feed term f in the equation is then zero and the D_2O feed is included in the purge rate p_1 .) Steady state conditions for Case IV are assumed as initial conditions for Case VI. It is assumed that the mass in the dump tanks is constant, which means that D_2O is continually being evaporated and removed from the dump tanks to the condensate tanks.

Results and Discussion

Fuel concentrations as a function of time for the various cases are shown in Figures 2 through 9. (L. A. Haack calculated and plotted the curves from the equations for the various cases.)

Comparison of the curves show that there is a peaking of the core fuel concentration at the lower transfer rates between the core and blanket high pressure systems, i.e., below 50 lbs/min. for a feed rate of 8 lbs/min. This peaking is less severe for lower feed rates, but the time to reach steady state conditions is longer for the lower feed rates. Steady state conditions are reached in about 4 to 5 hours with 8 lb/min. feed and in about 3 to 4 hours with 12 lb/min. feed. At higher transfer rates between the two high pressure systems, i.e., 75 to 100 lbs/min., the time to reach steady state conditions is about the same as that for infinite transfer rates between the two high pressure systems. Therefore, very high transfer rates would contribute little to shortening the mixing time.

Dilution of the fuel solution in the high pressure system requires a longer period of time, as shown in Figure 7. The boundary conditions are the reverse of those shown in Figure 5, and it can be seen that about 20 hours are required to dilute the high pressure fuel solution as compared to about 4 hours to concentrate this solution. This is due to the fact that the same mass of U-235 is in a more dilute fuel solution when in the high pressure system than when in the core dump tanks prior to feeding.

Conclusion

Transfer rates between the HRT high pressure systems of 75 to 100 lbs/min. will give reasonable mixing times, about 4 hours, without peaking of fuel concentration which may cause premature critical conditions in the core. Lower transfer rates could be used for lower feed rates, but the mixing time will be longer. Transfer rates greater than 100 lbs/min. would not shorten the mixing time appreciably and, therefore, they need not be considered.

Bibliography

1. Haubenreich, P. N., Personal Communication.
2. Kasten, P. R., et al, "Operation of the HRT as a One-Region Reactor", HRP-58-143, April 11, 1958.

Appendix A

TWO DEPENDENT MIXING EQUATIONS

Referring to Figure 1, time dependent U-235 material balances for each of the three systems are as follows:

Core High Pressure System

$$M_c \frac{dC_c}{dt} = R_2 C_b + f c_c - (R_1 + l) C_c \quad (1)$$

Blanket High Pressure System

$$M_b \frac{dC_b}{dt} = R_1 C_c - R_2 C_b \quad (2)$$

Core Dump Tanks

$$m_c \frac{dc_c}{dt} = l C_c - f c_c \quad (3)$$

In these equations, it is assumed that the U-235 concentration in each of the three systems is uniform. It is further assumed to simplify the solution of these equations that the mass of each system and the flow rates are constant.

Solving these three equations for the three unknowns, C_c , C_b , and c_c , by the method of Laplace transformation, the following solutions are obtained:

Core High Pressure System Concentration

$$C_c = A + B e^{\alpha t} + D e^{\beta t} \quad (4)$$

Blanket High Pressure System Concentration

$$C_b = E + F e^{\alpha t} + G e^{\beta t} + H e^{-\gamma t} \quad (5)$$

Core Dump Tank Concentration

$$c_c = J + K e^{\alpha t} + L e^{\beta t} + M e^{-\gamma t} \quad (6)$$

where,

$$\alpha = \frac{-\left(\frac{R_1}{M_c} + \frac{\ell}{M_c} + \frac{R_2}{M_b} + \frac{f}{m_c}\right) + \sqrt{\left(\frac{R_1}{M_c} + \frac{R_2}{M_b} - \frac{\ell}{M_c} - \frac{f}{m_c}\right)^2 + 4 \frac{R_1}{M_c} \frac{\ell}{M_c}}}{2}$$

$$\beta = \frac{-\left(\frac{R_1}{M_c} + \frac{\ell}{M_c} + \frac{R_2}{M_b} + \frac{f}{m_c}\right) - \sqrt{\left(\frac{R_1}{M_c} + \frac{R_2}{M_b} - \frac{\ell}{M_c} - \frac{f}{m_c}\right)^2 + 4 \frac{R_1}{M_c} \frac{\ell}{M_c}}}{2}$$

$$\gamma = \frac{R_2}{M_b}$$

$$\delta = \frac{f}{m_c}$$

$$A = \frac{R_2 f}{\alpha \beta} \left[\frac{C_c^o}{M_b m_c} + \frac{C_b^o}{m_c M_c} + \frac{C_c^o}{M_b M_c} \right]$$

$$B = \frac{1}{\alpha(\alpha - \beta)} \left[(\alpha + \gamma)(\alpha + \delta) C_c^o + (\alpha + \delta) \frac{R_2}{M_c} C_b^o + (\alpha + \gamma) \frac{f}{M_c} C_c^o \right]$$

$$D = \frac{1}{\beta(\beta - \alpha)} \left[(\beta + \gamma)(\beta + \delta) C_c^o + (\beta + \delta) \frac{R_2}{M_c} C_b^o + (\beta + \gamma) \frac{f}{M_c} C_c^o \right]$$

$$E = \frac{R_1 f}{\alpha \beta} \left[\frac{C_c^o}{M_b m_c} + \frac{C_b^o}{m_c M_c} + \frac{C_c^o}{M_b M_c} \right]$$

$$F = \frac{1}{\alpha(\alpha - \beta)} \left[(\alpha + \delta) \frac{R_1}{M_b} c_c^o + \frac{f}{M_c} \frac{R_1}{M_b} c_c^o + \frac{(\alpha + \delta) \gamma \frac{R_1}{M_c} c_b^o}{\alpha + \gamma} \right]$$

$$G = \frac{1}{\beta(\beta - \alpha)} \left[(\beta + \delta) \frac{R_1}{M_b} c_c^o + \frac{f}{M_c} \frac{R_1}{M_b} c_c^o + \frac{(\beta + \delta) \gamma \frac{R_1}{M_c} c_b^o}{\beta + \gamma} \right]$$

$$H = \left[1 + \frac{(\gamma - \delta) \frac{R_1}{M_c}}{(\alpha + \gamma)(\beta + \gamma)} \right] c_b^o$$

$$J = \frac{R_2 \ell}{\alpha \beta} \left[\frac{c_c^o}{M_b m_c} + \frac{c_b^o}{m_c M_c} + \frac{c_c^o}{M_b M_c} \right]$$

$$K = \frac{1}{\alpha(\alpha - \beta)} \left[(\alpha + \gamma) \frac{\ell}{m_c} c_c^o + \frac{R_2}{M_c} \frac{\ell}{m_c} c_b^o + \frac{(\alpha + \gamma) \delta \frac{\ell}{M_c} c_c^o}{\alpha + \delta} \right]$$

$$L = \frac{1}{\beta(\beta - \alpha)} \left[(\beta + \gamma) \frac{\ell}{m_c} c_c^o + \frac{R_2}{M_c} \frac{\ell}{m_c} c_b^o + \frac{(\beta + \gamma) \delta \frac{\ell}{M_c} c_c^o}{\beta + \delta} \right]$$

$$M = \left[1 + \frac{(\delta - \gamma) \frac{\ell}{M_c}}{(\alpha + \delta)(\beta + \delta)} \right] c_c^o$$

Appendix B

TIME DEPENDENT MIXING EQUATIONS FOR INFINITE MIXING
IN THE HIGH PRESSURE SYSTEM

Referring to Figure 1, time dependent U-235 material balances for the high pressure system and the core dump tanks are as follows:

High Pressure System

$$(M_c + M_b) \frac{dc_{cb}}{dt} = fc_c - lc_{cb} \quad (7)$$

Core Dump Tanks

$$m_c \frac{dc_c}{dt} = lc_{cb} - fc_c \quad (8)$$

In these equations, it is assumed that the U-235 concentration in each of the two systems is uniform. It is further assumed to simplify the solution of these equations that the mass of each system and the flow rates are constant.

Solving these two equations for the two unknowns, C_{cb} and c_c , by the method of Laplace transformation, the following solutions are obtained:

High Pressure System Concentration

$$C_{cb} = P + Qe^{\epsilon t} \quad (9)$$

Core Dump Tanks Concentration

$$P_c = R + Se^{\epsilon t} \quad (10)$$

where $\epsilon = - \left[\frac{l}{M_c + M_b} + \frac{f}{m_c} \right]$

9.

$$P = -\frac{f}{\alpha} \left[\frac{c_c^o}{M_c + M_b} + \frac{c_{cb}^o}{m_c} \right]$$

$$Q = \frac{1}{\alpha(M_c + M_b)} \left[f c_c^o - l c_{cb}^o \right]$$

$$R = -\frac{l}{\alpha} \left[\frac{c_c^o}{M_c + M_b} + \frac{c_{cb}^o}{m_c} \right]$$

$$S = \frac{1}{\alpha m_c} \left[l c_{cb}^o - f c_c^o \right]$$

Appendix C

NOMENCLATURE

- C_b = concentration of U-235 in blanket high pressure system; g/lb solution.
 C_c = concentration of U-235 in core high pressure system, g/lb solution.
 C_{cb} = concentration of U-235 in blanket and core high pressure systems, infinite mixing in high pressure systems, g/lb solution.
 c_c = concentration of U-235 in core dump tanks, g/lb solution.
 f = feed rate from core dump tanks to core high pressure system, lbs/min.
 l = letdown rate from core high pressure system to core dump tanks, lbs/min.
 $\quad = f + p_1 + p_2$.
 M_b = mass of material in blanket high pressure system, lbs.
 M_c = mass of material in core high pressure system, lbs.
 m_c = mass of material in core dump tanks, lbs.
 p_1 = purge rate to core high pressure system, lbs/min.
 p_2 = purge rate to blanket high pressure system, lbs/min.
 R_1 = transfer rate from core high pressure system to blanket high pressure system, lbs/min.
 R_2 = transfer rate from blanket high pressure system to core high pressure system, lbs/min.
 t = time after change.
 Superscript, "o" refers to initial conditions.

Figure 1. Schematic Diagram of the HRT Mixing Problem

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