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Use of an Eductor to Reliably Dilute a Plutonium Solution

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Use of an Eductor to Reliably Dilute a Plutonium Solution

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ABSTRACT
Savannah River Site (SRS) in South Carolina is dissolving Pu239 scrap, which is a legacy from the production of nuclear weapons materials, and will later convert it into oxide form to stabilize it. An eductor has been used to both dilute and transfer a plutonium containing solution between tanks. Eductors have the advantages of simplicity and no moving parts. Reliable control of dilution is important because the geometry of the receiving tank could potentially allow a nuclear criticality. Dilution factor was to have been controlled by the appropriate choice of flow restrictor in the line between the plutonium solution tank and the eductor. However, dilution factors measured for liquid transfers with different flow restrictors showed unexpected trends, causing concern that the process was not well understood. As a result, the performance of the eductor and associated piping were analyzed using a mathematical model. The one dimensional, two phase model accounted for eductor performance and for air and vapor coming out of solution at low pressures. The unexpected trends were shown to be the result of variations in viscosities and densities of both the plutonium solution and the nitric acid solution used as both the motive fluid and diluent. The model agreed well with existing data and was then used to make pre-test predictions of flows for four solution transfers with good agreement. This provided confidence that the eductor system was a reliable method for obtaining specified dilution factors. Based on model results, recommendations were made and implemented for the operation of the eductor transfer system. One unexpected result of the analysis was the observation that slow corrosion inside the eductor is increasing the dilution factor, which is a conservative trend.

1. INTRODUCTION
An eductor is used to both dilute and pump a plutonium containing solution from one of two supply tanks to a receiving tank at SRS. Dilution must be reliably controlled because of criticality concerns with the receiving tank. The dilution ratio, the ratio of flowrate of diluent, which is also the eductant, to the flowrate of plutonium solution pumped from the supply tank, had been controlled by installing a flow restrictor with an appropriate internal diameter in the piping between the supply tank and the eductor. Historical dilution ratios ranged from 3 to 9. It had been expected that the dilution ratio would be a smoothly varying function of restrictor diameter. However, dilution ratios measured for liquid transfers showed unexpected trends. As a result, the performance of the eductor and associated hardware was analyzed.

2. ANALYSIS
2.1 Description of Eductor and Associated Hardware
Figure 1 shows the equipment layout. One of the two supply tanks is selected by opening and closing the appropriate ball valves. A "U" shaped flow restrictor tube with the desired inside diameter is selected and installed in the line between the supply tank and the eductor. A pump, not shown, pressurizes the eductant in a header, usually to 308 kPa. This pressure is monitored with a gage located close to the header on the eductant line. The eductant line has an inside diameter of 16.56 mm and contains tubing bends. Eductant enters the top of the eductor, is accelerated to approximately 23 m/s in the nozzle and then decelerates in the mixing chamber of the eductor, creating a pressure calculated to be as low as 3 kPa for the smallest restrictor used. This partial vacuum draws liquid out of the supply tank, through the restrictor and into the suction side of the eductor. With the exception of the restrictor, the suction line has an inside diameter of 10.20 mm and contains tubing bends and fittings.

Each flow restrictor consists of three pieces of tubing welded together: a machined transition piece going from a diameter of 10.20 mm to a smaller diameter, a piece of smaller tubing with two bends and a machined transition piece going from the smaller diameter to 10.20 mm. The total included angle for the transition pieces is 20°. Flow restrictor inside diameters range from 3.86 mm to 10.20 mm. The welding process is likely to cause metal to intrude into the flow passage by an amount equal to 25% of the tubing wall thickness. The tubing had a wall thickness of 1.24 mm so the inside diameter at the welds was reduced by approximately 0.31 mm. This reduced diameter was assumed to be hydraulically identical to an orifice plate.

Eductant and plutonium solution mix in the eductor, exit to a phase separator tank and then flow by gravity to the receiving tank. The phase separator tank, the plutonium solution supply tank and the receiving tank are connected to the vent system and are at the same, slightly sub-atmospheric pressure. Tank levels are monitored in both the plutonium solution tank and the eductant tank. Measured tank levels are converted to volumes in liters from which flowrate is calculated as rate of change in volume with time.

There are two corrosion issues with the eductor and associated piping. The eductor was constructed from 316 stainless steel and everything else was constructed from 304L stainless steel. The first issue is that 316 stainless steel will slowly corrode in the acidic solution that flows through it. It was estimated that corrosion could remove as much as 0.05 mm of metal per year or increase diameter by as much as 0.1 mm per year. The eductor has been used for about 9 years. The effect was most noticeable for the eductor nozzle, which had a manufactured diameter of 5.0 mm. The other corrosion issue is that the 304L stainless steel has been exposed to fluorides. The fluoride was estimated to have created a tubing roughness equal to 0.05 mm.

2.2 Mathematical Model of Eductor

The eductor manufacturer, Schutte and Koerting, published operating data for the Model 264, 1" eductor. For those tests both the eductant and pumped fluid were water. Eductant pressure, suction head and discharge pressure were varied and eductant and suction flows were measured. Eductant flow is limited by flow through a nozzle and should be proportional to the square root of the difference between eductant pressure and suction pressure. Using vendor data, the equation for nozzle pressure drop was determined as follows where the pressure difference is in kPa and the eductant flow is in L/s.

$$\Delta P_{noz} = 1407\, F_e^2 \qquad (1)$$

The theoretical equation for the pressure drop through a nozzle follows.

$$\Delta P = \frac{\rho V^2}{2\, C^2} = \frac{\rho}{2}\left(\frac{4}{C\, \pi\, D^2}\right)^2 F_e^{\,2} \qquad (2)$$

The term C is the discharge coefficient for the nozzle. Using the manufacturing diameter of the nozzle, 5 mm, and equations 1 and 2, C was determined to be 0.96, which is reasonable for a nozzle. As was mentioned before, corrosion could have increased the diameter of the nozzle by as much 0.1 mm per year or to a diameter as large as 5.9 mm. Because pressure drop is inversely proportional to nozzle diameter to the fourth power, this dimensional change is expected to change the pressure drop equation to the following for C equal to 0.96.

$$\Delta P_{noz} = 718\ F_e^2 \qquad (3)$$

However, the best fit to the SRS flow data for the eductor and associated piping gave the following equation, which was used in the model.

$$\Delta P_{noz} = 1182\ F_e^2 \qquad (4)$$

Equation 4 has a constant that is between the constants of equations 1 and 3. This indicates some corrosion but not as much as the maximum amount possible.

Eductor pump curves for the Model 264, 1" eductor used with water (sp. gr. = 1.00) are plotted using vendor data in Figure 2 with eductant supply pressure as the parameter. Note that the pump curves for a particular eductant pressure fall nearly on a line. Linear interpolation was used to determine the operating curves for eductant pressures between 240 and 308 kPa. Note that as suction flow increases, the pressure gain generated by the eductor decreases. The data in Figure 2 were for water. An eductor vendor recommendation was followed that the operating data could be extended to fluids with specific gravities different than water by multiplying flows by the inverse square root of specific gravity. No change is necessary for eductor pressure increases.

2.3 Mathematical Model of Associated Piping

The equation for pressure drop for single-phase flow in a pipe is given below (Crane, 1988).

$$\Delta P = \rho\ g\ \Delta h + \left(\frac{L\ f}{D} + \sum_{i=1}^{n} K_i\right) \frac{\rho\ V^2}{2} \qquad (5)$$

The terms ρ, g, Δh, L, f, D, K_i, V are fluid density, acceleration of gravity, elevation change, pipe length, friction factor, inside diameter of the pipe, resistance coefficient for the i-th component and fluid velocity, respectively. Friction factor is computed using the following equation (Aleman, et al., 1993).

$$f = \left[1.14 - 2\log_{10}\left(\frac{\varepsilon}{D} + \frac{21.25}{Re^{0.9}}\right)\right]^{-2} \qquad (6)$$

The terms ε and Re are the roughness of the pipe and Reynolds number, respectively. The equation is valid for turbulent Reynolds numbers up to 1,000,000. The equation for Reynolds number follows where the term μ is viscosity.

$$Re = \frac{V\ D\rho}{\mu} \qquad (7)$$

The following resistance factors (Crane, 1988) were used for pipe components where θ is the total included angle for a gradual expansion or gradual contraction and β is the ratio of the smaller diameter to the larger diameter for a contraction, expansion or orifice plate. The resistance factor for an orifice plate is from Blevins (1984) as well as tabular data for the orifice discharge coefficient, C, and the dimensionless coefficient, ζ.

Table 2 Hydraulic Resistance Factors

Component	K
pipe inlet	0.78
standard 90° elbow	30 f
standard tee, flow through run	20 f
standard tee, flow through branch	60 f
welded miter joint, 90°	60 f
pipe bend 90°, r/D = 1.5	14 f
pipe bend 90°, r/D = 2	12 f
for the restrictor:	
gradual contraction, θ <45°	$K_c = 0.8 (\sin \theta/2)(1 - \beta^2)$
gradual expansion, θ <45°	$K_e = 2.6 (\sin\theta/2)(1 - \beta^2)^2$
orifice plate	$K_o = \frac{\zeta}{C^2} \frac{1}{\beta^2} [1 - \beta^4]$

For some previous transfers the molarity of the eductant or plutonium solution was recorded but not the specific gravity. Therefore, a capability was needed to convert molarity to specific gravity. Data for the specific gravities, S, of solutions of nitric acid with a range of molarities were found in Perry, et al., [1984] and fit with the following polynomial.

$$S = 0.999 + 0.03364\, M - 0.0001535\, M^2 - 0.00001988\, M^3 \qquad (8)$$

The viscosities of the eductant and plutonium solution were not measured for the plutonium solution or the eductant. For the purpose of estimating viscosity the fluid was assumed to be an aqueous solution of nitric acid. Data for viscosities of solutions of nitric acid with a range of specific gravities were found in Perry, et al. (1984) and fit with the following polynomial where μ_w is the viscosity of water at the same temperature.

$$\mu/\mu_w = 0.0256 + 7.805\, S - 13.14\, S^2 + 6.313\, S^3 \qquad (9)$$

The temperature of the eductant and the plutonium solution is always close to 20°C. Kreith (1973) states that the viscosity of water at 20°C is 0.96 cp.

The plutonium solution was assumed to be saturated with air since it was in contact with air for a long period. For the purpose of the gas solubility calculation the fluid was assumed to be water. Henry's Law states that absolute pressure of a solution of gas in a liquid divided by mole fraction of dissolved gas is equal to a constant. The Henry's Law constant for air in water (Perry, et al., 1984) is 6.64 x 10^4 atm at 20°C. Therefore, at one atmosphere the mole fraction of dissolved air is 1.51 x 10^{-5}. One liter of water has a mass of 1 kg or 55.6 moles. Therefore, at saturation that liter contains 8.4 x 10^{-5} moles of air or 2% air by volume at ambient conditions. Decreasing the pressure brings this air out of solution and also increases its volume in accordance with the Ideal Gas Law.

$$\alpha = \frac{0.02\ P_v}{P_v - \Delta P_{suc} - P_{sat}} \qquad (10)$$

The term P_v is the slightly sub-atmospheric pressure in the ventilation system, ΔP_{suc} is the pressure drop from the plutonium solution tank to the suction of the eductor and P_{sat} is the vapor pressure of water, 17 torr or 2.3 kPa at 20°C. The denominator of equation 10 is the partial pressure of air at the suction of the eductor. The pressure in the suction line decreases from essentially atmospheric in the plutonium solution tank to the lowest value at the suction to the eductor. Therefore, the void fraction increases in the direction of flow. The effective void fraction in the suction line was approximated as half of the maximum void fraction calculated to occur at the location of the eductor suction using equation 11.

Adding gas to a liquid flow creates a two phase mixture and changes the calculation of pressure drop in equation 5 because the frictional pressure drop increases and the head term decreases. There are various methods to calculate the two-phase effect. The homogeneous model [Wallis, 1969] is simple and fairly accurate for void fractions less than 25%. In this model frictional terms are divided by the term (1 - α) and head terms are multiplied by (1 - α). The result of converting equation 5 to two phase flow follows.

$$\Delta P_{tp} = \rho\ g\ \Delta h\ (1 - \alpha) + \left(\frac{L\ f}{D} + \sum_{i=1}^{n} K_i\right) \frac{\rho\ V^2}{2\ (1 - \alpha)} \qquad (11)$$

2.4. Method of Solution

The equation set was entered into a spreadsheet. Tubing lengths, diameters and specific gravities were entered. Trial values of the eductant flow and plutonium solution flow were input. Two loop pressures were computed, the first for the suction line, the second for the eductant line. The sum of the pressure gains and losses going from the plutonium solution tank to the phase separator should be zero. Also, the sum of the pressure gains and losses going from the eductant supply tank to the phase separator should be zero. Iteration was used on the two flows until both loop pressure drops were equal to zero.

3. RESULTS OF MODEL

3.1 Parametric Results

Figure 3 plots the computed dilution ratio as a function of restrictor diameter with specific gravity of the plutonium as a parameter. In all cases the specific gravity of the eductant is 1.065 or 2 molar nitric acid and the eductant header is at 308 kPa. For restrictor diameters less than 6 mm the dilution ratio is a strong function of restrictor diameter. For restrictor diameters greater than 8 mm, the dilution ratio is a weak function of restrictor diameter. Increasing the plutonium solution specific gravity increases the dilution ratio. The reason is that it is harder to pump a liquid that is denser and more viscous. By inspection of Figure 3 note that changing the specific gravity of the plutonium solution from 1.13 to 1.385 for a restrictor tube diameter of 10 mm has a bigger effect than changing the diameter of the restrictor tube from 7 mm to 10 mm. This calculational result explained the unexpected trends from historical data.

Figures 4 through 6 replot the dilution ratios of Figure 3 and compare the model with existing transfer data for plutonium solution specific gravities of 1.13, 1.248 and 1.385, respectively. The pressure in the eductant header was always 308 kPa. There is good agreement between calculated and measured dilution ratios.

The model was used to make pre-test predictions of flows during planned transfers. Table1 compares predictions of flows and dilution ratios (the first line of a pair) to the actual values measured later (the second line of the pair).

Table 1 Validation of Model with Pre-Test Predictions.

	restrictor i. d., mm	Pu solution sp. gr.	eductant sp. gr.	eductant pres., kPa	eductant flow, L/s	Pu solut. flow, L/s	dilution ratio
pred. #1	3.9	1.254	1.07	240	0.39	0.047	8.38
meas. #1	3.9	1.254	1.07	240	0.38	0.050	7.63
pred. #2	8.5	1.015	1.385	240	0.34	0.126	2.66
meas. #2	8.5	1.015	1.385	240	0.35	0.141	2.50
pred. #3	3.9	1.015	1.385	308	0.41	0.066	6.24
meas. #3	3.9	1.015	1.385	308	0.41	0.061	6.81
pred. #4	3.9	1.015	1.385	240	0.35	0.057	6.01
meas. #4	3.9	1.015	1.385	240	0.34	0.057	6.06

Figures 7 and 8 plot measured and predicted flows for the four transfers of plutonium solutions. In Figure 7, the predicted and measured eductant flows agreed to within ±6%. In Figure 8, the predicted and measured plutonium solution flows agreed to within ±8%. The flow ratios agreed to within ±10%. Overall, the agreement is very good considering all of the factors that had to be accounted for and the fact that the eductant pressure measurement is probably accurate to no better than 7 kPa. The root sum square method was used for the uncertainty analysis. The 99% confident uncertainty of the calculated dilution ratio was ±12%.

4. CONCLUSIONS

a. The unexpected trends in dilution ratio were primarily the result of changes in the specific gravities of the plutonium solution and the eductant.

b. Because of corrosion of the eductor, the dilution ratio is expected to slowly increase at a rate of about 1% per year. If the eductor were replaced with the same model, the dilution ratio is expected to decrease by about 8%.

c. The calculation indicated that the use of eductant at 308 kPa with a small diameter restrictor could create pressures in the suction line as low as 3 kPa, which will result in void formation and possible foaming. Decreasing the eductant pressure to 240 kPa should reduce the formation of void. The resulting reduction of plutonium solution flowrate is only 17% which has a modest impact on the time required to complete a transfer.

d. Increasing the size of the flow restrictor decreases the dilution ratio; however, the effect is small for restrictor diameters greater than 8 mm.

e. Increasing the eductant specific gravity decreases the dilution ratio. Increasing the plutonium solution specific gravity increases the dilution ratio.

f. Increasing the eductant temperature would decrease its viscosity and increase the dilution ratio. Increasing the plutonium solution would decrease its viscosity and decrease the dilution ratio.

6. REFERENCES

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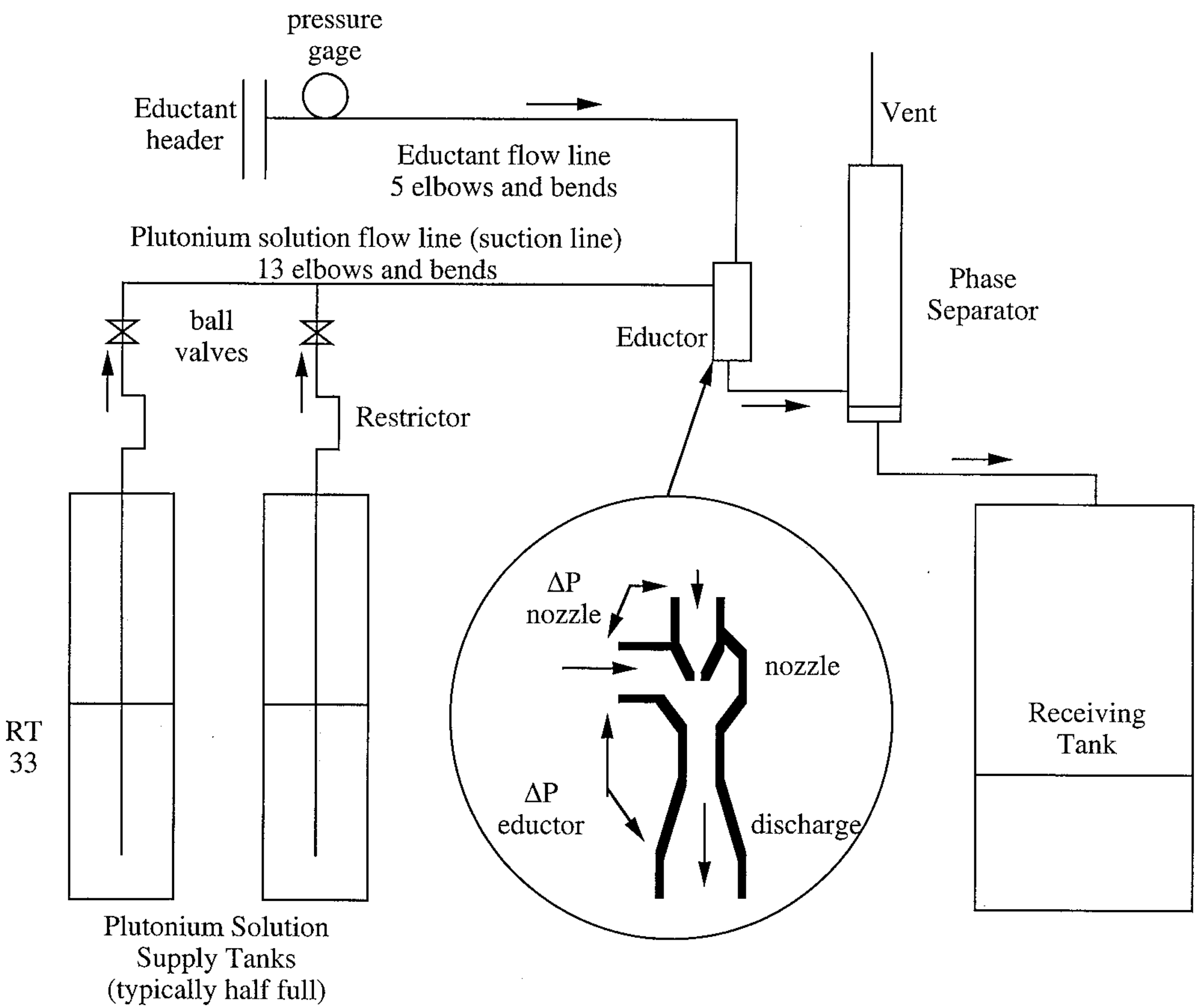

Figure 1
Eductor and Associated Piping

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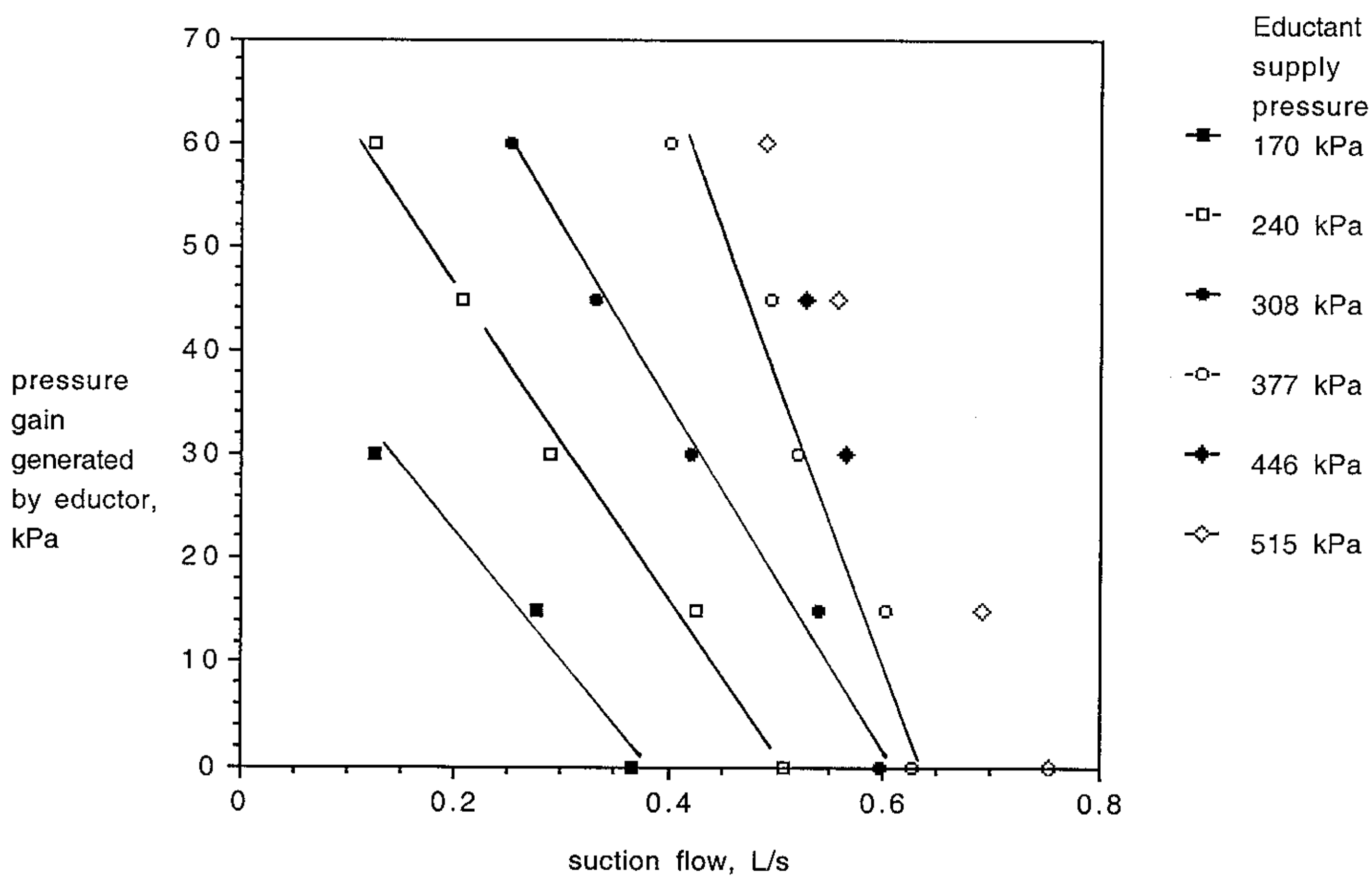

Figure 2 Pressure Generated by 1" Eductor for Water

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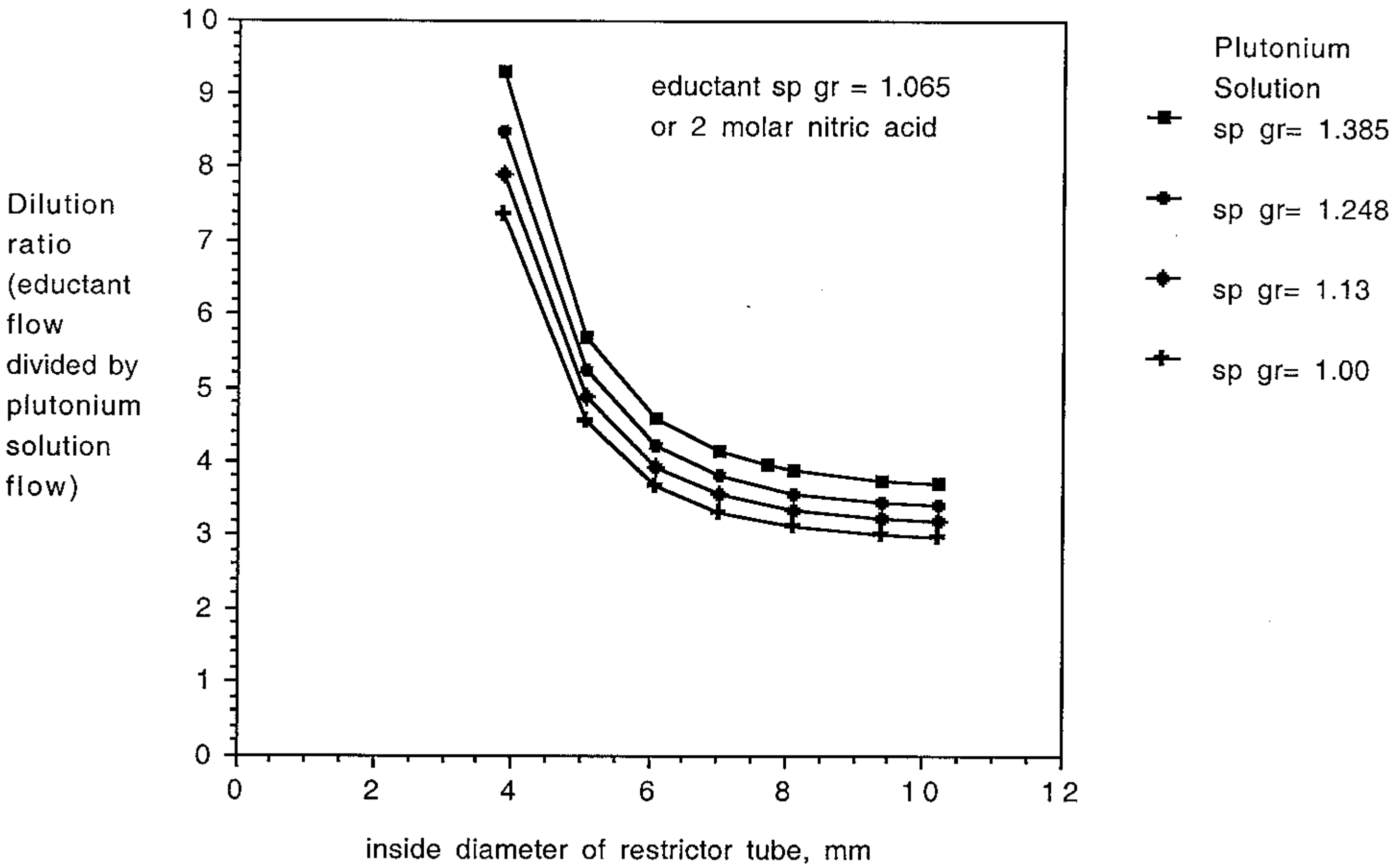

Figure 3
Calculated Dilution Ratios for Different Plutonium Solution Specific Gravities and Restrictor Diameters

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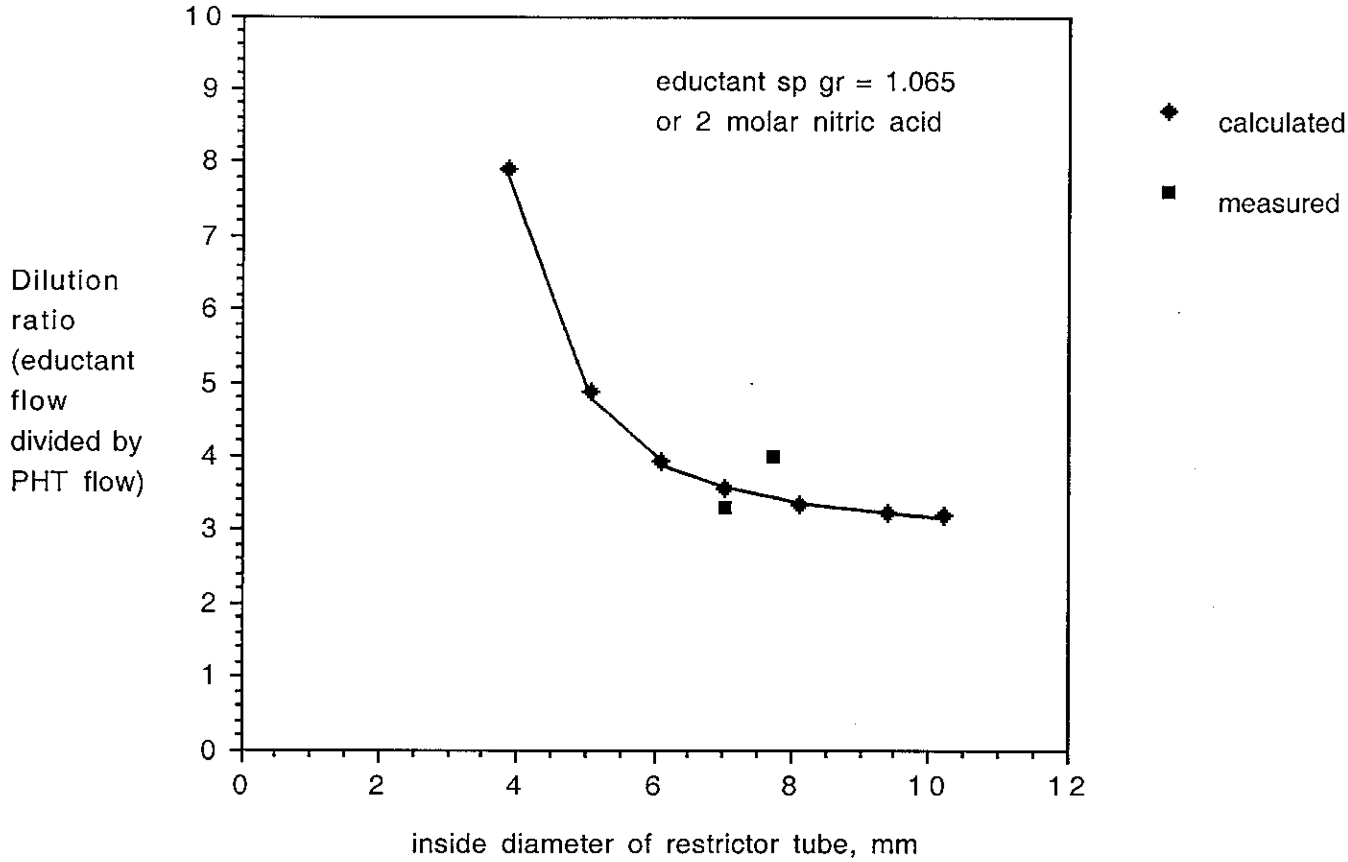

Figure 4
Calculated and Measured Flow Ratios for Plutonium
Solution Specific Gravity = 1.13 (4 M)

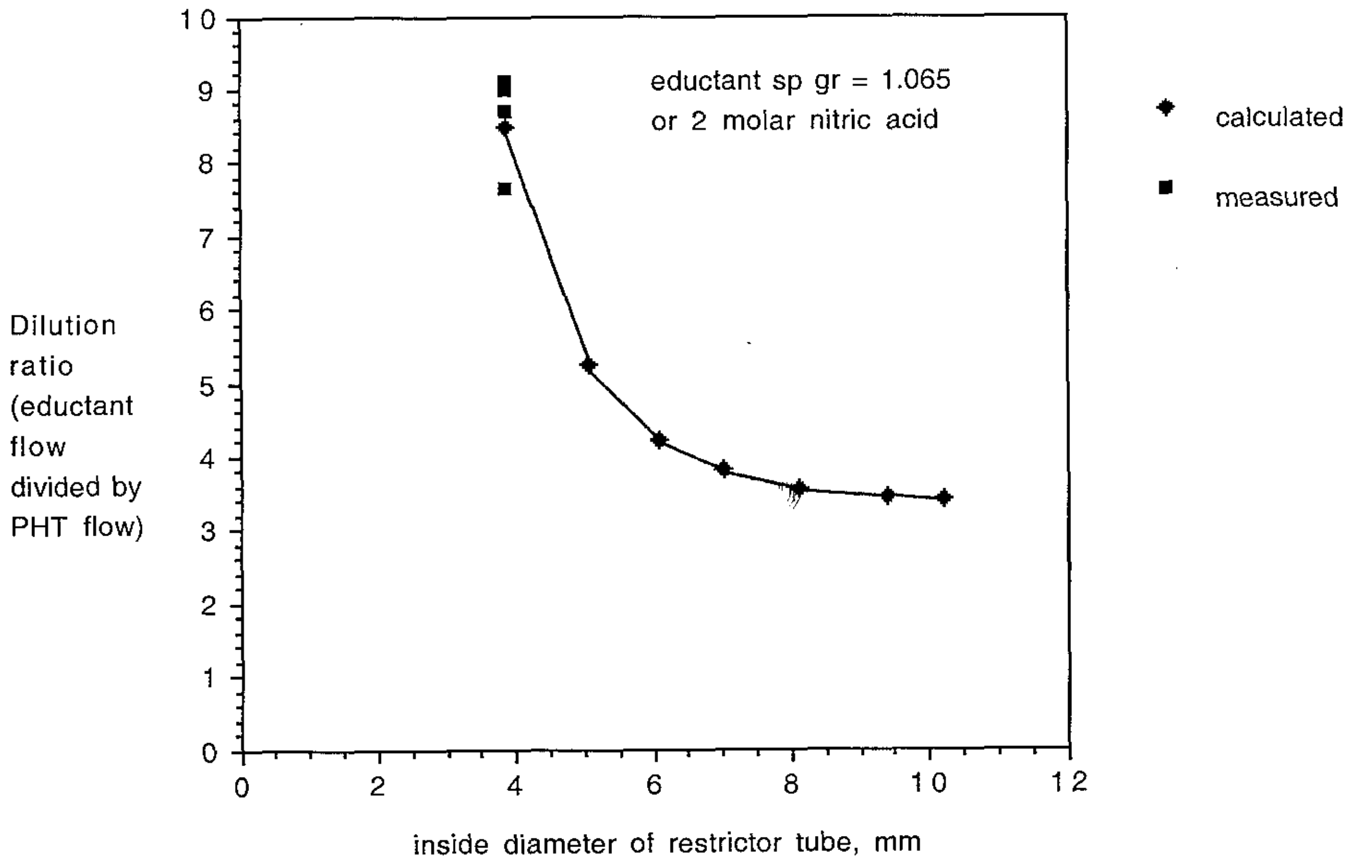

Figure 5
Calculated and Measured Flow Ratios for Plutonium
Solution Specific Gravity = 1.248 (8 M)

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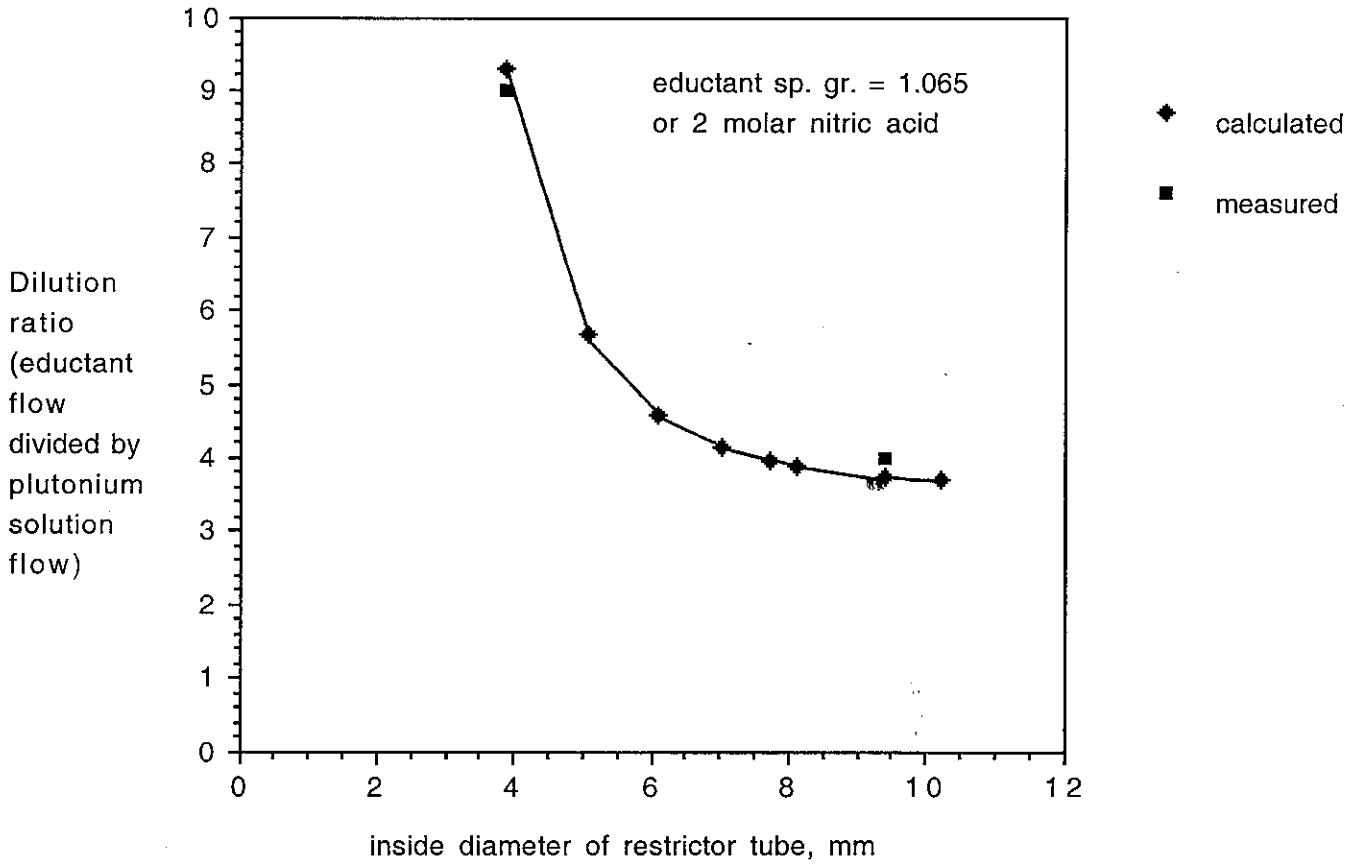

Figure 6
Calculated and Measured Dilution Ratios for Plutonium Solution Specific Gravity = 1.385 (14 M)

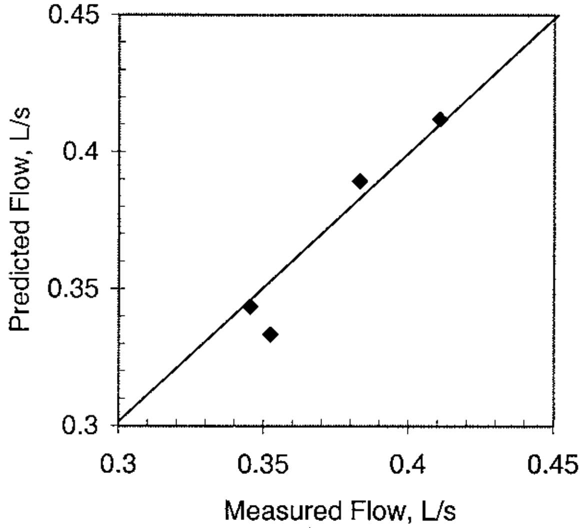

Figure 7 Measured and Predicted Eductant Flows

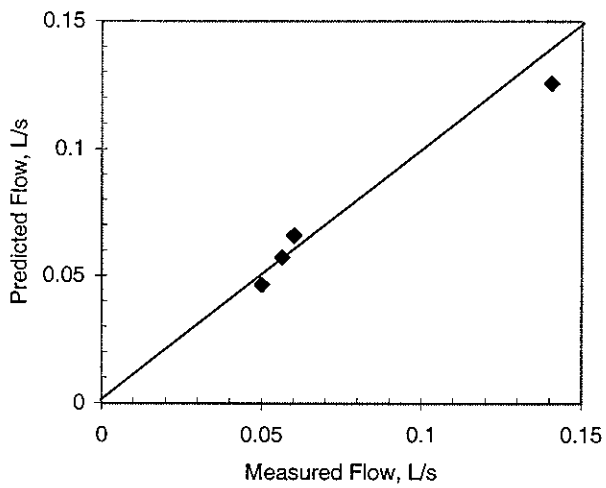

Figure 8 Measured and Predicted Plutonium Solution Flows