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Evaluation of a Commercially Available Low-Flow Steam Jet

B. E. Lewis
H. J. Marquess

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Consolidated Fuel Reprocessing Program

EVALUATION OF A COMMERCIALLY AVAILABLE LOW-FLOW STEAM JET

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ABSTRACT

A commercially available steam jet designed to deliver relatively low flow rates was evaluated for the transfer of heavy metal solutions in an advanced small-scale (0.1 metric ton/d) fast reactor fuel reprocessing plant. The steam jet was tested using 350-g/L uranyl nitrate solutions and 3- to 4-*M* HNO_3 solutions at various operating temperatures. The steam jet performed reasonably well within its design range; however, at low-delivered flow rates (<1 L/min), dilution levels ranging from ~5 to 25% were obtained. Variations in delivered flow rate appear to be too large to use the steam jet to feed equipment requiring relatively constant flow without using a flow smoothing device. The temperature rise in the transferred solution can be expected to range from ~10 to 80°C for solution transfer rates <2.5 L/min.

1. INTRODUCTION

Steam jets provide a convenient and reliable means of transferring fluids from tanks. However, this method of fluid transfer has three potential drawbacks: (1) excessive dilution at low flows, (2) solution temperature increase, and (3) plutonium polymer formation. For efficiently operated steam jets, the percentage increase in the mass flow of the supply stream resulting from steam condensation (the dilution factor) can be expected to range from 3 to 5%. As a result of the low flow rates (1 to 5 L/min) required in certain steam-jet-supplied process steps in the preconceptual design of an advanced small-scale fuel reprocessing plant (0.1 metric ton/d), commercially available jets may be required to operate at much less than optimum efficiency. Any decrease in efficiency increases dilution resulting from excess steam condensation, thus producing a larger temperature rise for the solution being transferred. In plutonium-bearing solutions there is a potential for the formation of plutonium polymer. The rate of polymer formation depends primarily upon the Pu(IV) concentration, nitric acid concentration, and temperature, with lower acid concentrations and higher temperatures being more conducive to the formation of polymer.[1] Therefore, inefficient steam-jet operation could lead to an increased potential for polymer formation.

The objectives of the work reported here were to (1) determine the feasibility of using a commercially available steam jet to deliver relatively low flow rates (1 to 5 L/min), (2) determine the dilution for various pumping rates, and (3) measure the temperature rise of the pumped solution.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

These tests were conducted in the Integrated Equipment Test (IET) facility at the Fuel Recycle Division (FRD) of the Oak Ridge National Laboratory (ORNL). Solutions were transferred from the uranium product collection tank (19F05) to the uranium product accountability tank (19F07) using a Penberthy* jet, model GL-1/2A. The following design requirements (illustrated in Fig. 1) were imposed on the experimental setup: (1) suction lift range of ~1 to 6 ft, (2) horizontal length from the jet to the receiver tank of ~15 ft, (3) a discharge head of at least 4 ft, (4) regulated steam-supply pressure over the range of ~10 to 80 psig, and (5) uninsulated transfer lines and tankage. The installation was designed to simulate solution transfer from a dissolver digester tank to the primary centrifuge in the head-end of a small-scale (0.1-metric ton/d heavy metal throughput) fuel reprocessing plant, where the delivered flow to the centrifuge was less than or equal to ~1.75 L/min. Assuming a suction lift of 5 ft, a discharge head of 10 ft, a solution temperature of ~65.6°C, and a steam-supply pressure of 60 psig, the rated water pumping capacity of the GL-1/2A jet is ~3.4 L/min.

Each experiment began with a solution of known composition and volume in the supply tank, which was controlled to maintain a constant solution temperature. The receiver tank was emptied before each test to simplify the comparison of dilution and temperature measurements. The steam-supply pressure was set at the beginning of each test and held constant by a pressure regulator for the duration of the transfer. The level, density, and temperature of the liquid in the supply tank were measured and recorded using differential pressure cells and thermocouples. Samples of the liquids in both the supply and receiver tanks were analyzed for HNO_3 and uranium concentrations in those tests where uranium was present. The density of each sample at 25°C was also determined. The temperature in the receiver tank was not controlled, but allowed to increase as solution was transferred. This temperature measurement along with the solution temperature immediately downstream of the jet was recorded. At the end of each test, the temperature of the solution in the receiver was reduced to the supply tank temperature before the solution was transferred back to the supply tank. Each completed test resulted in the transfer of a minimum of ~50 L of solution.

The initial experiments used 3- to 4-*M* HNO_3 solutions as the test solution; a second group of experiments used an acidic solution of uranyl nitrate containing ~350 g U/L and having a density of ~1.5 kg/L. Two types of tests were completed with each of the test solutions: characterization tests and low-flow demonstration tests. In the characterization tests, the performance of the jet was studied for the supply-tank solution temperature and steam-supply pressure values given in Table 1.

*Penberthy Division, Houdaille Industries, Inc.

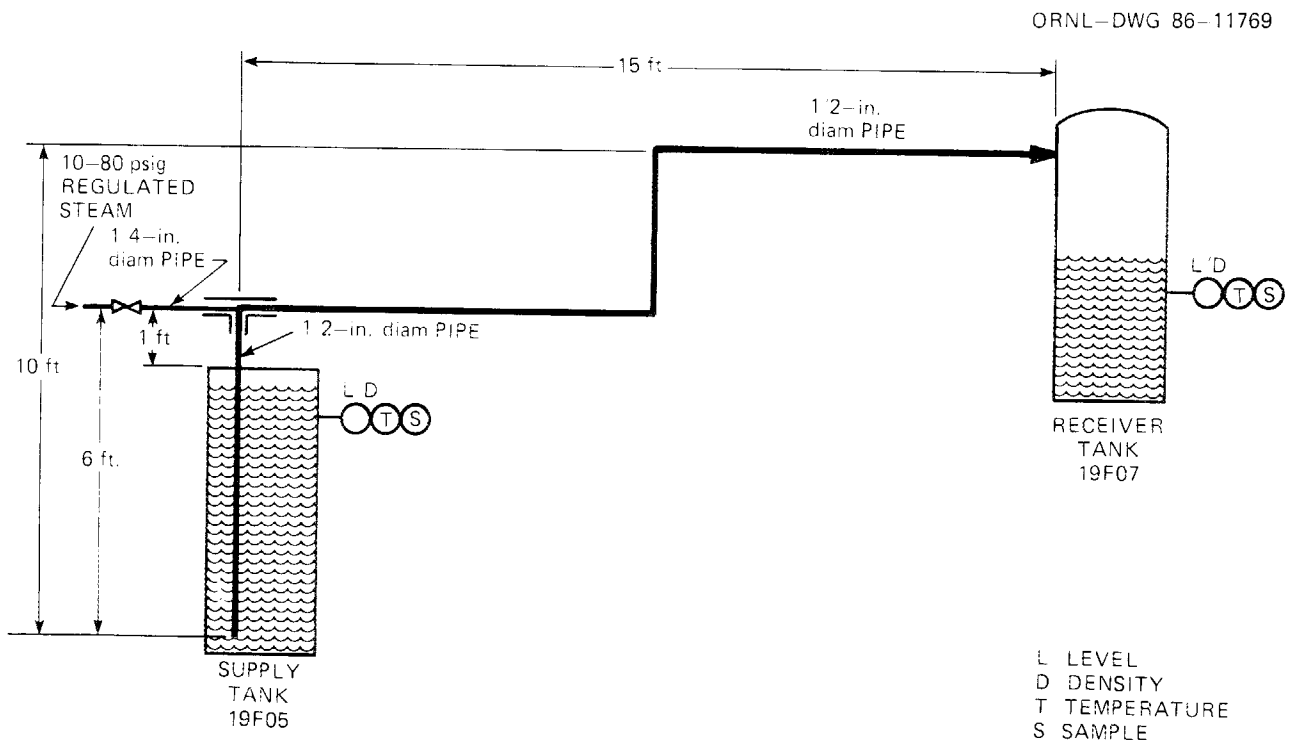

Fig. 1. Schematic diagram showing the experimental design requirements for the low-flow steam jet tests.

Table 1. Characterization test conditions

Run No.	Supply-tank solution temperature (°C)	Steam supply pressure (psig)
1	~25	30
2	~25	55
3	~25	76
4	40	30
5	40	55
6	40	76
7	60	30
8	60	55
9	60	76
10	80	30
11	80	55
12	80	76

The jet characterization tests provided a preliminary calibration of the performance of the steam jet. The low-flow demonstration tests provided a refined calibration of the jet at the target liquid delivery rates shown in Table 2. The steam-supply pressure was set at a value (estimated from the first test series) that provided a particular flow rate from Table 2. The supply-tank solution temperature was held at 60°C for all of the low-flow demonstration tests.

Table 2. Target flow rates for low-flow demonstration tests

Run No.	Flow rate to receiver tank (L/min)
1	1.00
2	1.33
3	1.75
4	2.50
5	5.00

2.1 CALCULATIONS

The dilution factor, D, was calculated using sample concentrations and density measurements at 25°C in the following:

$$D = \frac{100}{\alpha_{s_{25}}} \left(\frac{C_s}{C_r} - 1 \right) , \tag{1}$$

where C_s is the sample concentration of either HNO_3 or uranium in the supply tank, C_r is the sample concentration of either HNO_3 or uranium in the receiver tank, and $\alpha_{s_{25}}$ is the specific gravity of the solution in the supply tank defined by

$$\alpha_{s_{25}} = \frac{\rho_{s_{25}}}{\rho_{w_4}} , \tag{2}$$

where $\rho_{s_{25}}$ is the density of the solution in the supply tank at 25°C and ρ_{w_4} is the density of water at 4°C (1 g/cm^3). The physical significance of the dilution factor is that it is the percentage of the mass flow of solution from the supply tank that is added as condensate by the steam jet transfer. All sample concentration measurements were assumed to be taken at 25°C. In the uranium runs, the density at ~25°C was determined from the sample analysis. However, in the 4-M HNO_3 runs, the density at 25°C was determined from in-line density measurements at the average tank temperature using:

$$\rho_{25} = \frac{\rho_T - 0.0029366\,T + 0.073416}{1.0789 - 0.0031548\,T} , \tag{3}$$

where ρ_{25} is density at 25°C and ρ_T is density at temperature T.[2]

The average flow rate from the supply tank was calculated from incremental changes in the in-line level measurements using the appropriate tank calibration curve to convert the level measurements to volume.[3] The standard deviation of the calculated flow rates was also determined. The delivered flow rate to the receiver tank was estimated using total volume change in the supply tank plus the volume of dilution from the condensing steam divided by the total run time. The volume of dilution was determined from the dilution factor. Normally, level measurements in the receiver tank would be used to determine delivered flow, but for these experiments the solution level in the receiver tank was not high enough to give accurate level readings.

3. DISCUSSION OF RESULTS

The data from these experiments are summarized in the appendix. In the jet characterization tests, the effects of varying the supply-tank temperature and steam pressure on the delivered flow rate, temperature rise, and dilution factor were studied. In the low-flow demonstration tests, the solution temperature was held at ~60°C, while the steam flow was set to give the desired flow rate.

Figures 2 and 3 show the variation in delivered flow with steam-supply pressure and solution temperature for the HNO_3 and uranium solution tests, respectively. The lower

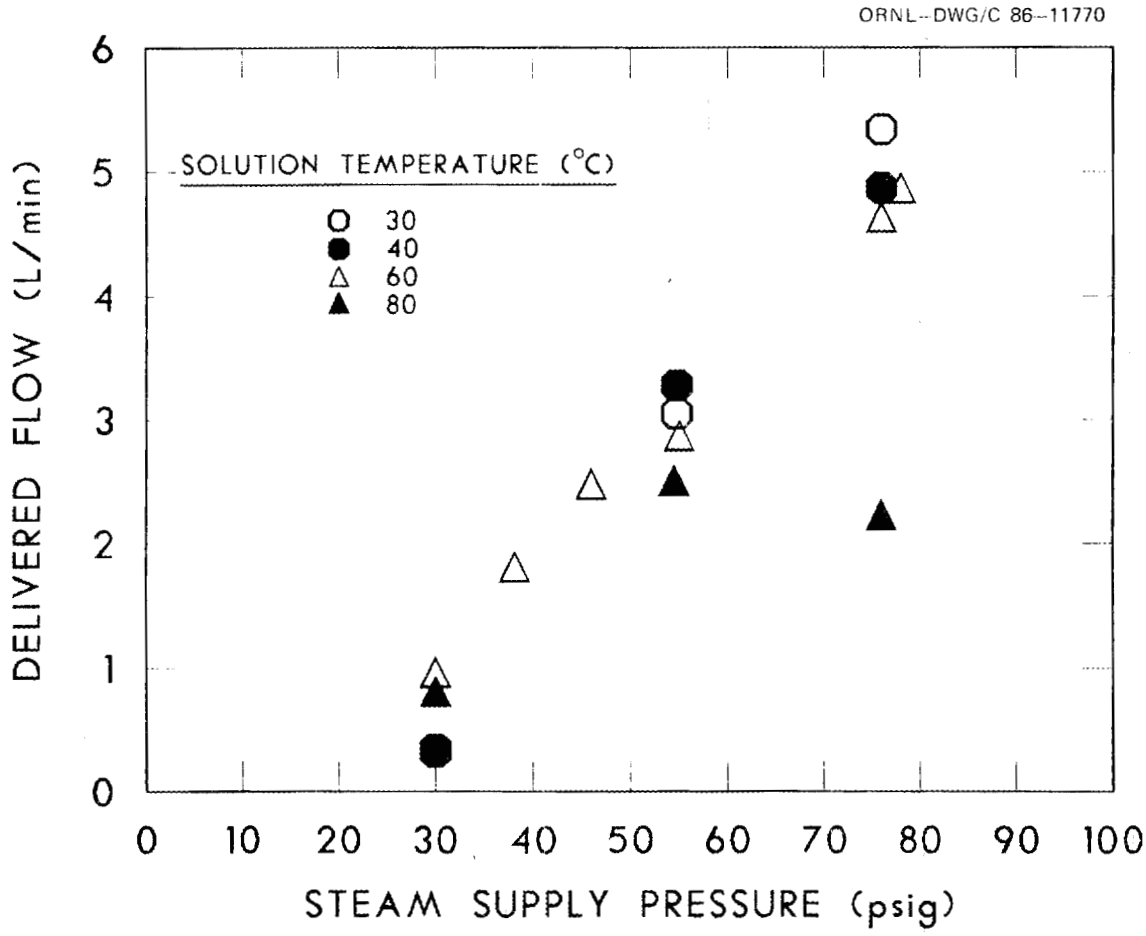

Fig. 2. Variation of delivered flow with steam-supply pressure and solution temperature for HNO_3 solution transfers.

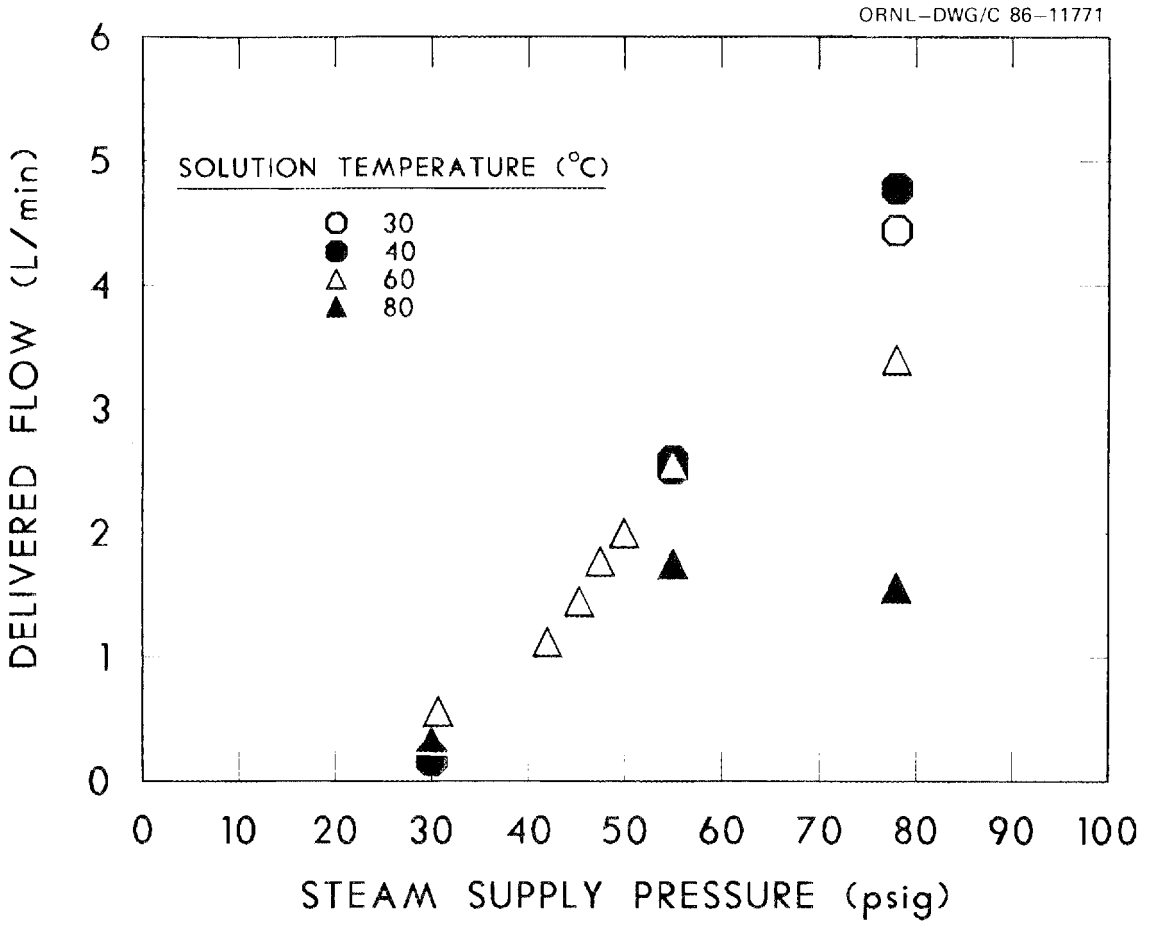

Fig. 3. Variation of delivered flow with steam-supply pressure and solution temperature for uranyl nitrate solution transfers.

operating steam-pressure limit for the jet was ~30 psig. Generally, for solution temperatures less than ~60°C, the delivered flow rate, which included the condensate from the steam, increased with increasing steam-supply pressure. However, for the 80°C runs, the maximum delivered flow occurred at the 55-psig steam-supply pressure setting. It appears that cavitation may have been a problem at the higher supply-tank solution temperatures because the delivered flow decreased at the highest steam supply pressure. Specific gravities ranged from ~1.373 to 1.470 for the uranium tests and from 1.103 to 1.137 for the HNO_3 tests. The flow rates for the uranium tests were always less than those for the HNO_3 tests for the same steam supply pressure.

3.1 DILUTION FACTORS

The variation of the dilution factor with delivered flow at different solution temperatures for the HNO_3 and uranium solution transfers is shown in Figs. 4 and 5, respectively. The higher density solutions generally had higher dilution factors because less solution was

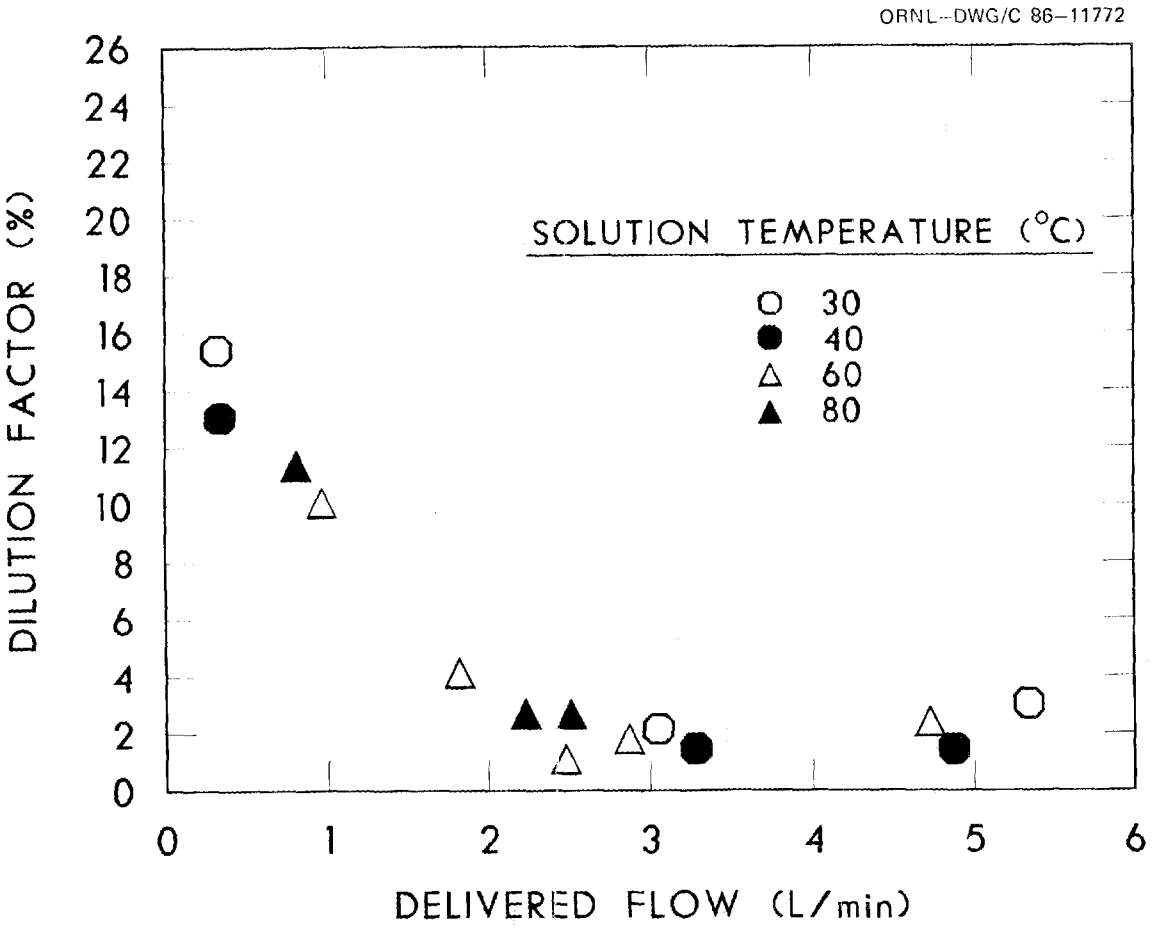

Fig. 4. Variation of dilution factor with delivered flow for the transfer of HNO_3 solutions at various temperatures.

delivered per unit time for a given steam flow. Dilution factors for flows <1 L/min were much larger than normally acceptable. It is therefore not recommended that the low-flow jet studied here be used for applications requiring flow rates <1 L/min. Dilution factors at delivery rates of >1.5 L/min were typically <4%. Variations in the supply-tank solution temperature had very little effect on the dilution factor. The variation of dilution factor with solution temperature at various steam-supply pressures is shown in Figs. 6 and 7. Generally, the lower steam-supply pressures resulted in lower delivery rates. Average dilution factors <4% were obtained at the two highest steam-supply pressures.

3.2 FLOW STABILITY

The average flow rates from the supply tank and their standard deviations are given in the Appendix. From Fig. 8 it can be seen that the flow variation as a percentage of average flow is usually largest at the lower flow rates. The larger flow variations at the lower delivery rates may result from some instability in the steam-supply pressure regulator at

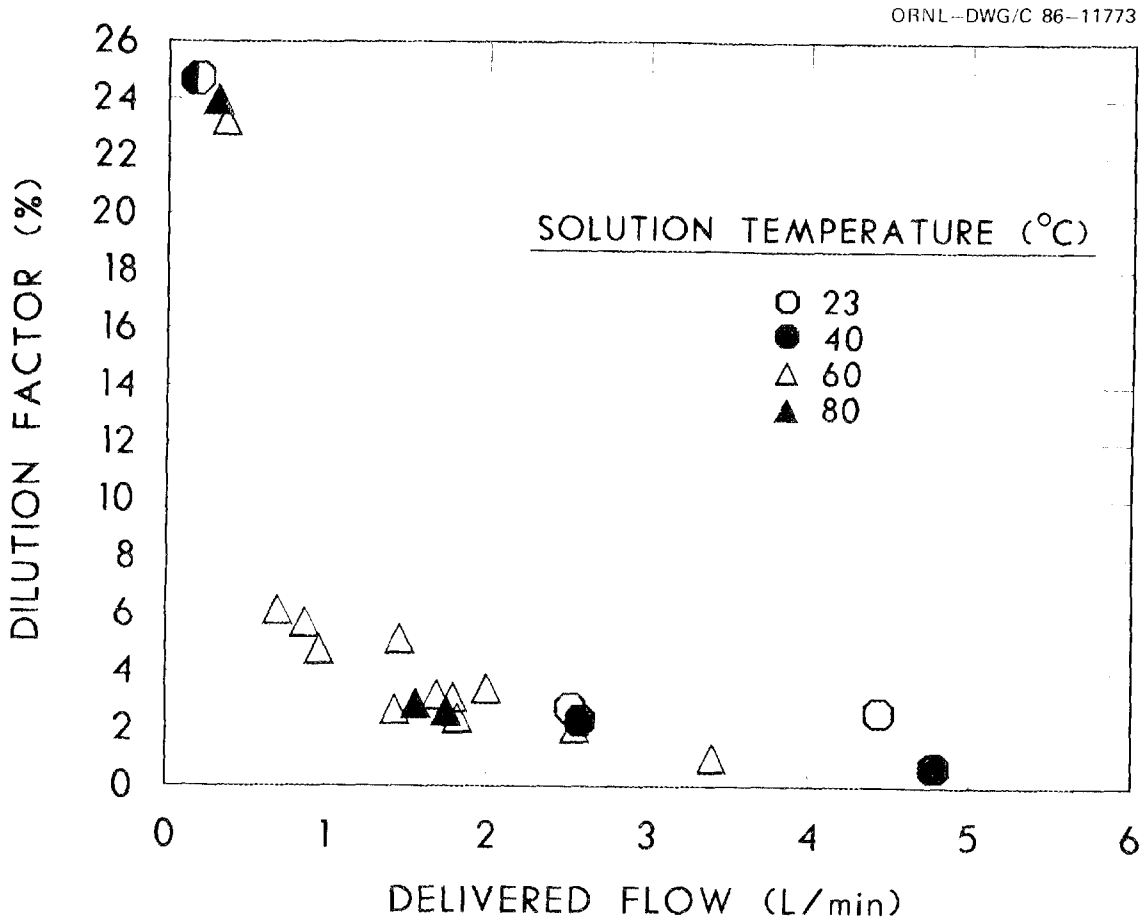

Fig. 5. Variation of dilution factor with delivered flow for the transfer of uranium solutions of various temperatures.

the lower pressures although no significant instability was noticed. Typical flow variations with time for the transfer of 350 g/L uranium solution at average supply flow rates of 1.40 and 2.56 L/min are shown in Fig. 9. This type of unstable flow is not suitable for use with the current centrifuge design without the employment of some type of flow-smoothing device, assuming the delivered flow varies the same as did the flow to the supply tank. The variation in the flows shown in Fig. 9 may explain most of the scatter in the data previously given. The reasons for these flow variations are not well understood and will be the subject of future study. However, the variations may be attributable to the following: (1) fluctuation of the steam-supply pressure, (2) temperature fluctuations in the supply-tank solution, (3) variations in the tank-level readings used to compute flow rate, (4) foreign material in the steam-supply system, (5) downstream pressure fluctuations, or (6) the occurrence of two-phased flow resulting from cavitation.

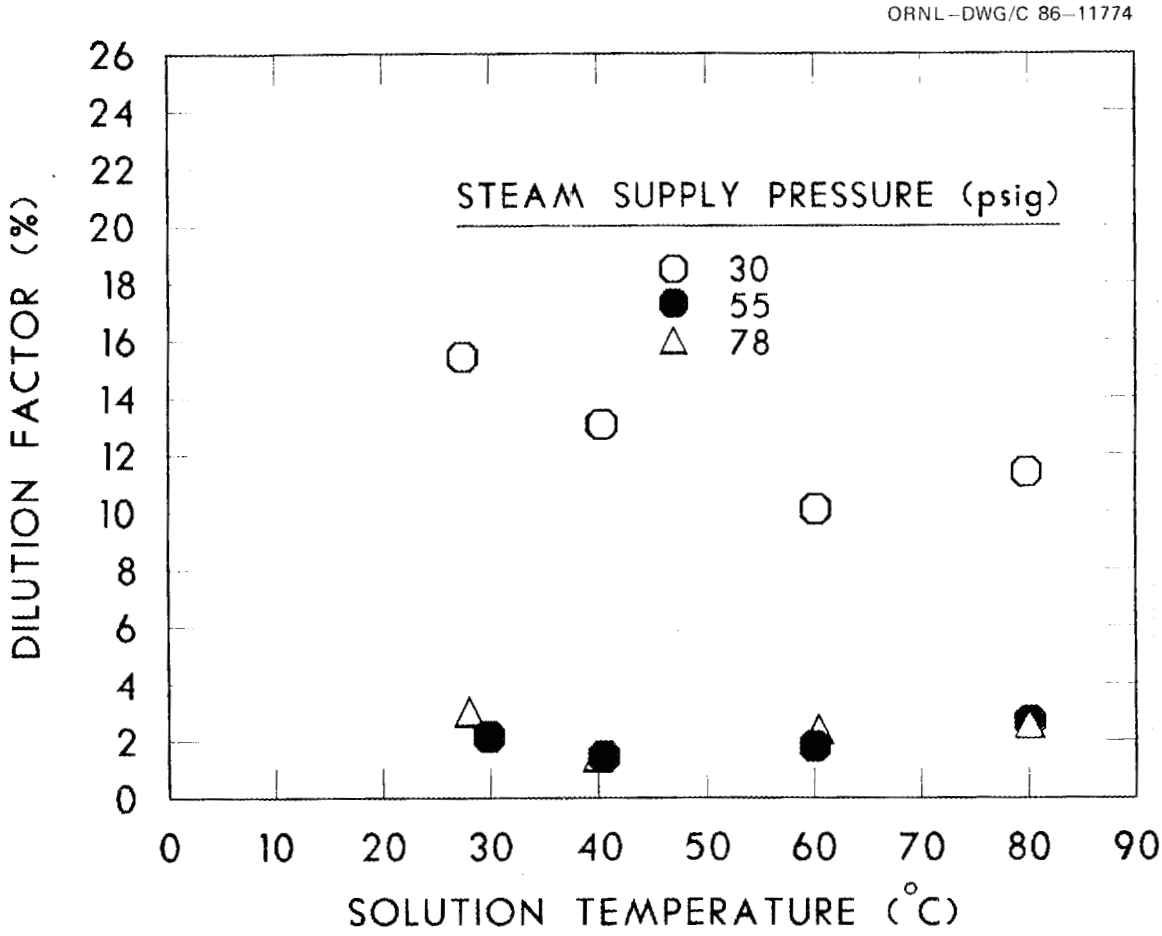

Fig. 6. Variation of dilution factor with solution temperature at various steam-supply pressures for the transfer of HNO_3 solution.

3.3 TEMPERATURE RISE

The average temperature rise data for all the experiments run with both the nitric acid and uranyl nitrate solutions are summarized in Figs. 10 and 11, respectively. The temperature rise for the uranyl nitrate solution transfers was higher than that for the nitric acid solutions. For all the supply-tank solution temperatures tested, except 80°C, the temperature rise was greater for the lower delivered flow rates (<2.5 L/min). This result is a direct consequence of the higher dilution levels at the lower flow rates. The temperature rise for the tests conducted with the 80°C solution did not change appreciably with changes in flow rate.

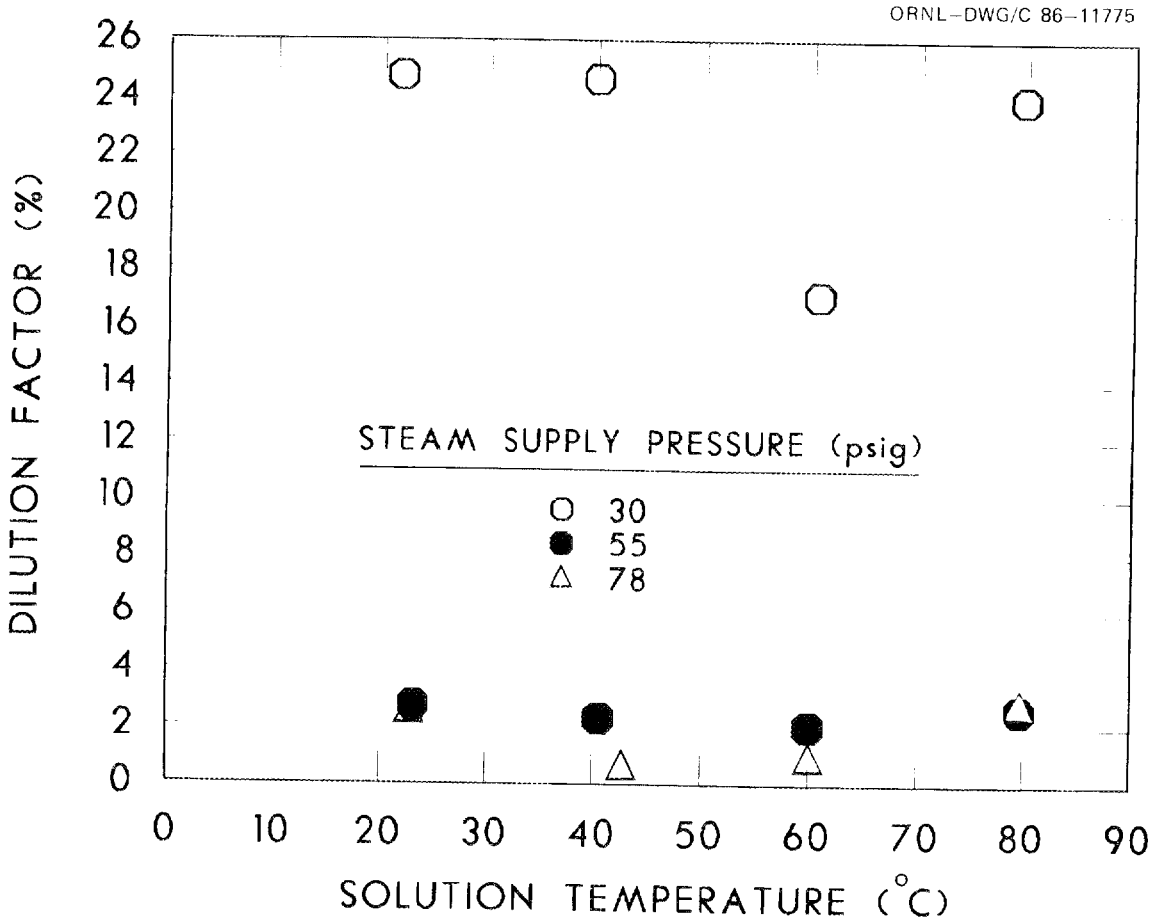

Fig. 7. Variation of dilution factor with solution temperature at various steam-supply pressures for the transfer of uranyl nitrate solution.

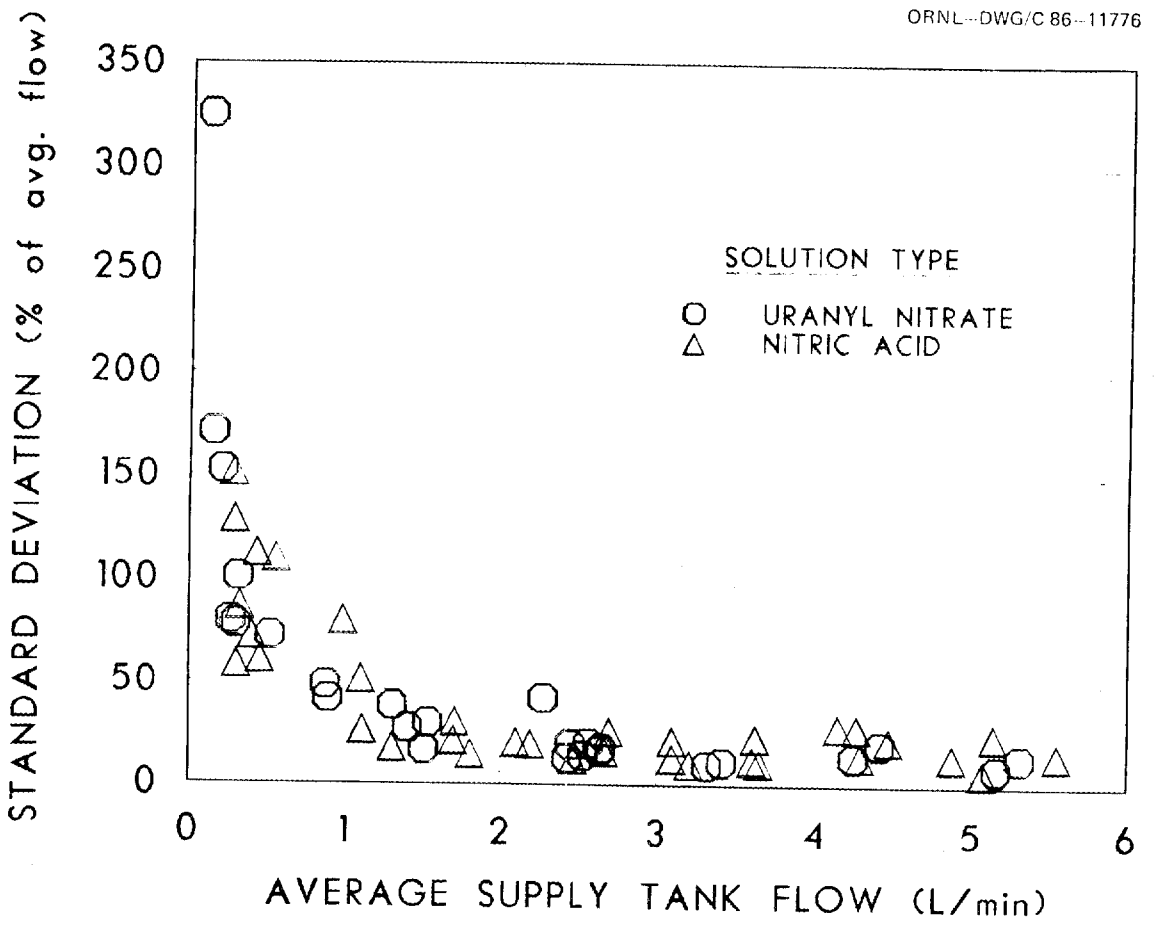

Fig. 8. Flow variation relative to average supply tank flow.

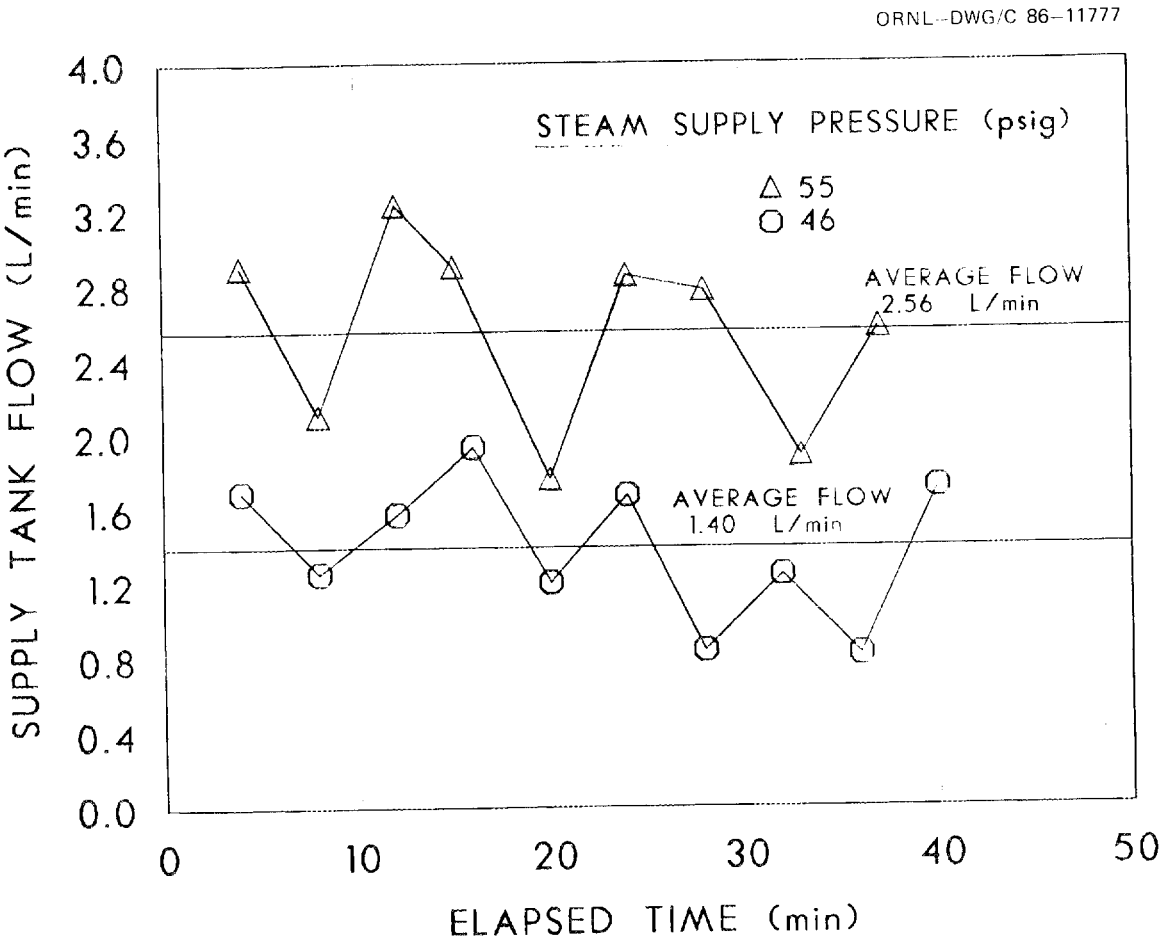

Fig. 9. Typical flow variation with time.

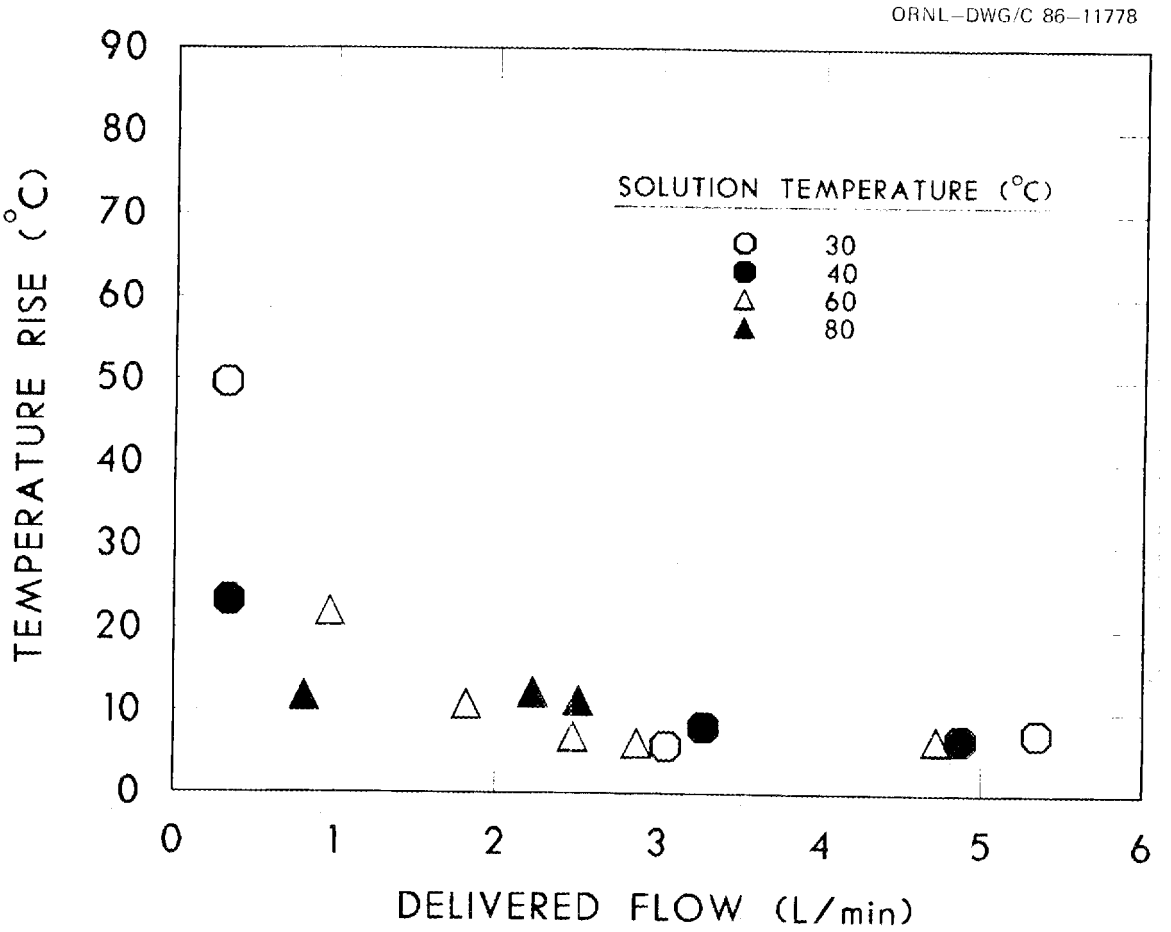

Fig. 10. Average temperature rise measurements for the transfer of HNO_3 solutions at various temperatures.

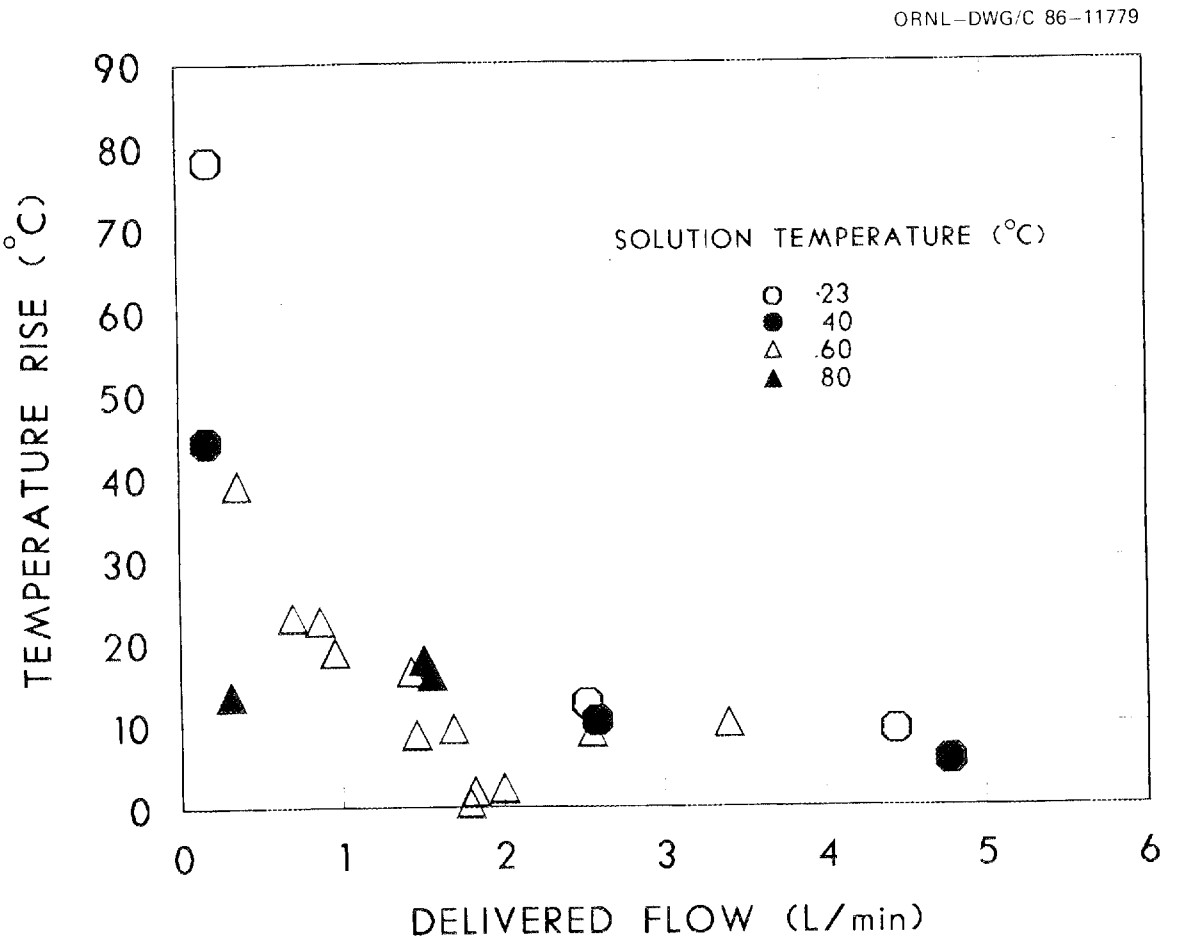

Fig. 11. Average temperature rise measurements for the transfer of uranyl nitrate solutions at various temperatures.

4. CONCLUSIONS

The experiments conducted with the Penberthy low-flow steam jet have shown that the jet performs reasonably well within its specified range of operation. However, at very low flows (<1 L/min), dilution levels in the range of ~5 to 25% were obtained.

Variations in delivered flow rate appear to be too large to use the steam jet to feed equipment requiring relatively constant flow without using a flow smoothing device. The temperature of the supply tank solution had very little effect on the performance of the jet, except for the 80°C runs, where it is suspected that cavitation may have occurred.

The temperature rise in the delivered solution can be expected to range from ~10 to ~80°C for solution transfer rates <2.5 L/min. At these flow rates, the temperature rise increases with decreasing feed solution temperatures.

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2. E. D. Blakeman Oak Ridge National Laboratory, personal communication to Distribution, Sept. 27, 1978.

3. T. L. Hebble, J. W. Wachter, and H. T. Kerr, *IET Tank Calibration Study*, ORNL/TM-9633, August 1985.

APPENDIX

Table A.1. Summary of the tests with HNO_3 solutions

Run No.	Avg supply tank temp (°C)	Max soln temp (°C)	Steam press (psig)	Supply tank soln density (kg/L)	Trans time (min)	Vol trans (L)	Avg supply tank flow (L/min)	Std dev of supply tank flow	Dev (%)	Avg receiver tank flow (L/min)	Supply tank HNO_3 conc (m/L)	Receiver tank HNO_3 conc (m/L)	Dilution factor (%)
1	60.50	67.90	76.0	1.137	40.0	179.10	4.265	1.186	27.80	4.66	4.230	4.060	3.682
2	60.45	66.85	76.0	1.133	40.0	181.82	4.469	0.971	21.73	4.61	4.090	4.030	1.315
3	60.20	66.22	55.0	1.131	40.0	141.69	3.604	0.437	12.13	3.61	4.080	4.000	1.768
4	60.20	66.10	55.0	1.127	40.0	146.60	3.624	0.830	22.90	3.72	4.050	3.990	1.335
5	60.60	85.33	30.0	1.129	40.0	41.49	0.397	0.287	72.10	1.16	4.010	3.600	10.085
6	59.80	79.00	30.0	1.126	40.0	27.83	0.429	0.481	112.12	0.77	4.010	3.600	10.110
7	79.70	83.33	30.0	1.130	40.0	29.25	0.451	0.273	60.61	0.82	4.000	3.550	11.214
8	80.00	100.00	30.0	1.126	40.0	28.39	0.552	0.606	109.84	0.80	4.000	3.540	11.542
9	80.05	100.00	54.5	1.125	40.0	97.41	2.467	0.301	12.21	2.47	3.930	3.870	1.379
10	80.20	82.80	54.5	1.128	40.0	97.79				2.55	3.950	3.780	3.986
11	29.30	38.53	54.5	1.128	50.0	158.57	3.095	0.667	21.56	3.26	3.900	3.790	2.574
12	40.65	48.72	54.5	1.116	45.0	147.37	3.205	0.325	10.14	3.33	3.850	3.790	1.418
13	59.80	66.24	54.5	1.133	40.0	49.88	3.648	0.397	10.87	1.28	3.880	3.780	2.335
14	80.10	92.37	76.0	1.123	40.0	86.50	2.190	0.429	19.58	2.23	3.830	3.720	2.632
15	79.95	94.09	76.0	1.123	40.0	83.88	2.096	0.428	20.41		3.830		
16	40.60	47.00	76.0	1.123	45.0	252.26	5.547	0.819	14.76	5.68	3.780	3.730	1.193
17	39.35	46.16	76.0	1.124	40.0	176.03	4.289	0.594	13.85	4.50	3.750	3.670	1.940
18	39.75	46.45	76.0	1.122	40.0	174.66	4.148	1.166	28.11	4.43	3.700	3.650	1.221
19	30.45	32.73	55.0	1.125	40.0	111.34	2.665	0.432	16.20	2.84	3.670	3.600	1.728
20	40.30	48.42	55.0	1.119	50.0	159.44	3.096	0.402	12.99	3.24	3.650	3.590	1.494
21	39.80	79.93	30.0	1.120	90.0	28.14	0.288	0.370	128.48	0.36	3.600	3.160	12.435
22	27.05	76.82	30.0	1.117	90.0	24.74	0.322	0.279	86.60	0.32	3.580	3.080	14.531
23	27.90	77.37	30.0	1.117	60.0	16.19	0.300	0.175	58.15	0.32	3.570	3.020	16.309
24	28.05	35.49	76.0	1.117	28.0	144.31	4.873	0.671	13.77	5.35	3.530	3.400	3.424
25	28.05	35.42	76.0	1.113	28.0	144.76	5.140	1.231	23.95	5.32	3.520	3.420	2.628
26	40.90	47.37	30.0	1.116	60.0	16.52	0.280	0.423	151.30	0.32	3.470	3.010	13.691
27	59.35	71.98	36.0	1.117	40.0	49.08	1.108	0.292	26.36	1.27	3.470	3.340	3.484
28	60.55	72.02	37.0	1.104	41.0	152.61	1.302	0.231	17.75	3.89	3.450	3.300	4.116
29	60.30	71.55	38.0	1.113	40.0	49.51	1.097	0.561	51.16	1.29	3.420	3.290	3.549
30	59.80	68.92	41.0	1.112	40.0	70.31	1.806	0.266	14.73	1.83	3.410	3.280	3.565
31	60.30	69.80	40.0	1.111	40.0	68.09	1.695	0.362	21.33	1.78	3.400	3.250	4.154
32	60.45	66.29	78.0	1.105	40.0	190.21	5.073	0.323	6.37	4.87	3.370	3.290	2.201
33	59.90	66.77	46.0	1.109	40.0	98.20	2.694	0.698	25.91	2.48	3.320	3.280	1.100
34	60.25	73.30	36.0	1.103	40.0	34.07	0.980	0.780	79.59	0.90	3.340	3.150	5.471
35	60.65	69.08	39.0	1.106	41.0	68.11	1.703	0.520	30.53	1.74	3.360	3.200	4.520

Table A.2. Summary of the tests with uranyl nitrate solutions

Run No.	Avg supply tank temp (°C)	Max soln temp (°C)	Steam press (psig)	Supply tank soln density (kg/L)	Trans time (min)	Vol trans (L)	Avg supply tank flow (L/min)	Std dev of supply tank flow	Dev (%)	Avg receiver tank flow[a] (L/min)	Supply tank HNO_3 conc (m/L)	Receiver tank HNO_3 conc (m/L)	Supply tank U conc (g/L)	Receiver tank U conc (g/L)	Dilution factor (%)
36	43.00	48.74	78.0	1.468	40.0	189.88	5.158	0.429	8.32	4.80	0.460	0.460	346.0	342.0	0.797
37	42.50	47.86	78.0	1.468	43.0	203.08	5.310	0.726	13.67	4.76	0.460	0.420	346.0	343.0	0.596
38	59.90	68.56	55.0	1.458	42.0	101.22	2.561	0.515	20.11	2.49	0.430	0.415	337.0	326.5	2.206
39	60.05	69.41	55.0	1.460	59.0	149.65	2.527	0.360	14.25	2.61	0.390	0.340	338.0	329.0	1.874
40	60.25	71.01	78.0	1.460	60.0	198.82	3.317	0.322	9.71	3.32	0.340	0.310	329.0	328.0	0.209
41	59.85	69.36	78.0	1.457	50.0	169.38	3.411	0.383	11.23	3.48	0.330	0.320	333.0	324.5	1.798
42	60.90	100.00	30.0	1.449	25.0	9.81	0.149	0.255	171.14	0.54	0.335	0.295	328.0	237.0	26.499
43	21.30	100.00	30.0	1.444	90.0	15.41	0.295	0.230	77.97	0.23	0.340	0.240	319.5	235.0	24.901
44	22.05	99.88	30.0	1.444	95.0	10.40	0.313	0.315	100.64	0.15	0.330	0.240	316.5	233.5	24.616
45	22.75	35.34	55.0	1.434	45.0	108.88	2.427	0.314	12.94	2.52	0.310	0.290	314.0	302.0	2.771
46	23.60	36.08	55.0	1.436	50.0	121.42	2.446	0.481	19.66	2.52	0.320	0.310	312.5	301.0	2.661
47	40.90	51.24	55.0	1.427	42.0	100.13	2.635	0.443	16.81	2.42	0.325	0.320	306.0	302.0	0.928
48	21.75	31.06	78.0	1.428	40.0	175.21	4.247	0.584	13.75	4.51	0.325	0.330	309.0	300.0	2.101
49	23.90	33.01	78.0	1.426	42.0	176.02	4.414	0.877	19.87	4.38	0.310	0.330	308.0	295.0	3.090
50	40.20	50.73	55.0	1.417	40.0	104.08	2.647	0.476	17.98	2.74	0.325	0.325	304.0	289.0	3.663
51	60.75	100.00	30.0	1.427	80.0	11.06	0.265	0.211	79.62	0.18	0.335	0.270	298.0	232.0	19.936
52	79.45	96.69	78.0	1.416	40.0	58.92	1.506	0.255	16.93	1.52	0.310	0.290	295.0	285.0	2.478
53	80.00	94.64	78.0	1.415	41.0	62.41	2.271	0.956	42.10	1.59	0.320	0.270	295.0	282.0	3.258
54	39.75		30.0	1.409	94.0	12.54				0.18	0.315	0.220	296.0	214.0	27.195
55	40.45	68.80	30.0	1.404	73.0	8.97				0.16	0.290	0.220	288.0	216.0	23.742
56	79.95	90.90	30.0	1.400	30.0	11.01				0.49	0.300	0.240	288.0	216.0	23.810
57	79.35	88.90	30.0	1.400	75.0	12.82				0.23	0.290	0.210	285.0	216.0	22.817
58	78.95	78.20	55.0	1.401	40.0	72.05				1.87	0.310	0.260	285.0	274.0	2.866
59	80.00	60.70	55.0	1.407	84.0	151.47				1.86	0.290	0.290	287.0	278.0	2.301
60	60.45	85.80	38.0	1.398	40.0	12.00					0.300		283.0		
61	60.30	62.60	50.0	1.397	40.0	76.23				2.00	0.310	0.300	287.0	274.0	3.396
62	59.90	62.20	45.0	1.393	40.3	57.76				1.58	0.310	0.280	293.0	265.0	7.585
63	59.90	60.40	47.5	1.389	40.0	72.55				1.85	0.300	0.280	276.0	271.0	1.328
64	59.35	62.80	46.5		40.0										
65	60.65	64.70	47.0	1.385	40.0	66.76				1.73	0.290	0.290	274.0	265.0	2.452
66	61.25	62.30	47.0	1.384	40.0	72.17				1.89	0.300	0.290	273.0	261.0	3.322
67	60.05	79.10	39.0		30.0										
68	61.00	61.50	43.0	1.373	30.0	51.45				1.79	0.290	0.260	270.0	259.0	3.093
69	59.95	69.85	48.0	1.470	40.0	65.91				1.73	0.300	0.280	339.0	323.0	3.370
70	59.45	68.50	48.0	1.466	40.0	63.14				1.65	0.310	0.290	333.0	319.0	2.994
71	59.95	83.03	41.0	1.459	40.0	25.63	0.514	0.372	72.28	0.70	0.320	0.300	329.0	302.0	6.128
72	60.45	83.10	42.0	1.457	40.0	32.27	0.872	0.423	48.53	0.87	0.310	0.310	326.0	301.0	5.701
73	60.20	79.00	32.0	1.451	40.0	35.91	0.888	0.372	41.83	0.96	0.340	0.290	326.0	305.0	4.745
74	60.10	76.54	46.0	1.453	43.0	59.13	1.401	0.383	27.35	1.43	0.320	0.290	323.0	311.0	2.656
75	59.55	74.79	45.0	1.455	40.0	51.08	1.302	0.500	38.40	1.33	0.320	0.290	321.0	309.0	2.669
76	79.80	100.00	30.0	1.466	97.0	14.25	0.209	0.319	152.89	0.20	0.310	0.230	322.0	235.0	25.253
77	80.10	97.93	55.0	1.441	60.0	87.46	1.530	0.459	30.00	1.51	0.310	0.270	317.0	305.0	2.730
78	39.80	100.00	30.0	1.443	90.0	11.58	0.123	0.400	325.17	0.17	0.300	0.250	317.0	238.0	23.003

[a]Calculated based on total volume transferred plus the dilution volume.

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