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AN EVALUATION OF GEOPRESSURED BRINE INJECTABILITY: Department of Energy Pleasant Bayou No. 2 Well Brazoria County, Texas

L. B. Owen
C. K. Blair
J. E. Harrar
R. Netherton

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DISCLAIMER

An Evaluation of Geopressured Brine Injectability: Department of Energy, Pleasant Bayou No. 2 Well, Brazoria County, Texas

L. B. Owen*, C. K. Blair*, J. E. Harrar† and R. Netherton†

*Terra Tek, Inc., 420 Wakara Way, Salt Lake City, Utah 84108
†University of California, Lawrence Livermore National Laboratory, Livermore, California 94550

ABSTRACT

A field evaluation of geopressured brine injectability was completed during September 22-25, 1980 at the DOE, Brazoria test site in Texas. Membrane filters, with pore sizes of 0.4-μm and 10.0-μm, were used as the basis for obtaining suspended solids data and for developing performance-life estimates of typical spent brine injection wells. Field measurements were made at 130°C and line pressures up to 3800 psig. Scale inhibited (phosphonate-polyacrylate threshold-type, carbonate scale inhibitor), prefiltered-scale-inhibited, and untreated brine were evaluated. Test results indicated that raw brine was highly injectable, while scale-inhibited brine had extremely low quality. The poor injectability of scale-inhibited brine resulted from partial precipitation of the scale inhibitor.

INTRODUCTION

New concepts for the high temperature/high pressure recovery of methane from geopressured brine have been developed by Lawrence Livermore National Laboratory (LLNL).[1,2] The primary objective of these methane recovery processes is to preserve sufficient hydraulic energy to drive the subsequent subsurface disposal of spent brine effluents at substantial reductions in operating and maintenance costs associated with use of injection pumps. However, a key

element in determining the feasibility of the overall methane recovery process is the need to quantitatively establish injectability characteristics of geopressured brine at elevated temperature and pressure.

Typical geopressured wells are expected to produce in excess of 20,000 barrels of brine per day. Subsurface disposal of large quantities of "spent" brine effluent, to be cost-effective, will require control of brine quality (i.e., low suspended solids concentration), minimization of scaling and corrosion, and knowledge of the injection potential of the disposal sand. Brine disposal in conjunction with operation of the U. S. Strategic Petroleum Reserve (SPR) is a close operational analog to a geopressured system. The SPR program required long term disposal of nearly saturated NaCl brines (20-35°C) at rates of 30,000 barrels per day per well. However, SPR disposal wells were rapidly impaired and design injection rates could not be maintained. It has recently been demonstrated that SPR injection wells became impaired as a result of poor brine quality, including corrosion-generated particulates, and insufficient cleaning of the original gravel packed completions.[3-4] Problems which lead to the impairment of injection wells can be recognized by implementing a properly designed brine injectability monitoring program. At the geopressured sites where carbonate scale inhibitors may be used, a real need exists to monitor brine quality to insure that inhibitor-derived pseudoscales and particulates do not cause injection well impairment.

A field evaluation was conducted at the Pleasant Bayou No. 2 well, located at the DOE-Brazoria geopressured test site south of Houston, Texas (September 22-25, 1980). The objectives of the field work were to establish the nominal injectability of spent geopressured brine as a function of temperature and pressure and estimate the useful life of wells into which spent brine is injected. Injectability data were obtained by means of in-line membrane filtration experiments.

INJECTABILITY TESTING METHODOLOGY

The most reliable method of establishing water quality in conjunction with full-scale injection tests is based on the use of membrane filters (and core samples) as analogs of the injection formation.[5-13] The permeability of a representative membrane filter with the appropriate pore size distribution to injected water is continuously monitored. Observed permeability variations can then be interpreted in terms of the performance characteristics of a typical injection well.[14-16] Given the injection rate, wellbore radius, length of completion interval, brine viscosity, and disposal formation hydraulic parameters, the useful lifetime of the injection well can be estimated.

Membrane filtration data reveal the matrix permeability impairment potential of injected water resulting from scale formation or deposition of suspended solids. Loss of disposal capacity resulting from insufficient disposal formation volume, pre-existing skin change, or other reservoir insufficiencies, however, cannot be directly identified by filtration tests. Similarly, factors which may favorably impact disposal capacity such as the presence of high permeability thief zones or fractures within the disposal interval can not be accounted for by the membrane filtration methodology.

Selection of membrane filters with the appropriate pore size for the work reported here was based on an empirical method described by Champlin et al,[17] which permits calculation of mean formation pore size if formation porosity and permeability are known. We estimated that a disposal formation with properties as shown in Table 1 would have a mean pore diameter of 16-μm. We selected Nuclepore, polycarbonate, 10-μm pore size membrane filters as conservative analogs of shallow, high permeability disposal zones. Nuclepore, polycarbonate membrane filters with 0.4-μm pore size, were also used to obtain baseline suspended solids data and as conservative analogs of deep geopressured disposal zones where formation permeability might be less than 100 md.

TABLE 1

ASSUMED DISPOSAL FORMATION AND INJECTION PARAMETERS:
DOE'S BRAZORIA GEOPRESSURED-GEOTHERMAL TEST SITE

Brine Temperature	130°C
Brine Salinity[1]	13.5 wt % NaCl
Brine Density[2]	1.1 g/cc
Brine Viscosity[3]	0.32 cp
Injection Rate	22,000 BBL/Day
Radius of Injection Tubing[1]	0.0699 m
Length of Injection Interval[1]	53 m
Injection Formation Permeability	1000 md
Injection Formation Porosity	20%
Radius of Effect	182.9 m
Invasion Radius	3.05 m
Filter Cake Density[4]	2.70 g/cc
Exposed Area of Membrane Filters	13.2 cm^2

References:

1. R. Batten, Fenix and Scisson, Personal Communication
2. Ref. 20
3. Ref. 21
4. Density of calcium carbonate (calcite)

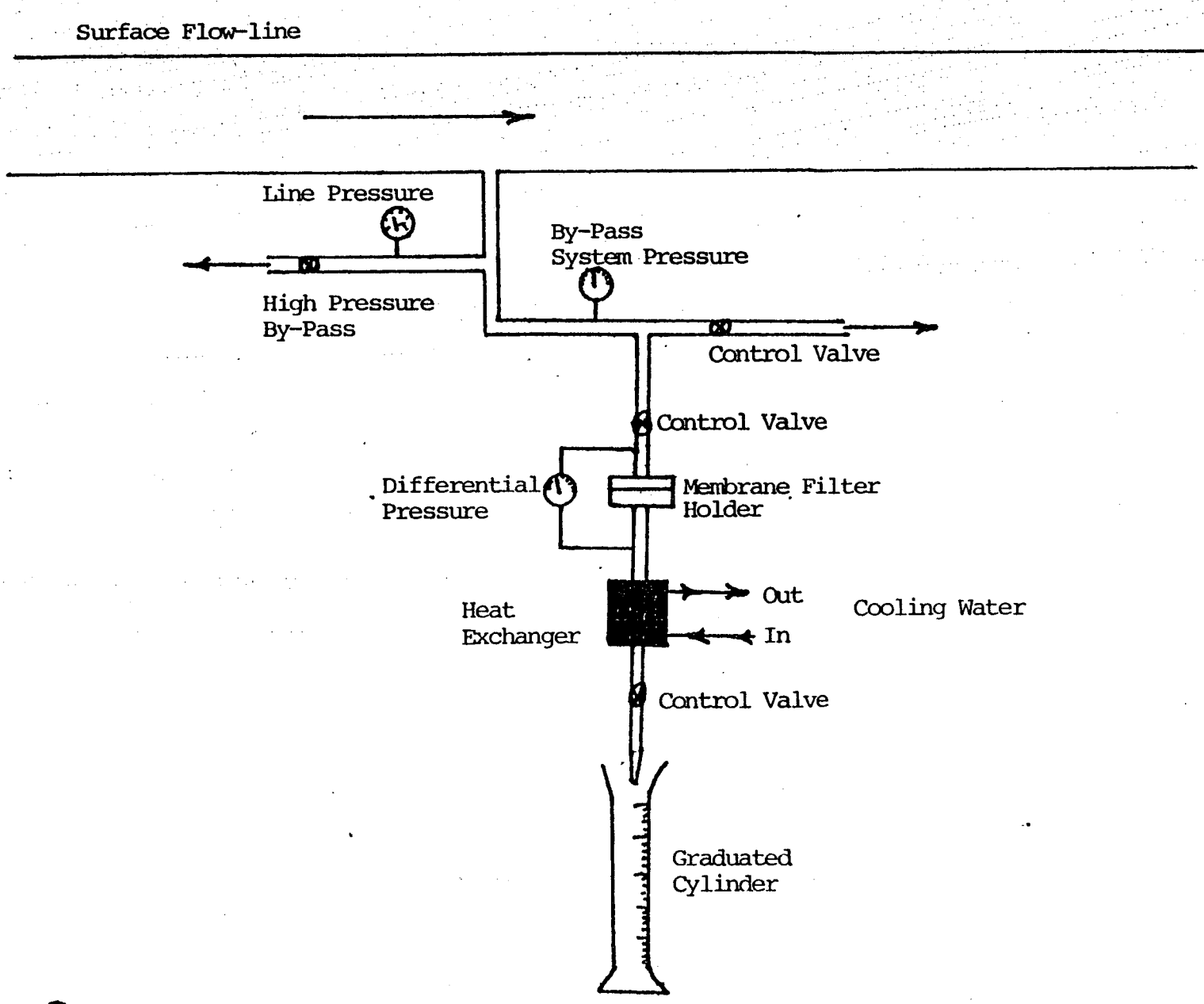
TEST APPARATUS DESIGN

A schematic of the injectability test apparatus is shown in Figure 1. The test frame, based on previously field proven designs,[18-19] was connected, as a bypass system, to the main site flowline via a suitably designed high pressure manifold. Injectability tests were carried out at constant differential pressure across the filtration membrane. Coarse and fine control valves were used to initially set and maintain differential pressure. Cumulative flow and instantaneous flowrate were obtained by direct measurement using 2-litre graduated cylinders. Flashing of the brine following passage through the membrane filter was prevented by use of a water-cooled, Inconel-600 heat exchanger upstream of the final control valve. All system piping was constructed from Inconel-600 high pressure tubing for adequate corrosion control. Valves and fittings were made of 316 stainless steel. The system was designed for in-line testing of geopressured brine at pressures and temperatures to 2000 psi and 150°C, respectively. Inclusion of the by-pass manifold permitted testing geopressured brine at wellhead pressure to 4000 psig. Prior to each run, membrane filters were evacuated by means of an on-board vacuum system to prevent partial blockage of membrane filters by entrained air. The vacuum system was also used to bleed the system of residual brine following each run. A high pressure, cartridge filter assembly was used occasionally to prefilter brine, at high temperature and pressure, prior to its passage through a membrane filter to establish the potential benefits of prefiltering brine before subsurface disposal.

BRINE SAMPLING POINTS

Injectability tests were carried out at wellhead conditions, about 5 feet downstream of the scale inhibitor injection port, immediately upstream of the gas separator and in the injection line about 70 feet downstream of the gas

Figure 1. SIMPLIFIED SCHEMATIC OF THE MEMBRANE FILTRATION INJECTABILITY TEST APPARATUS



separator. The three sampling points are shown on the generalized Brazoria system schematic (Figure 2).

The various brine sources used in the injectability test were designated as follows:

LN- Series: Low pressure injection line (380 psig, 130°C). Sampling port on top of injection line.

MN- Series: Moderate pressure production line immediately upstream of the gas separator (800 psig, 130°C). Sampling port on side of vertical riser.

HN- Series: High pressure wellhead production line immediately upstream of choke and about 5 feet downstream of scale inhibitor injection port (3800 psig, 130°C). Sampling port on bottom of production line.

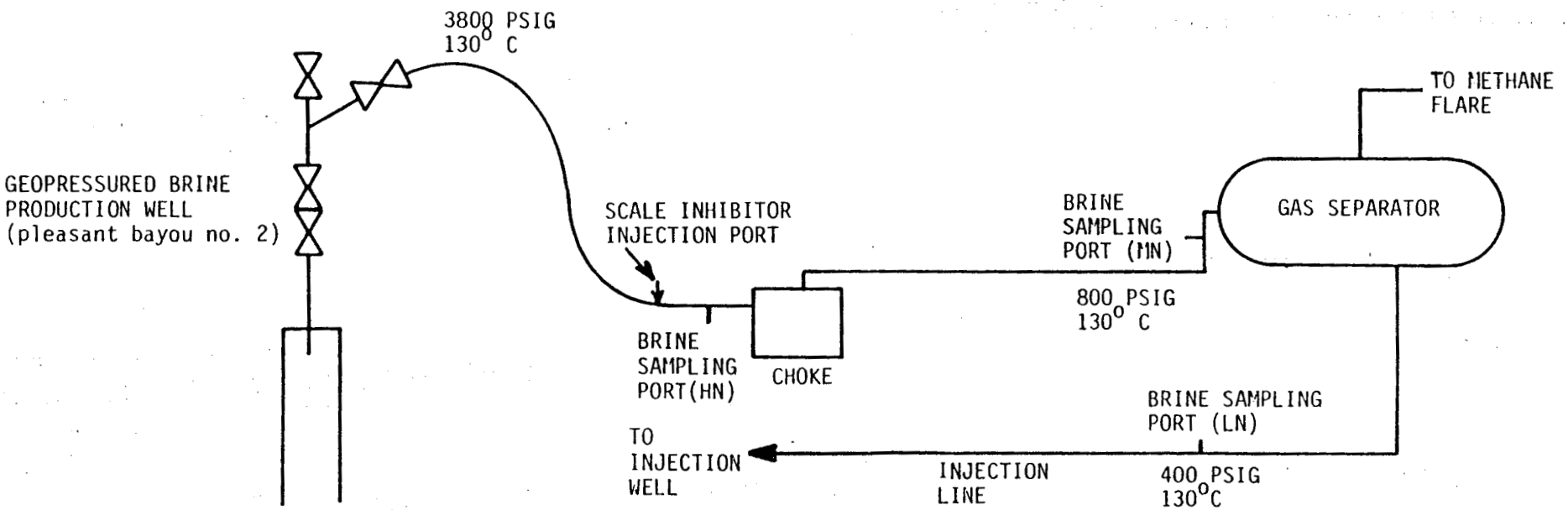
INJECTION WELL HALF-LIFE ESTIMATES

Half-life estimates for the Brazoria test site brine disposal well were calculated after the method of Barkman and Davidson[14] for a constant pressure drop process. The calculated half-life is the time required for the injection rate to decline to one-half of its initial value. Disposal well impairment was calculated for the cases of well bore narrowing and invasion. Well bore narrowing results when a filter cake forms on the sand face and then builds inward eventually partially filling the well bore. The invasion model accounts for penetration of the disposal formation by fine suspended solids which ultimately form an internal filter cake within the disposal formation. For each mechanism, the half-life is given by the product:

$$T_{\frac{1}{2}} = (F)(G) \qquad (1)$$

Relevant formation and injection parameters that form the basis for the halflife estimates are provided in Table 1. The F-factor is a constant given by:

Figure 2. **GENERALIZED SCHEMATIC OF DOE'S BRAZORIA GEOPRESSURED -GEOTHERMAL TEST SYSTEM**



$$F=(1.723\times10^{4})\left(\frac{\pi\cdot r_w^{2}\cdot h\cdot\rho_c}{i_o\cdot w\cdot\rho_w}\right) \quad (2)$$

where: F = time to fill the wellbore with solids at the initial flow rate (years)

r_w = wellbore radius (meters)

h = injection interval (meters)

i_o = initial injection rate (STBD)

w = concentration suspended solids (μg/g)

ρ_c/ρ_w = density ratio, filter cake: brine

Estimates of the permeability of filter cakes were developed from calculation of the water quality ratio given by:

$$\frac{w}{K_c} = (8166.11)\left(\frac{1}{S^2}\right)\left(\frac{2\rho_c A^2\Delta P}{\mu\rho_w}\right) \quad (3)$$

where: w = weight concentration of solids in water (μg/g)

K_c = filter cake permeability (md)

S = slope of cumulative volume vs. square root of time ($ml/\sqrt{min}$)

ρ_c = bulk density of filter cake (gm/cm^3)

ρ_w = density of water (gm/cm^3)

A = exposed area of filter cake (cm^2)

ΔP = total pressure differential across filter (psi)

μ = fluid viscosity (cp)

G-factors for wellbore narrowing and invasion were estimated as follows:

Well bore narrowing: $$G = 1 + \frac{1}{2\ln\theta} - \left(\frac{1}{\alpha} + \frac{1}{2\ln\theta}\right)\theta^{2(\alpha-1)/\alpha} \quad (4)$$

where: $\alpha = 0.5$

$\theta = (r_e/r_w)^{k_c/k_F}$

r_e = radius of effect

r_w = well bore radius

k_c = filter cake permeability

k_F = formation permeability

$$\text{Invasion:} \quad G = \left[\frac{r_a^2 \phi^2}{r_w^2}\right]\left[1 + \frac{\beta}{2\ln\theta} - \left(\frac{1}{\alpha} + \frac{\beta}{2\ln\theta}\right)\theta^{2(\alpha-1)/\alpha\beta}\right] \qquad (5)$$

where: r_a = invasion radius

$\beta = 1-(k_c/k_F)$

ϕ = fractional porosity

TEST RESULTS

Half-life estimates based on Equations (1)-(4) are summarized in Table 2. The slopes used in the water quality calculations were based on least squares regression of the filtration curves. The filtration data and the corresponding filtration curves are provided in Appendix I. Because of the limited field time available for testing, we limited most of the injectability runs to about 15 minutes. In general, this time interval was sufficient to define the linear portion of the filtration curves. A typical filtration curve indicating no invasion (negative intercept) is shown in Figure 3. Only data points indicated by solid circles were used in the regression analysis. In some cases, it was necessary to reject erratic data points (as determined by inspection of the filtration curves), which were generated as a result of severe fluctuations in line pressure and by difficulties associated with maintaining constant differential pressure. The suspended solids data indicated in Table 2 were not corrected for membrane filter elution loss because, in several attempts to measure elution loss, the weight loss membrane filter gained weight due to scale formation. However, this correction is usually very small. The scaling

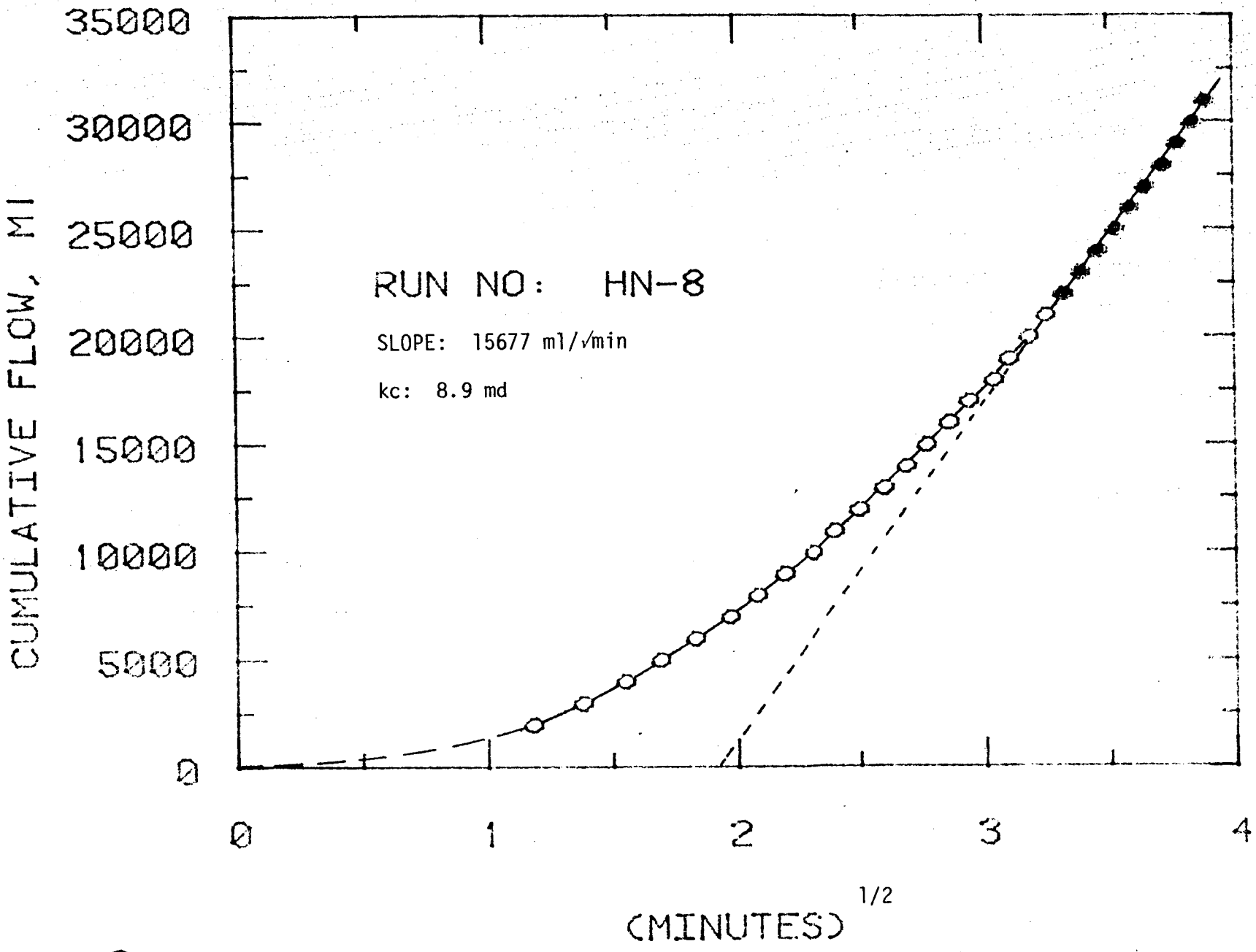
Table 2.

INJECTION WELL HALF-LIFE ESTIMATES FOR THE DOE-BRAZORIA GEOPRESSURED TEST SITE

Run	Date (Sept,1980)	Membrane Filter Pore Size (μm)	1 μm Cuno Cartridge Prefilter	Pressure (PSI)		Membrane Filter ΔP(PSI)	Temperature (°C)		Scale Inhibitor (PPM)	Filtered Volume (ml)	Suspended Solids (mg/l)
				Source	Memb. Filter		Source	Filter			
LN-1	22	0.4	No	360	360	50	130	90	50	2,598	10.0
LN-3	22	10.0	No	350	350	50	130	90	50	2,920	6.0
LN-5	22	0.4	No	360	360	50	130	107	50	1,920	6.8
LN-7	22	10.0	No	360	360	50	130	122	50	2,300	8.7
LN-11	23	10.0	Yes	380	380	0.03	130	126	50	39,490	0.05
LN-13	23	0.4	No	370	370	50	130	119	50	1,620	14.8
LN-14	23	10.0	No	400	400	50	130	115	50	1,610	9.9
LN-15	24	10.0	No	400	400	50	130	115	50	1,960	8.0
LN-16	25	10.0	No	400	400	0.03	130	130	0	28,310	0.021
MN-1	23	0.4	No	800	800	50	130	112	50	2,530	13.5
MN-2	23	10.0	No	800	800	50	130	120	50	3,340	11.8
MN-3	23	10.0	Yes	760	760	0.03	130	129	50	36,000	0.031
HN-1	24	0.4	No	3800	400	50	130	120	50	2,630	1.4
HN-2	24	10.0	No	3800	400	5	130	128	50	19,300	0.067
HN-3	24	0.4	No	3800	1000	70	130	119	50	4,320	0.69
HN-4	24	10.0	No	3800	1000	0.1	130	130	50	13,540	0.27
HN-5	25	0.4	No	3800	1800	50	130	120	15	4,620	1.3
HN-6	25	10.0	No	3800	1800	1	130	120	15	5,360	1.3
HN-7	25	10.0	No	3800	1500	20	130	125	50	10,110	0.41
HN-9	25	10.0	No	3800	1000	1	130	127	50	5,850	0.48
HN-8	25	10.0	No	3800	1000	0.03	130	129	0	31,000	0.026

Filtration Curve		Water Quality	kc	F-Factor	$G_{\frac{1}{2}}$-Factor	Halflife	$G_{\frac{1}{2}}$-Factor	Halflife	Run
Intercept (ml)	Slope (ml/min)	(PPM/md)	(md)	(22,000 B/D)	(No Invasion)	(YRS)	(Invasion)	(YRS)	
- 1.4	624.2	2801.2	0.0032	0.17			0.0061	0.0011	LN-1
+ 510.5	640.2	2662.9	0.0021	0.29			0.0038	0.0011	LN-3
- 91.1	482.9	4680.3	0.0013	0.25	3.0×10^{-5}	1×10^{-5}			LN-5
+ 365.3	534.9	3814.5	0.0021	0.20			0.0038	0.0008	LN-7
-28627.2	13579.4	0.0036	12.8	34.4	0.27	9.3	20.8	717.3	LN-11
- 587.2	546.1	3659.7	0.0037	0.12	0.0001	1×10^{-5}			LN-13
- 3.9	383.2	7432.5	0.0012	0.17	3.0×10^{-5}	5×10^{-6}			LN-14
+ 71.8	462.1	5111.1	0.0014	0.22			0.0031	0.0007	LN-15
-23497.7	14853.9	0.0030	6.4	81.9	0.14	11.8	11.0	902	LN-16
- 770.9	708.7	2173.0	0.0057	0.13	0.0001	1.7×10^{-5}			MN-1
- 157.1	740.5	1990.9	0.0054	0.15	0.0001	1.9×10^{-5}			MN-2
-29990.0	17009.7	0.0023	12.5	55.5	0.26	14.7	20.3	1129	MN-3
- 325.4	737.7	2005.5	0.00064	1.23	$<1\times10^{-6}$	$<1\times10^{-6}$			HN-1
-17272.7	9090.9	1.32	0.046	25.7	0.0011	0.028			HN-2
- 1400.8	1447.2	729.6	0.00086	2.5	2×10^{-5}	5×10^{-5}			HN-3
+15300.0	833.3	3.14	0.078	6.4			0.14	0.89	HN-4
- 1582.0	1527.7	467.6	0.0025	1.3	0.0001	0.0001			HN-5
- 2474.0	740.4	39.8	0.030	1.3	0.0007	0.0009			HN-6
+ 5258.6	944.0	489.9	0.0008	4.2			0.0015	0.0063	HN-7
+ 4467.5	292.0	256.0	0.0017	3.6			0.0030	0.011	HN-9
-30202.8	15676.7	0.0027	8.9	66.2	0.20	12.8	14.9	985	HN-8

Figure 3. FILTRATION CURVE WITHOUT INVASION



was ultimately attributed to deposition of the scale inhibitor compound (15-50 ppm of a phosphonate-polyacrylate threshold-type carbonate inhibitor).

A summary of average suspended solids data for the Brazoria system is provided in Table 3. If we assume an average suspended solids concentration of 11.8 mg/l is supplied to the injection well at a brine flow rate of 22,000 BBL/day, then approximately 91 pounds of solids would be deposited in the injection well on a daily basis (16.5 tons per year). The suspended solids data suggest that about 24% of the suspended solids in the injection line are less than 10-μm in diameter.

The test results indicated, as shown in Figures 4 and 5, that brine treated with scale inhibitor had extremely low quality even after passage through the gas separator. Brine which was prefiltered with a 1-μm pore size Cuno cartridge filter had high quality. Ultimately it was demonstrated, by temporarily interrupting the injection of scale inhibitor, that the scale inhibitor itself was the cause of the poor injectability characteristics of the brine. Untreated brine had higher quality than prefiltered scale-inhibited brine!

Because the gauge we used was designed to measure pressures >5 psi, the indicated differential pressure across 10-μm pore size membrane filters was zero when prefiltered scale-inhibited brine and untreated brine were evaluated. In these cases, it was therefore not possible to directly estimate injection well half-lives. The half-lives indicated in Table 2 were generated after estimates of differential pressure were developed as follows:

The permeability of a 10-μm pore size membrane filter can be calculated from:

$$k = \frac{\mu Q L}{A \Delta P} \qquad (6)$$

TABLE 3

SUMMARY OF SUSPENDED SOLIDS DATA FOR THE
DOE-BRAZORIA GEOPRESSURED TEST SITE

Brine Source	Membrane Filter Pore Size (μm)	1-mm Prefilter	Carbonate Scale Inhibitor (PPM)	Suspended Solids (mg/l)
Low Pressure Injection Line (400 PSIG; 130°C)	0.4	No	50	10.8
	10.0	No	50	8.2
	10.0	No	0	0.02
Moderate Pressure Production (800 PSIG; 130°C)	0.4	No	50	13.5
	0.4	Yes	50	0.07
	10.0	No	50	11.8
	10.0	Yes	50	0.03
High Pressure Wellhead (3800 PSIG; 130°C)	0.4	No	50	1.1
	10.0	No	50	0.5
	10.0	No	0	0.03

Figure 4. HIGH PRESSURE WELLHEAD PRODUCTION LINE
(3800 psi; 130°C)

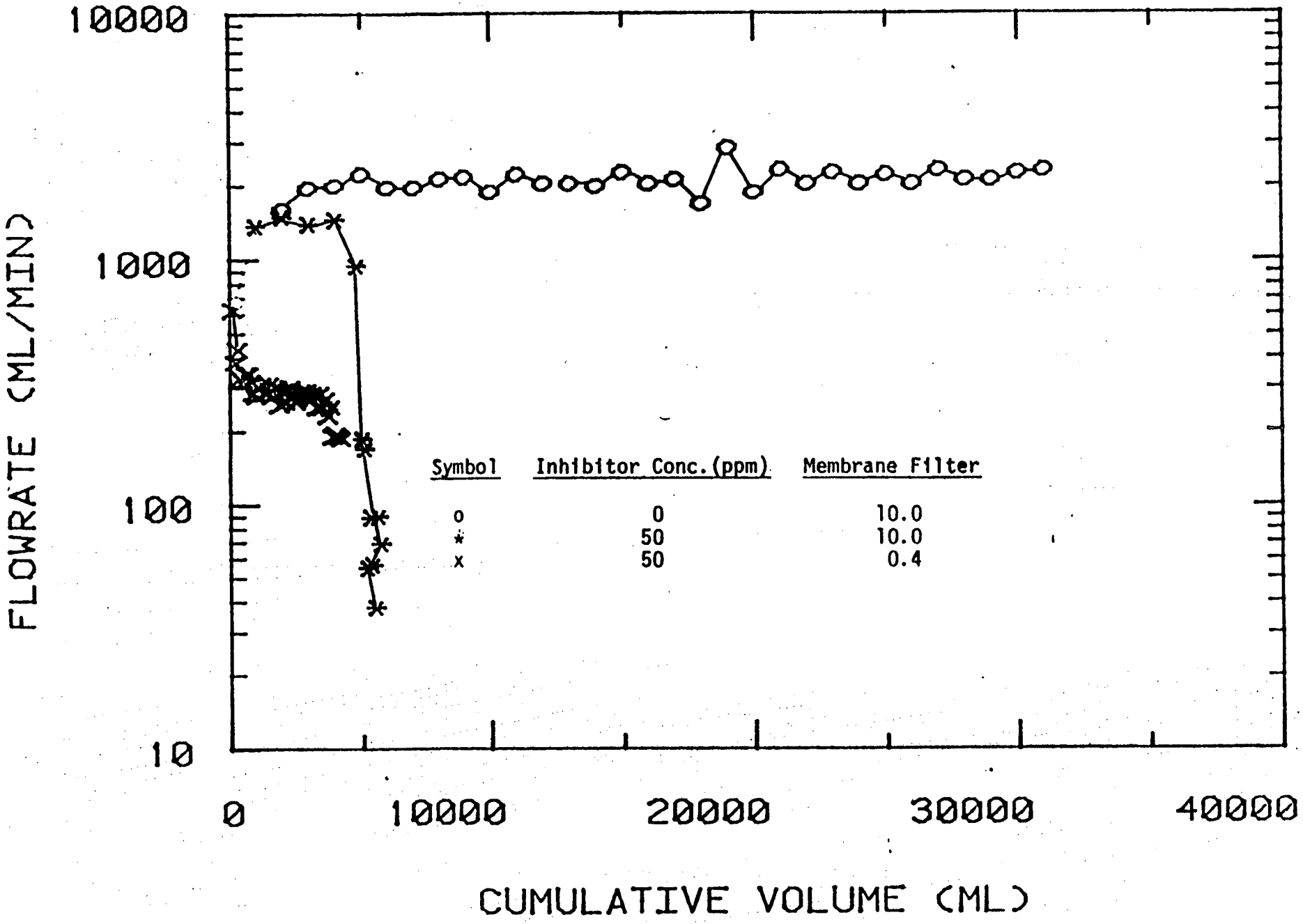
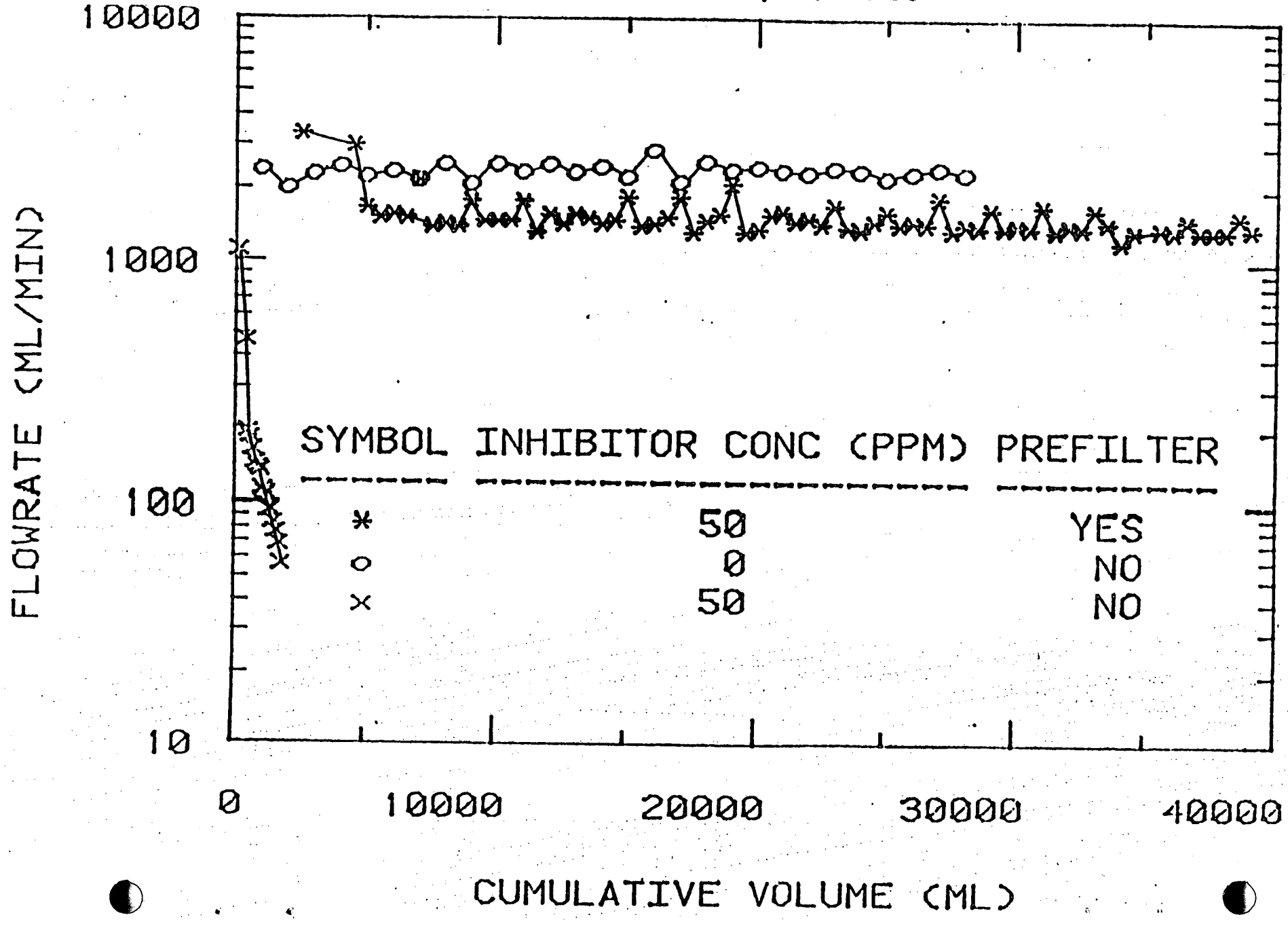


Figure 5. 10.0 MICRON MEMBRANE FILTRATION DATA
LOW PRESSURE INJECTION LINE
(380 PSI; 130C)



where: k = permeability (darcy)

μ = viscosity (cp)

Q = flowrate (cm^3/sec)

L = thickness (cm)

A = cross-sectional area (cm^2)

ΔP = differential pressure (atm)

Permeability data obtained from the manufacturer for Nuclepore membrane filters for clean water at ambient temperature are shown in Figure 6. Unfortunately, flow data for 10-μm pore size polycarbonate membrane filters are not provided. However, if we assume a flowrate of at least 2000 $ml/cm^2 \cdot min$ at a differential pressure of 1 psi, we can calculate a permeability of about 400 md for the filter. If we next assume that the permeability of the membrane filter is independent of temperature, Eq. 7 can be used to solve for differential pressure:

$$\Delta P = \frac{(0.32\ cp)(42\ ml/sec)(8x10^{-4}cm)}{(0.4d)(13.2cm^2)} \qquad (7)$$

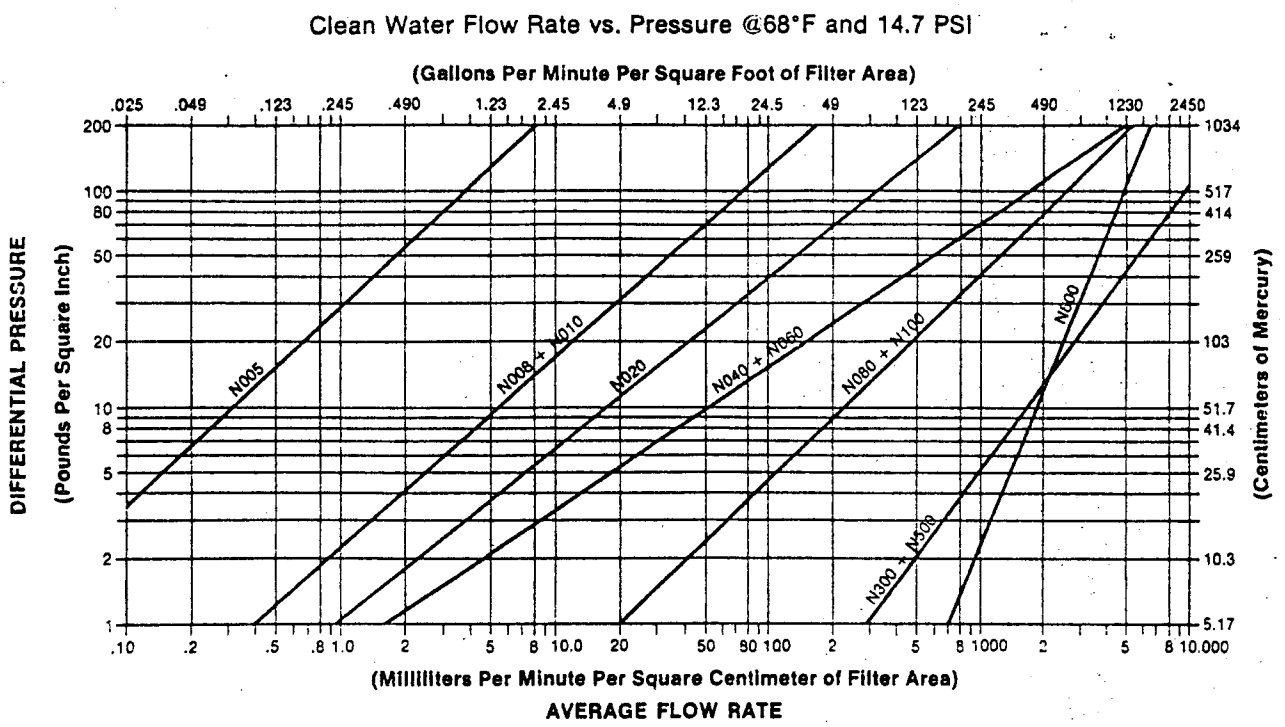
$$\Delta P = 0.03\ psi$$

Where 0.32 cp is the viscosity of brine (13.5 weight percent NaCl) at 130°C (from Ref. 21) and 42 ml/sec is the highest flowrate observed when prefiltered, scale-inhibited brine or untreated brine were evaluated with a 10-μm pore size membrane filter.

COMPOSITION OF SUSPENDED SOLIDS

The solids collected on several of the filters were analyzed by x-ray diffraction and by energy dispersive x-ray fluorescence (EDAX) in conjunction with scanning electron microscopy. The results are summarized in Table 4. In the case of the experiments conducted when no inhibitor was being injected,

Figure 6



NUCLEPORE MEMBRANE SPECIFICATIONS

Pore Size (μm)[1]	Code Number	Nominal Pore Density (pores/cm^2)	Nominal Thickness (μm)	Flow Rates[2] Water ml/min/cm^2	Flow Rates[2] Air l/min/cm^2	Bubble Point[3] (psi)
12.0	N1200	1×10^5	6	>2000	65	<1
10.0	N1000	1×10^5	8	>2000	50	<1
8.0	N800	1×10^5	10	2000	45	2
5.0	N500	4×10^5	10	2000	42	4
3.0	N300	2×10^6	10	2000	42	6
2.0	N200	2×10^6	10	2000	36	10
1.0	N100	2×10^7	10	300	36	15
0.8	N080	3×10^7	10	300	36	18
0.6	N060	3×10^7	10	80	16	25
0.4	N040	1×10^8	10	80	16	33
0.2	N020	3×10^8	10	26	6	60
0.1	N010	3×10^8	5	8	2.2	>100
0.08	N008	6×10^8	5	8	2.2	>100
0.05	N005	6×10^8	5	0.45	0.25	>100
0.03	N003	6×10^8	5	0.03	0.03	>100
0.015	N001	Experimental Material — Firm specifications not yet established.				

[1] Maximum pore diameter
[2] 25°C, 70 cm Hg (13.5 psi)
[3] Bubble point value is the pressure required to force air through the pores of a water-wet filter.

(From Nuclepore Filtration Products for the Laboratory: Catalog LAB 30)

TABLE 4

SUMMARY OF RESULTS OF CHEMICAL ANALYSIS
OF SUSPENDED SOLIDS

Filter Number	Brine Conditions	Compound Analysis by X-Ray Diffraction	Elemental and Compound Analysis by EDAX-SEM
HN-1	High Pressure, Inhibitor	Large amorphous component. Some calcite	
HN-8	High Pressure, No inhibitor	not analyzed	Small amount of silica
MN-1	Med. Pressure, Inhibitor	Large amorphous component. Some quartz	
LN-13, 15	Low Pressure, Inhibitor	Large amorphous component. Some halite	
LN-15	Low Pressure, Inhibitor	not analyzed	High Cl; Med. P, Ca, Na; Low Ba, Fe. No silica seen.
LN-16	Low Pressure, No inhibitor	not analyzed	Main component is silica. Low Na, Cl, Fe, S, Al, Ba (prob. $BaSO_4$). No P seen.

not enough material was collected to do a definitive x-ray diffraction analysis; however, a good indication of the composition of these solids was obtained by EDAX-SEM.

When no inhibitor was being injected (HN-8 wellhead sample and LN-16 injection line sample), the small quantity of solids were mostly silica, perhaps sand from the formation, and some particles of $BaSO_4$. When the inhibitor was being injected, a large amorphous component was present in the solids, which was rich in phosphorous, calcium, sodium, and chlorine. This is a strong indication that the phosphonate inhibitor either precipitated directly or reacted with the brine calcium to form a precipitate, and in the process occluded some of the brine NaCl. Note that no calcite could be identified in the solids from the brine being injected. None of the techniques used would have detected the acrylate component of the inhibitor formulation, but it too is known to precipitate calcium in overfeed conditions.

SIMPLIFIED HALF-LIFE ESTIMATES

In order to utilize the Barkman and Davidson method for estimating injection well half-life, it is first necessary to measure a suspended solids concentration for the water being evaluated. Field measurement of suspended solids concentration, while not difficult, is laborious. A method suggested by Huggins[22] can be used to eliminate the necessity of measuring suspended solids concentrations. This method also eliminates the necessity of estimating the filter cake to brine density ratio.

The basis for simplified well bore narrowing half-life estimates (for the case of no invasion) can be developed as follows:

$$T_{\frac{1}{2}} = (F)(G)$$

For $\frac{k_c}{k_f} < 0.05$

$$G \cong 3\left(\frac{k_c}{k_f}\right) \ln \frac{r_e}{r_w}$$

Since $$F = \left(\frac{\pi r_w^2 h}{i_o}\right)\left(\frac{\rho_c}{\rho_w}\right)$$

$$T_{1/2} = \left(\frac{k_c}{w}\right)\left(\frac{\rho_c}{\rho_w}\right)\left(\frac{\pi r_w^2 h}{i_o}\right)\left(\frac{3}{k_F}\right)\left(\ln \frac{r_e}{r_w}\right)$$

But $$\frac{k_c}{w} = \left(\frac{S^2 \mu}{2A^2 \Delta p}\right)\left(\frac{\rho_w}{\rho_c}\right)$$

where S is the slope of the cumulative volume vs. the square root of of time curve

Substituting:

$$T_{1/2} = \left(\frac{S^2 \mu}{2A^2 \Delta p}\right)\left(\frac{\pi r_w^2 h}{i_o}\right)\left(\frac{3}{K_F}\right)\left(\ln \frac{r_e}{r_w}\right) \qquad (8)$$

and

$$T_{1/2} \propto \frac{S^2}{i_o}$$

To evaluate the applicability of Eq. 8, we performed a linear regression analysis of measured filtration curve slopes (using 5 points) and associated half-lives (from Table 2) for all non-invading runs which yielded a filter cake permeability (k_c) of 0.05 md or greater. The analysis yielded a coefficient of correlation (r^2) of 0.992. The following equation was derived for estimating a half-life, given the slope (ml/$\sqrt{\text{min}}$) of a filtration curve and assuming an injection rate of 22,000 BBL/day:

$$T_{1/2(\text{yrs})} = [(\text{Slope} - 8936.0)/525.0] \qquad (9)$$

Use of Eqs. 8 and 9 implies that measured filtration curve slopes of 8937.5 ml/$\sqrt{\text{min}}$ and 9465 ml/$\sqrt{\text{min}}$ would correspond to half-lives of about 1 day and 1 year, respectively.

SUMMARY AND CONCLUSIONS

An apparatus was designed, fabricated, and successfully utilized to evaluate the injectability characteristics of geopressured brine at temperatures and pressures of ≦150°C and ≦2000 psig, respectively. The apparatus permits measurement of suspended solids concentration and scaling potential by exposing membrane filters at in-situ, high pressure/high temperature line conditions.

Injectability tests were run at injection line conditions (130°C; 380 psig), immediately upstream of the gas separator (130°C; 800 psig) and at wellhead conditions just upstream of the choke (about 5 feet downstream of the scale inhibitor injection port) where line pressure was 3800 psig. Nuclepore, polycarbonate membrane filters with 0.4-μm and 10.0-μm pore size distributions were used to establish nominal suspended solids concentrations and to simulate injection into a high permeability Gulf Coast aquifer. The 10-μm pore size membrane filter is a reasonable analog of a high permeability, high porosity formation (1 darcy; 20% porosity).

Test results demonstrated conclusively that the threshold carbonate scale inhibitor, which was injected into the top of a two-phase (noncondensable gases-brine) mixture, upstream of the wellhead choke, caused precipitation of up to 15 ppm of suspended solids. The suspended solids carried through the gas separator and ultimately were deposited within the injection well and/or the injection formation. In the absence of scale inhibitor, the raw geopressured brine had extremely high quality. In fact, the raw brine without scale inhibitor had equivalent or better quality than scale-inhibited brine after filtration with a 1-μm pore size Cuno cartridge filter!

Based on these results, it can be concluded that Brazoria brine has high injectability at pressures varying from 380 to 3800 psi, even after gas

separation, provided scale control additives, if required, are used in a way that does not degrade brine quality.

It is of interest to speculate about the fact that the injection well at the Brazoria site (Pleasant Bayou No. 1) continued to accept low quality brine with a moderate rate of back pressure buildup while half-life estimates predicted an extremely short operating life for the well. A plausible explanation for this apparent anomalous behavior is related to the rather unique completion of the injection well.

The injection well was originally designed as a production well. However, problems encountered during drilling necessitated plugging of the borehole back from 15,675 feet to about 8,500 feet. The hole was then recompleted for use as a disposal well.

Our half-life estimates were based on an injection interval of about 150 feet. However, if brine was able to flow past the cement retainer, at the bottom of the completion interval, via an annulus behind the casing, then the actual injection interval would have been literally thousands of feet in length. Altering the injection interval length by a factor of 20 to 30 would be sufficient to yield much longer half-life estimates.

In the future, injection of scale inhibitor, when required, should be restricted to injection ports located on the bottom of flow lines to avoid partial evaporation and precipitation of limited solubility inhibitors. In addition, solubility (or reactivity) determinations for scale inhibitors should be made in simulated brine, at the maximum anticipated temperature of use, prior to their use in the field. Finally, such inhibitors should be injected using non-pulsating pumps so that solubility limits cannot ever be exceeded.

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APPENDIX I

DOE-Brazoria Geopressured-Geothermal Test Site Injectability Data and Filtration Curves.

	Pages
LN Series	28-54
MN Series	55-63
HN Series	64-90

INJECTABILITY TEST DATA

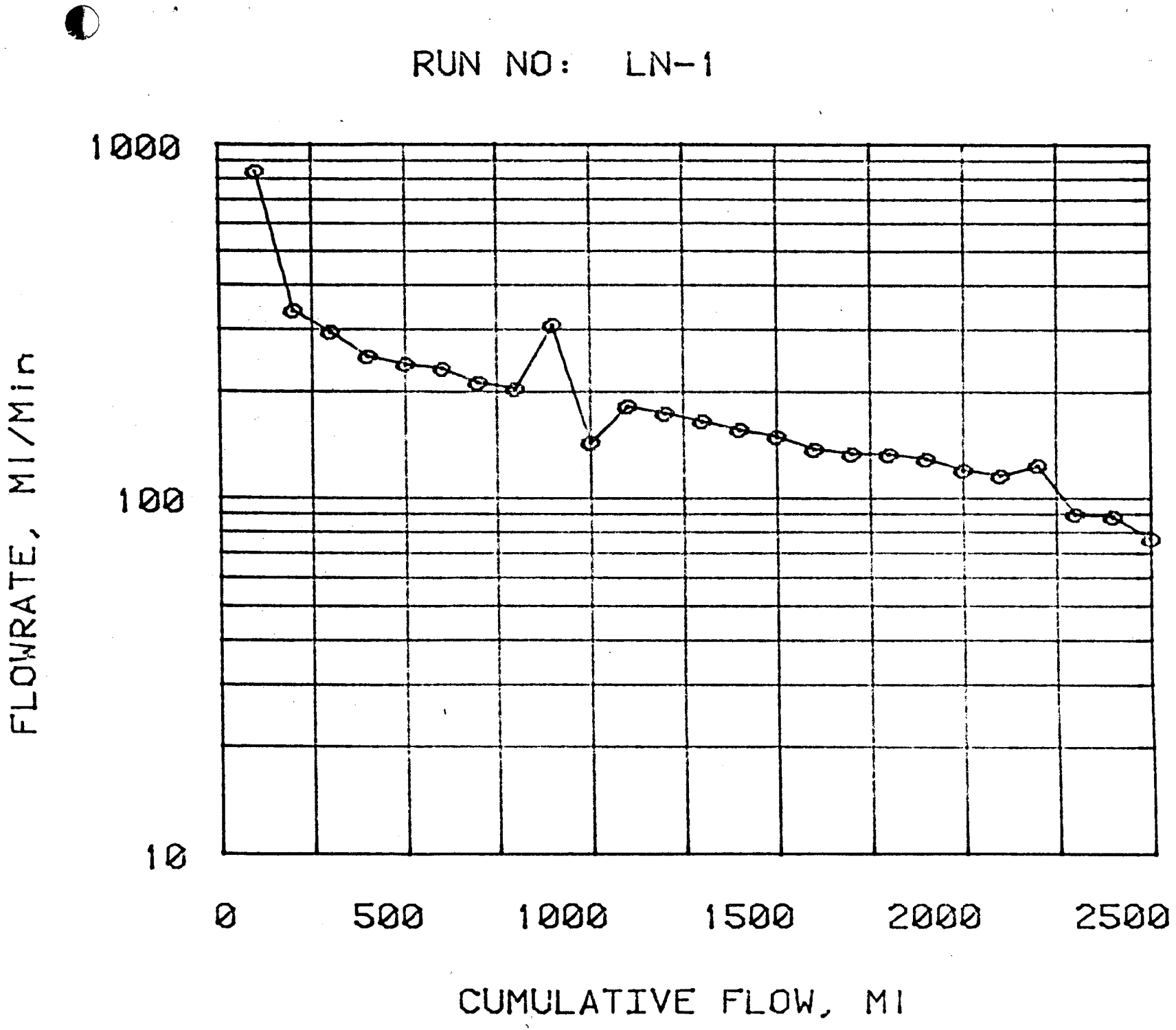
Run: LN 1 Membrane Filter: 0.4-μm 1-μm Cuno Prefilter: No

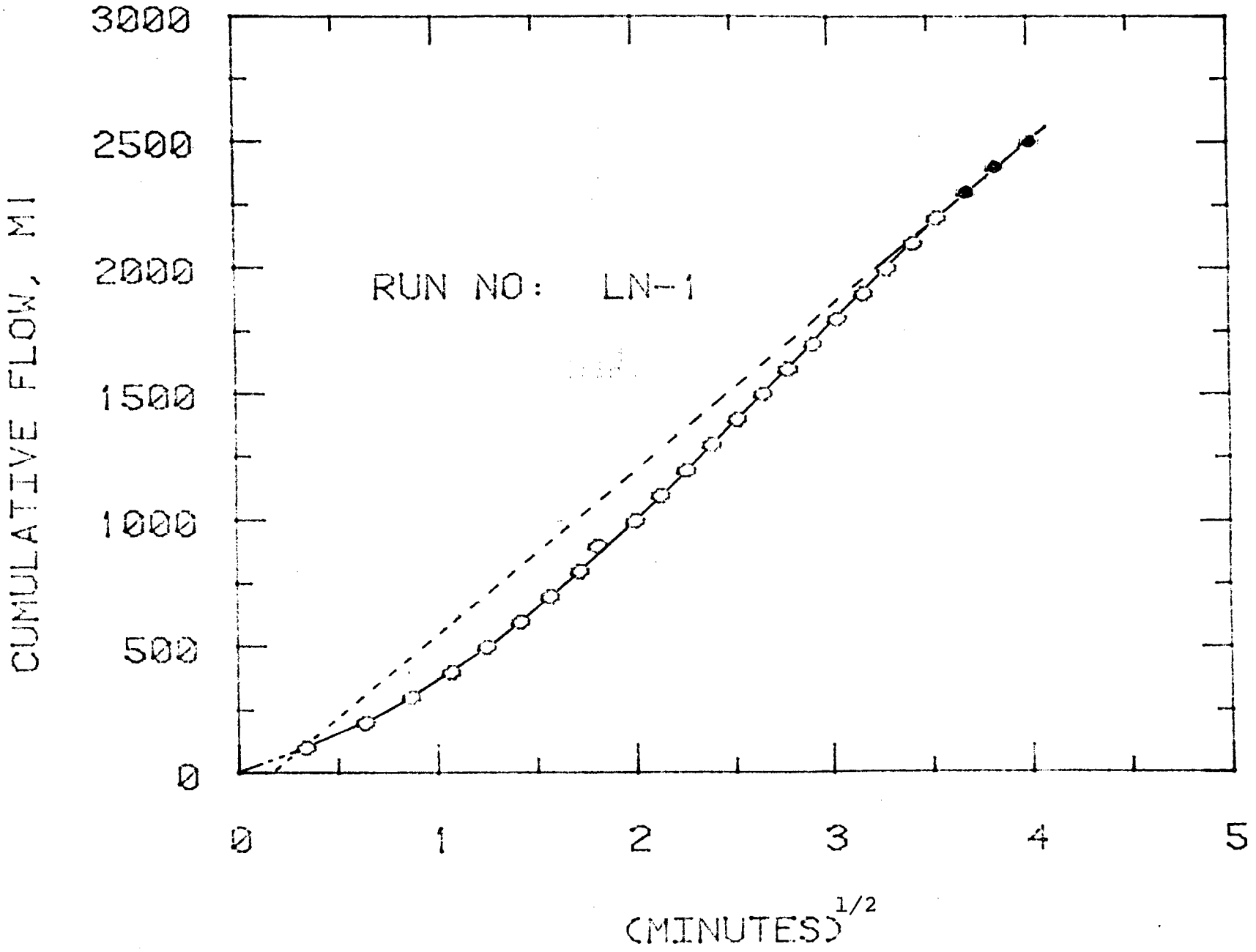
Source Press:360 psig Run Press:360 psig Differential Press:50 psig

Source Temp:130°C Run Temp:90°C

Total Filtered Volume:2598 ml Suspended Solids: 10.0 mg/l (9.09 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	.119	0.34	100	840.3
2	.415	0.64	200	337.8
3	.755	0.87	300	294.1
4	1.153	1.07	400	251.3
5	1.572	1.25	500	238.7
6	2.003	1.42	600	232.0
7	2.475	1.57	700	211.9
8	2.966	1.72	800	203.7
9	3.290	1.81	900	308.6
10	3.985	2.00	1000	143.9
11	4.533	2.13	1100	182.5
12	5.107	2.26	1200	174.2
13	5.710	2.39	1300	165.8
14	6.348	2.52	1400	156.7
15	7.016	2.65	1500	149.7
16	7.742	2.78	1600	137.7
17	8.491	2.91	1700	133.5
18	9.243	3.04	1800	133.0
19	10.018	3.17	1900	129.0
20	10.852	3.29	2000	119.9
21	11.716	3.42	2100	115.7
22	12.524	3.54	2200	123.8
23	13.639	3.69	2300	89.7
24	14.771	3.84	2400	88.3
25	16.078	4.01	2500	76.5


RUN NO: LN-1
1000
100
10
FLOWRATE, MI/Min
0
500
1000
1500
2000
2500
CUMULATIVE FLOW, MI


3000
2500
2000
1500
1000
500
0
CUMULATIVE FLOW, MI
RUN NO: LN-1
0
1
2
3
4
5
(MINUTES)^1/2

INJECTABILITY TEST DATA

Run: LN-3 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: No

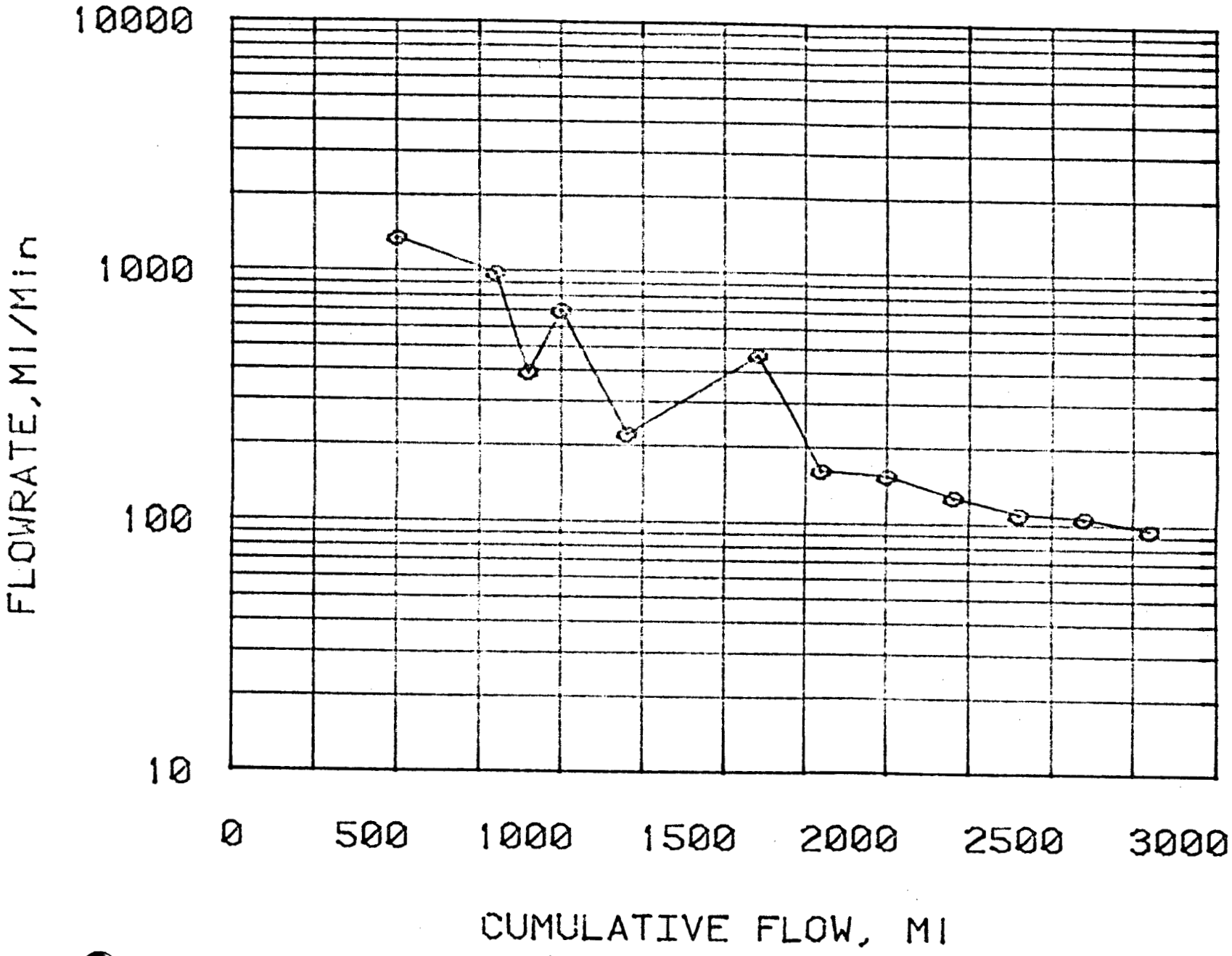
Source Press: 350 psig Run Press: 350 psig Differential Press: 50 psig

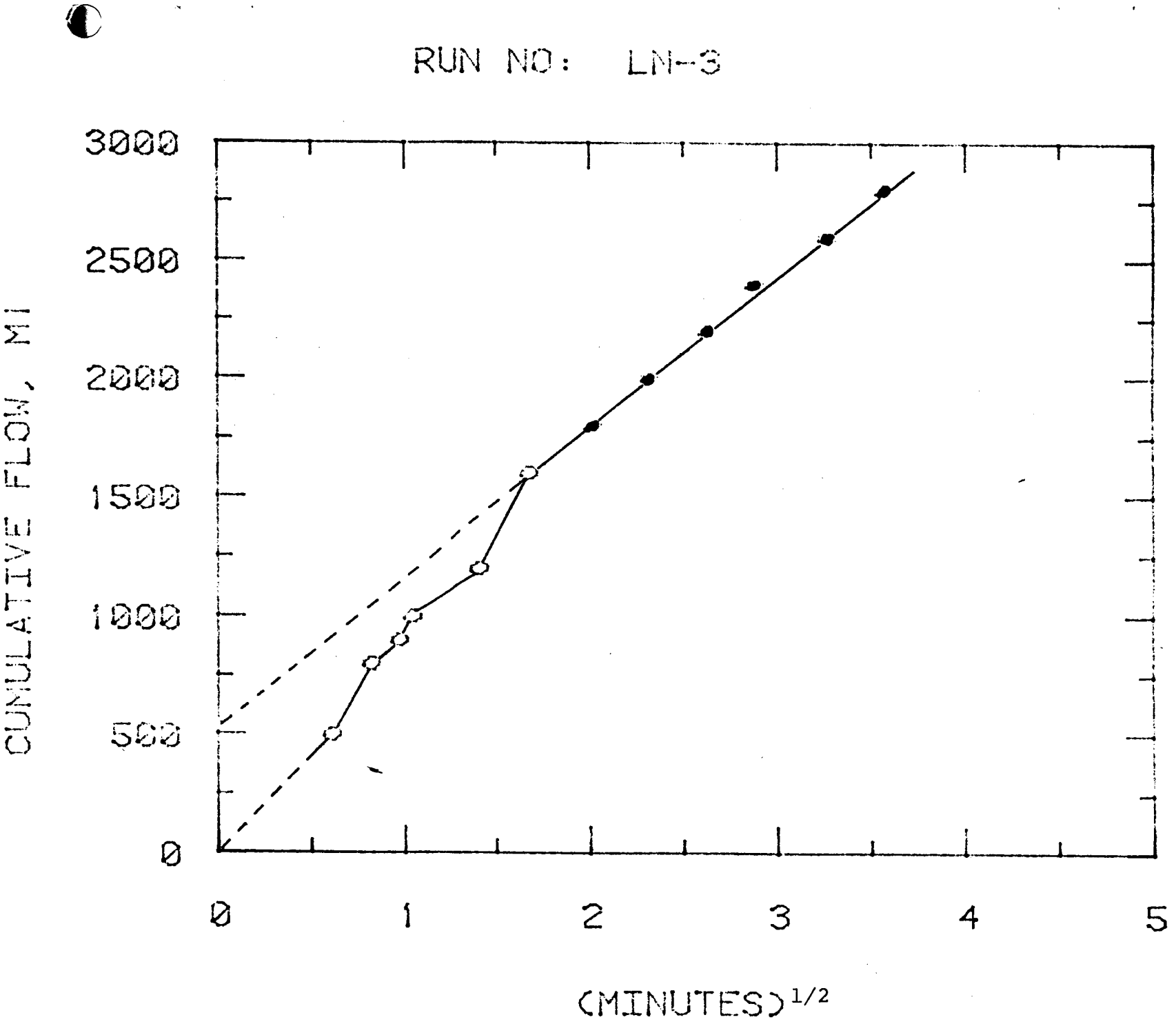
Source Temp: 130°C Run Temp: 95°C

Total Filtered Volume: 2920 ml Suspended Solids: 6 mg/l (5.5 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	.372	0.61	500	1344.1
2	.679	0.82	800	977.2
3	.935	0.97	900	390.6
4	1.079	1.04	1000	694.4
5	1.979	1.41	1200	222.2
6	2.835	1.68	1600	467.3
7	4.072	2.02	1800	161.7
8	5.367	2.32	2000	154.4
9	6.941	2.63	2200	127.1
10	8.776	2.96	2400	109.0
11	10.664	3.27	2600	105.93
12	12.763	3.57	2800	95.3

RUN NO: LN-3


10000
1000
100
10
FLOWRATE, MI/Min
0
500
1000
1500
2000
2500
3000
CUMULATIVE FLOW, MI


RUN NO: LN-3
CUMULATIVE FLOW, MI
3000
2500
2000
1500
1000
500
0
0
1
2
3
4
5
(MINUTES)1/2

INJECTABILITY TEST DATA

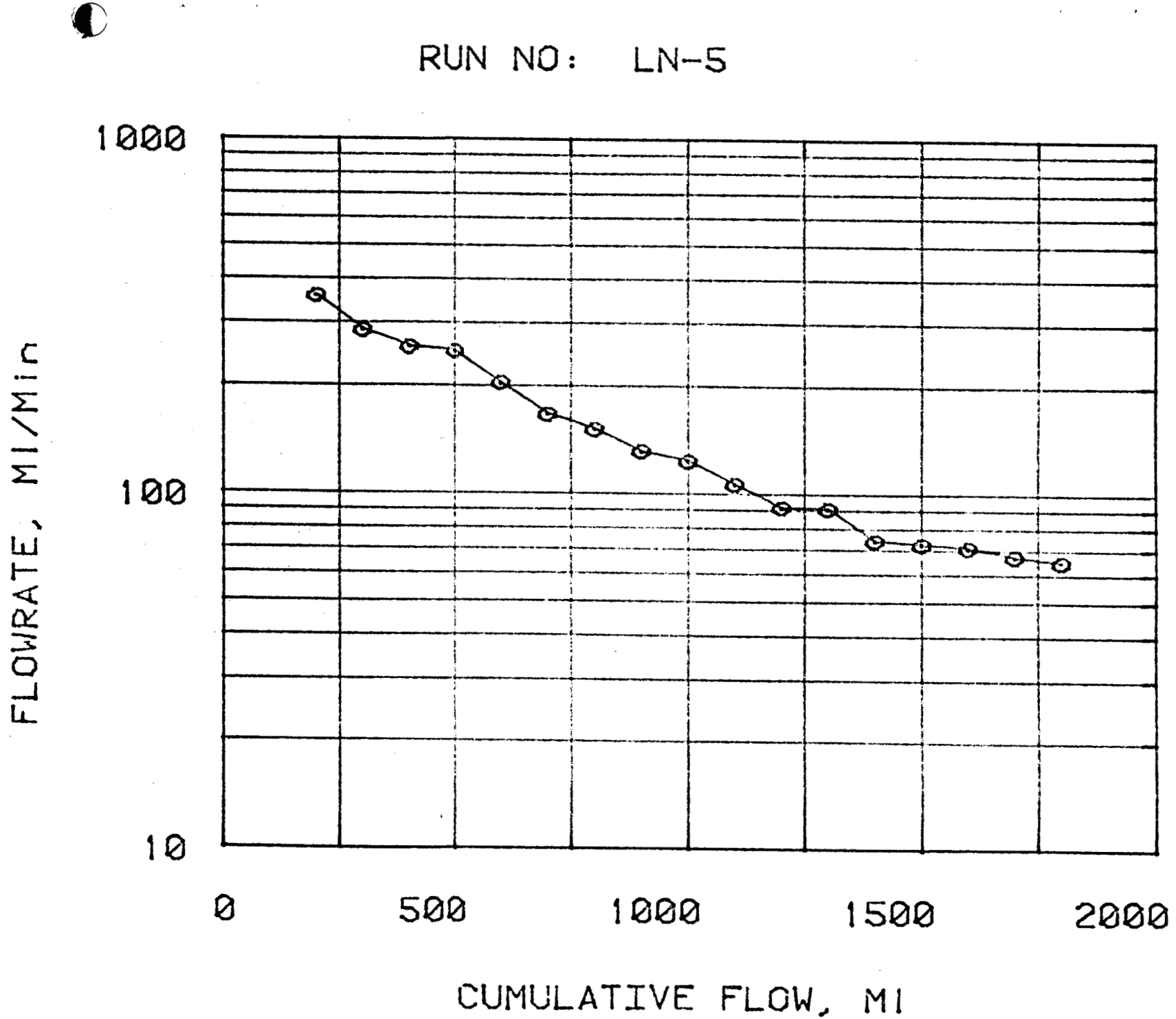
Run: LN-5 Membrane Filter: 0.4-μm 1-μm Cuno Prefilter: No

Source Press: 360 psig Run Press: 360 psig Differential Press: 50 psig

Source Temp: 130°C Run Temp: 107°C

Total Filtered Volume: 1920 ml Suspended Solids: 6.8 mg/l (6.2 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.56	0.75	200	357.1
2	0.91	0.95	300	285.7
3	1.30	1.14	400	256.4
4	1.70	1.30	500	250.0
5	2.19	1.48	600	204.1
6	2.79	1.67	700	166.7
7	3.45	1.86	800	151.5
8	4.21	2.05	900	131.6
9	5.02	2.24	1000	123.5
10	5.96	2.44	1100	106.4
11	7.05	2.66	1200	91.7
12	8.15	2.85	1300	90.9
13	9.50	3.08	1400	74.1
14	10.88	3.30	1500	72.5
15	12.29	3.51	1600	70.9
16	13.78	3.71	1700	67.1
17	15.32	3.91	1800	64.9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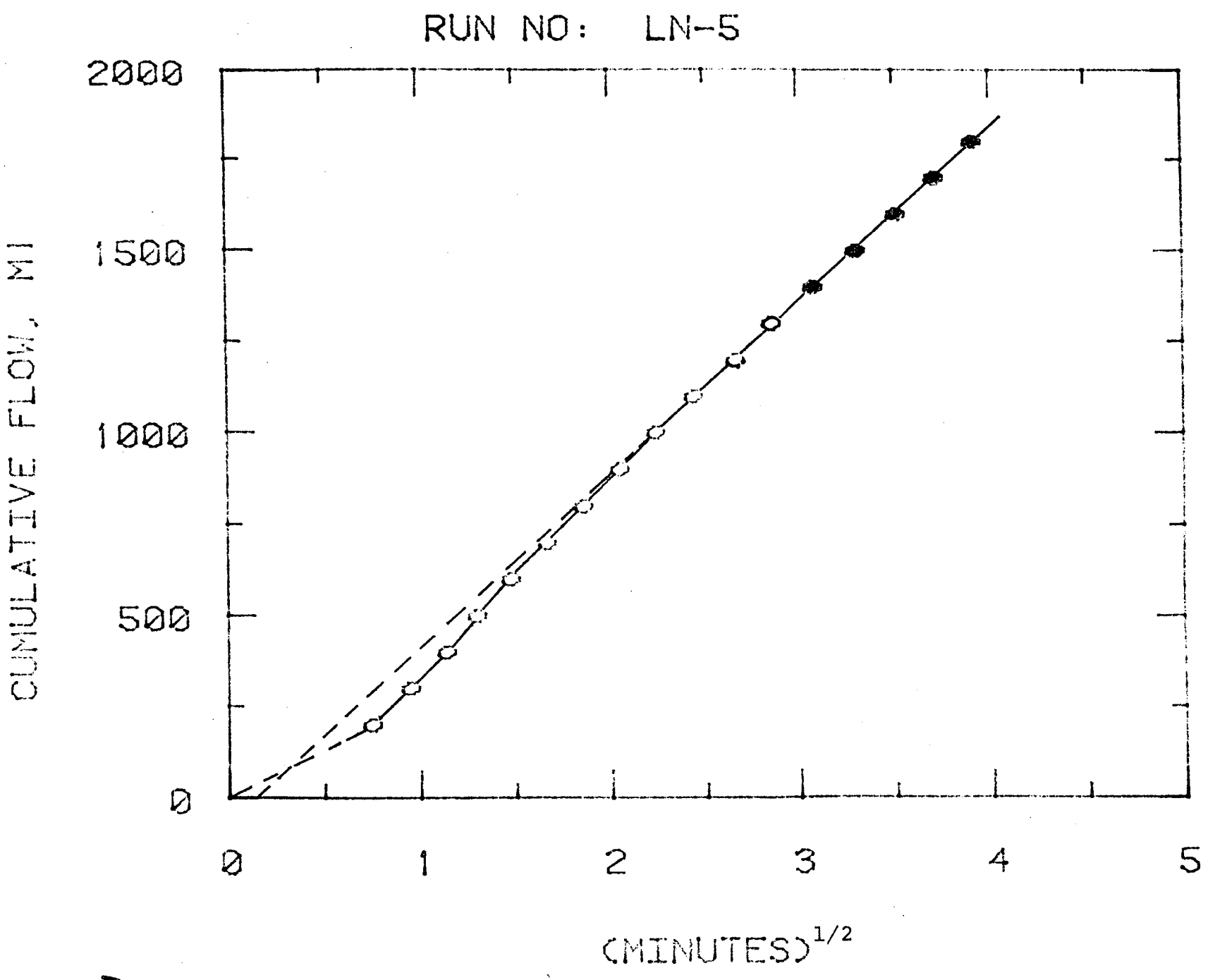
1000
100
10
FLOWRATE, MI/Min
0
500
1000
1500
2000
CUMULATIVE FLOW, MI


RUN NO: LN-5
2000
1500
1000
500
0
CUMULATIVE FLOW, MI
0
1
2
3
4
5
(MINUTES)1/2

INJECTABILITY TEST DATA

Run: LN-7 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: No

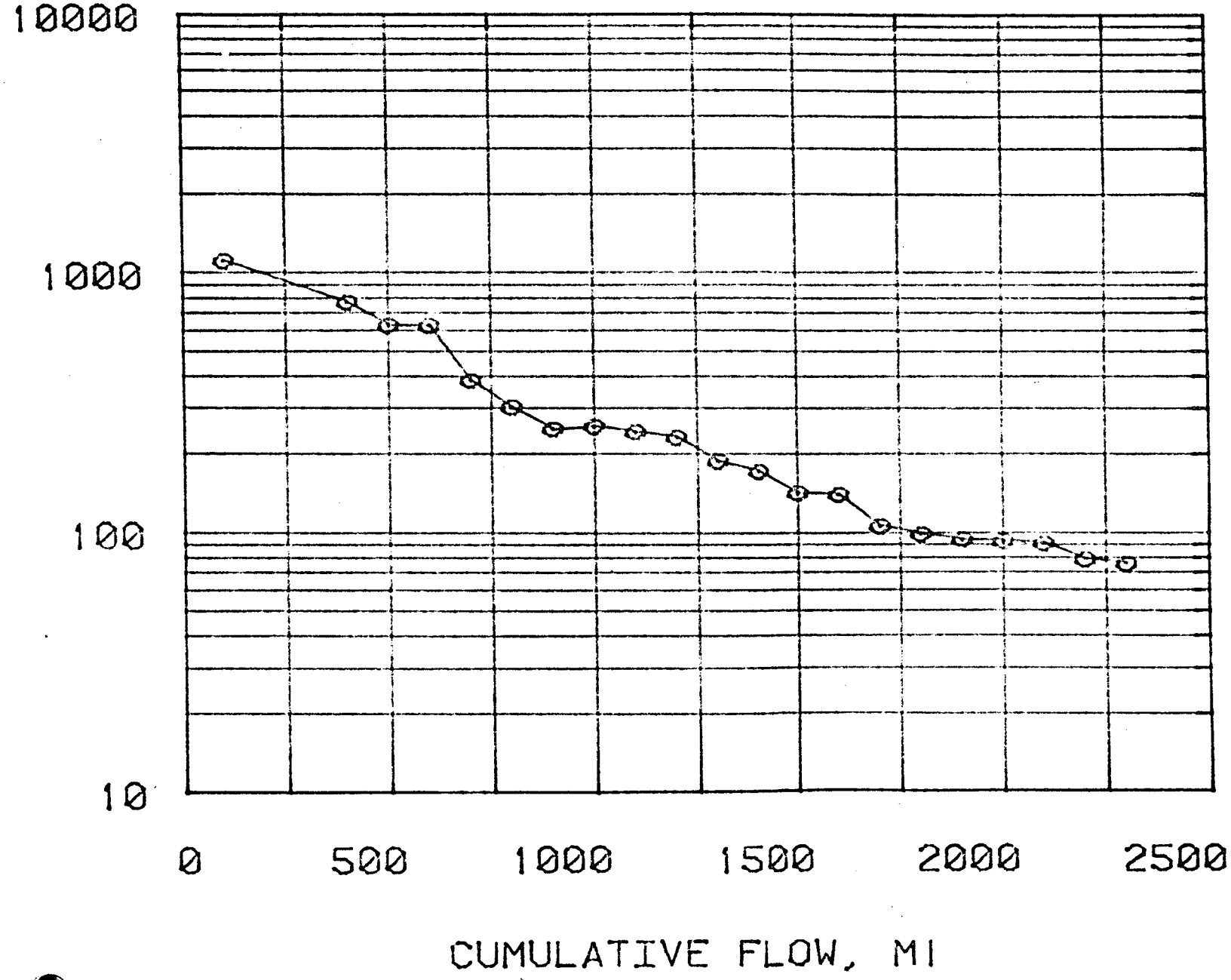
Source Press: 360 psig Run Press: 360 psig Differential Press: 50 psig

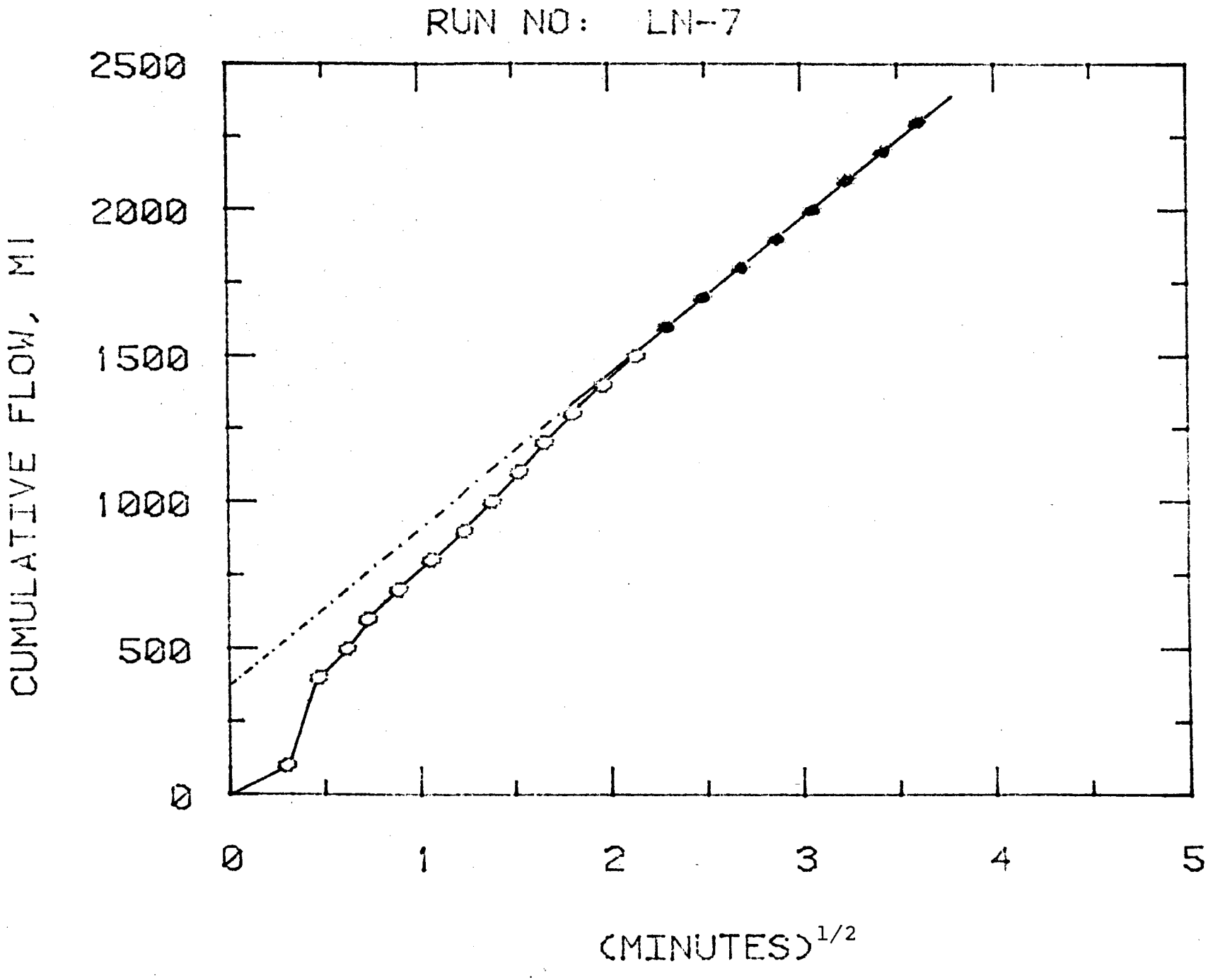
Source Temp: 130°C Run Temp: 122°C

Total Filtered Volume: 2300 ml Suspended Solids: 8.7 mg/l (7.9 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.09	0.30	100	1111.1
2	0.22	0.47	400	769.2
3	0.38	0.62	500	625.0
4	0.54	0.73	600	625.0
5	0.80	0.89	700	384.6
6	1.13	1.06	800	303.0
7	1.53	1.24	900	250.0
8	1.92	1.39	1000	256.4
9	2.33	1.53	1100	243.9
10	2.76	1.66	1200	232.6
11	3.29	1.81	1300	188.7
12	3.87	1.97	1400	172.4
13	4.57	2.14	1500	142.9
14	5.28	2.30	1600	140.9
15	6.22	2.49	1700	106.4
16	7.23	2.69	1800	99.0
17	8.29	2.88	1900	94.3
18	9.37	3.06	2000	92.6
19	10.47	3.24	2100	90.9
20	11.74	3.43	2200	78.7
21	13.06	3.61	2300	75.8

RUN NO: LN-7


10000
1000
100
10
FLOWRATE, Ml/Min
0
500
1000
1500
2000
2500
CUMULATIVE FLOW, Ml


RUN NO: LN-7
CUMULATIVE FLOW, MI
2500
2000
1500
1000
500
0
0
1
2
3
4
5
(MINUTES)1/2

INJECTABILITY TEST DATA

Run: LN 11 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: Yes

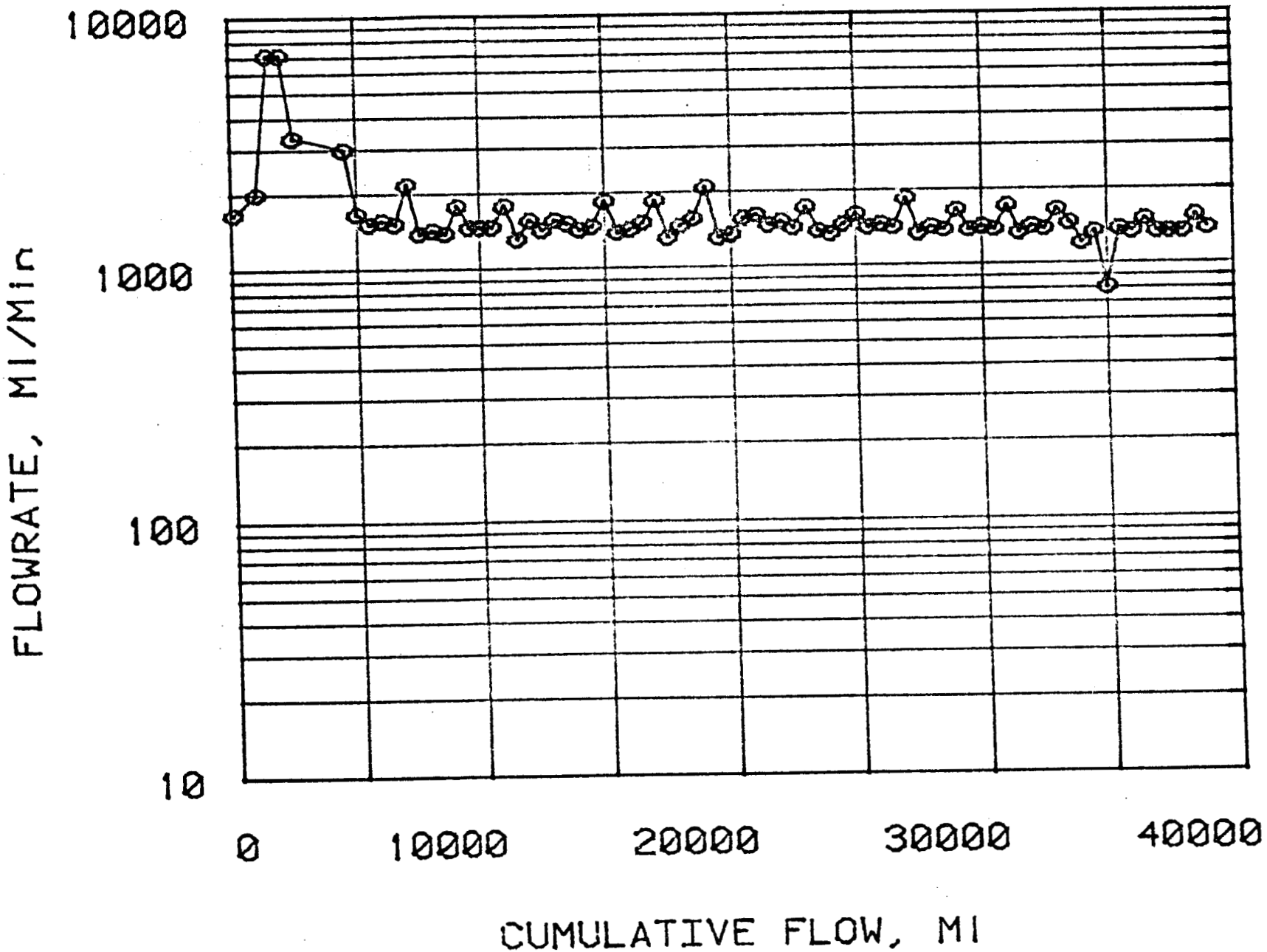
Source Press: 380 psig Run Press: 380 psig Differential Press: <0.1 psig

Source Temp: 130°C Run Temp: 126°C

Total Filtered Volume: 39,490 ml Suspended Solids: 0.05 mg/l (0.046 μg/g)

ITEM	Time(min)	√Min	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.06	0.24	100	1666.7
2	0.33	0.57	1000	2000.0
3	0.40	0.63	1500	7142.9
4	0.47	0.69	2000	7142.9
5	0.62	0.72	2500	3333.3
6	1.29	1.14	4500	2985.1
7	1.59	1.26	5000	1666.7
8	1.92	1.39	5500	1515.2
9	2.24	1.50	6000	1562.5
10	2.57	1.60	6500	1515.2
11	2.80	1.67	7000	2173.9
12	3.16	1.78	7500	1388.9
13	3.51	1.87	8000	1428.6
14	3.87	1.97	8500	1388.9
15	4.15	2.04	9000	1785.7
16	4.49	2.12	9500	1470.6
17	4.83	2.20	10000	1470.6
18	5.17	2.27	10500	1470.6
19	5.45	2.33	11000	1785.7
20	5.83	2.41	11500	1315.8
21	6.15	2.48	12000	1562.5
22	6.50	2.55	12500	1428.6
23	6.82	2.61	13000	1562.5
24	7.15	2.67	13500	1515.2
25	7.50	2.74	14000	1428.6
26	7.84	2.80	14500	1470.6
27	8.11	2.85	15000	1851.9
28	8.47	2.91	15500	1388.9
29	8.82	2.97	16000	1428.6
30	9.15	3.02	16500	1515.2
31	9.42	3.07	17000	1851.9
32	9.80	3.13	17500	1315.8
33	10.14	3.18	18000	1470.6
34	10.46	3.23	18500	1562.5
35	10.70	3.27	19000	2083.3
36	11.08	3.33	19500	1315.8
37	11.45	3.38	20000	1351.4
38	11.77	3.43	20500	1562.6

ITEM	Time(min)	√Min	Cumulative Volume(ml)	Flow Rate (ml/min)
39	11.45	3.48	21000	1351.4
40	12.42	3.52	21500	1470.6
41	12.75	3.57	22000	1515.2
42	13.10	3.62	22500	1428.6
43	13.39	3.66	23000	1724.1
44	13.75	3.71	23500	1388.9
45	14.12	3.76	24000	1351.4
46	14.46	3.80	24500	1470.6
47	14.77	3.84	25000	1612.9
48	15.12	3.89	25500	1428.6
49	15.46	3.93	26000	1470.6
50	15.81	3.98	26500	1428.6
51	16.08	4.01	27000	1851.9
52	16.45	4.06	27500	1351.4
53	16.80	4.10	28000	1428.6
54	17.16	4.14	28500	1388.9
55	17.46	4.18	29000	1666.7
56	17.82	4.22	29500	1388.9
57	18.17	4.26	30000	1428.6
58	18.53	4.30	30500	1388.9
59	18.82	4.34	31000	1724.1
60	19.19	4.38	31500	1351.4
61	19.54	4.42	32000	1428.6
62	19.90	4.46	32500	1388.9
63	20.20	4.49	33000	1666.7
64	20.54	4.53	33500	1470.6
65	20.95	4.58	34000	1219.5
66	21.32	4.62	34500	1351.4
67	21.94	4.68	35000	806.5
68	22.30	4.72	35500	1388.9
69	22.67	4.76	36000	1351.4
70	23.00	4.80	36500	1515.2
71	23.37	4.83	37000	1351.4
72	23.74	4.87	37500	1351.4
73	24.11	4.91	38000	1351.4
74	24.43	4.94	38500	1562.5
75	24.79	4.98	39000	1388.9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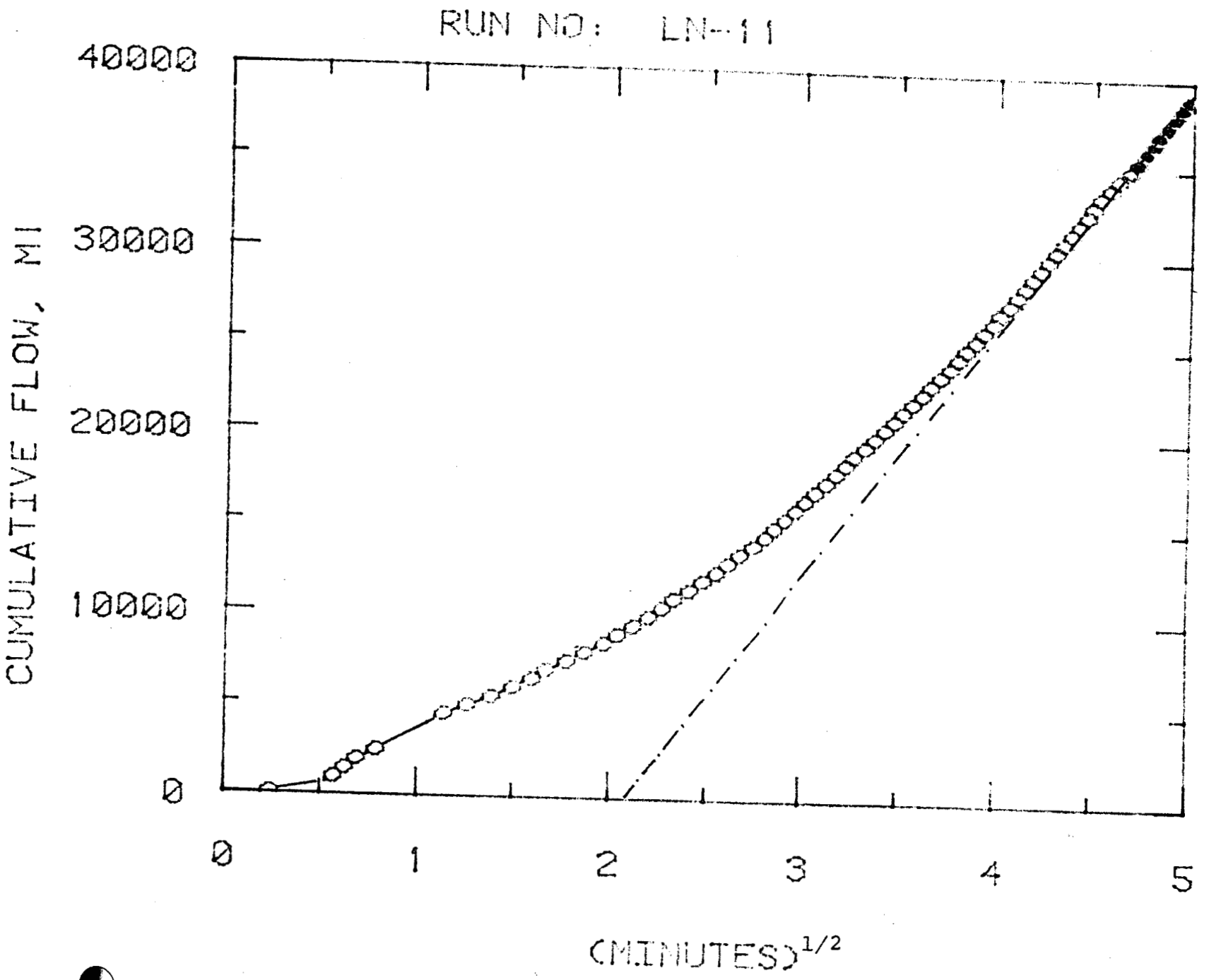
10000
1000
100
10
FLOWRATE, MI/Min
0
10000
20000
30000
40000
CUMULATIVE FLOW, MI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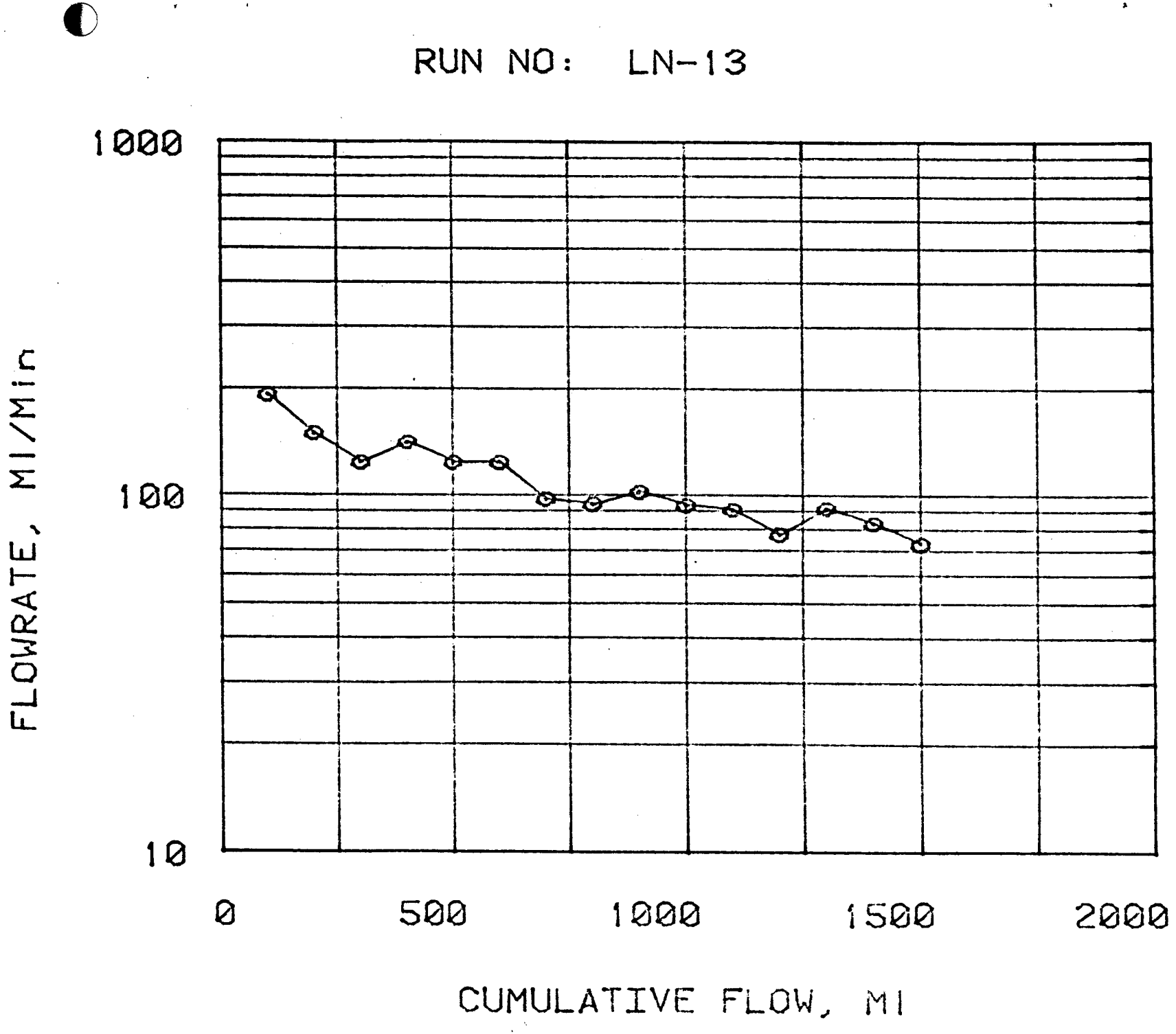
40000
30000
20000
10000
0
CUMULATIVE FLOW, MI
0
1
2
3
4
5
(MINUTES)^1/2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100
10
FLOWRATE, MI/Min
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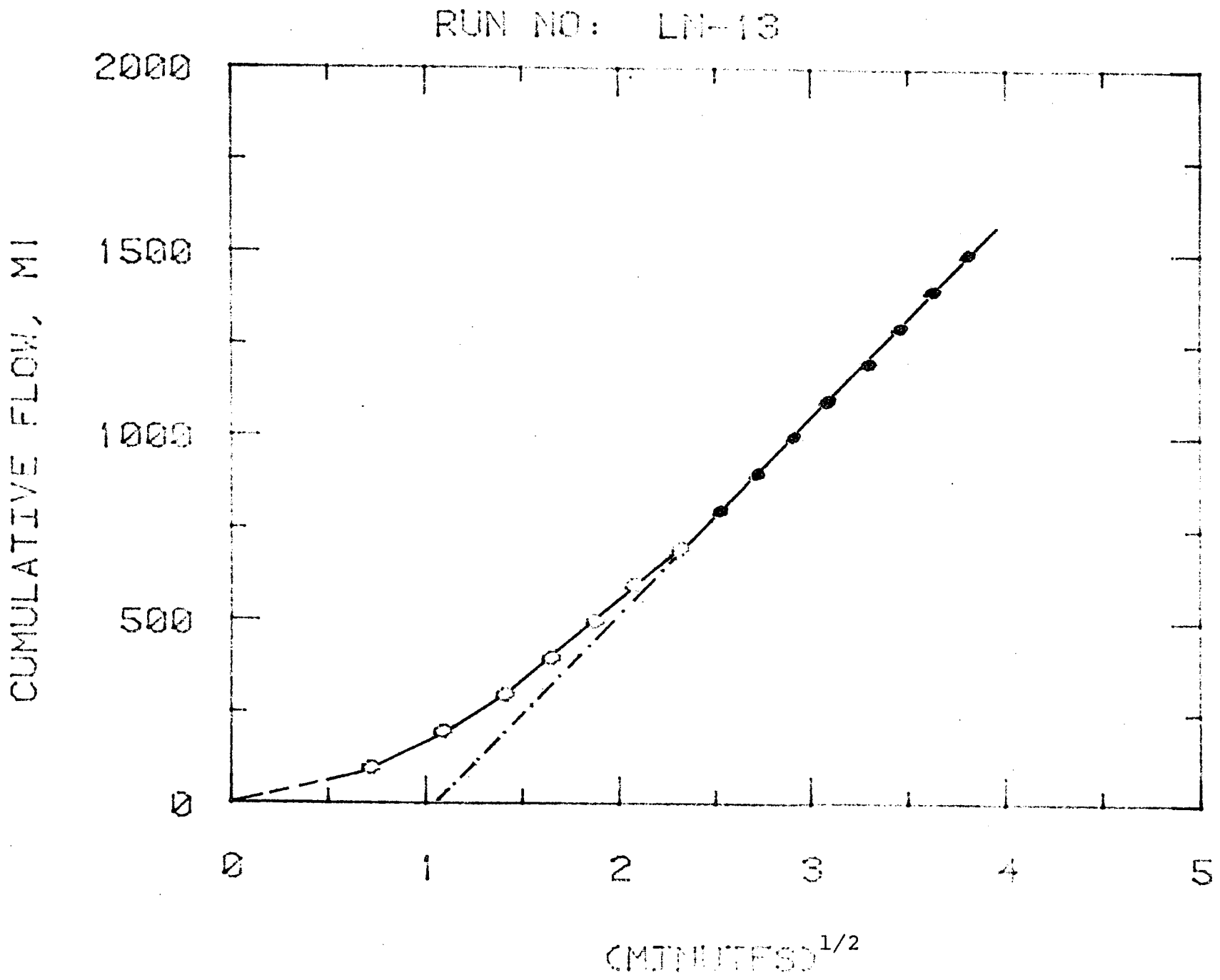
500
1000
1500
2000
CUMULATIVE FLOW, MI


RUN NO: LN-13
2000
1500
1000
500
0
CUMULATIVE FLOW, MI
0
1
2
3
4
5
(MINUTES)^1/2

INJECTABILITY TEST DATA

Run: LN-13 Membrane Filter: 0.4-μm 1-μm Cuno Prefilter: No

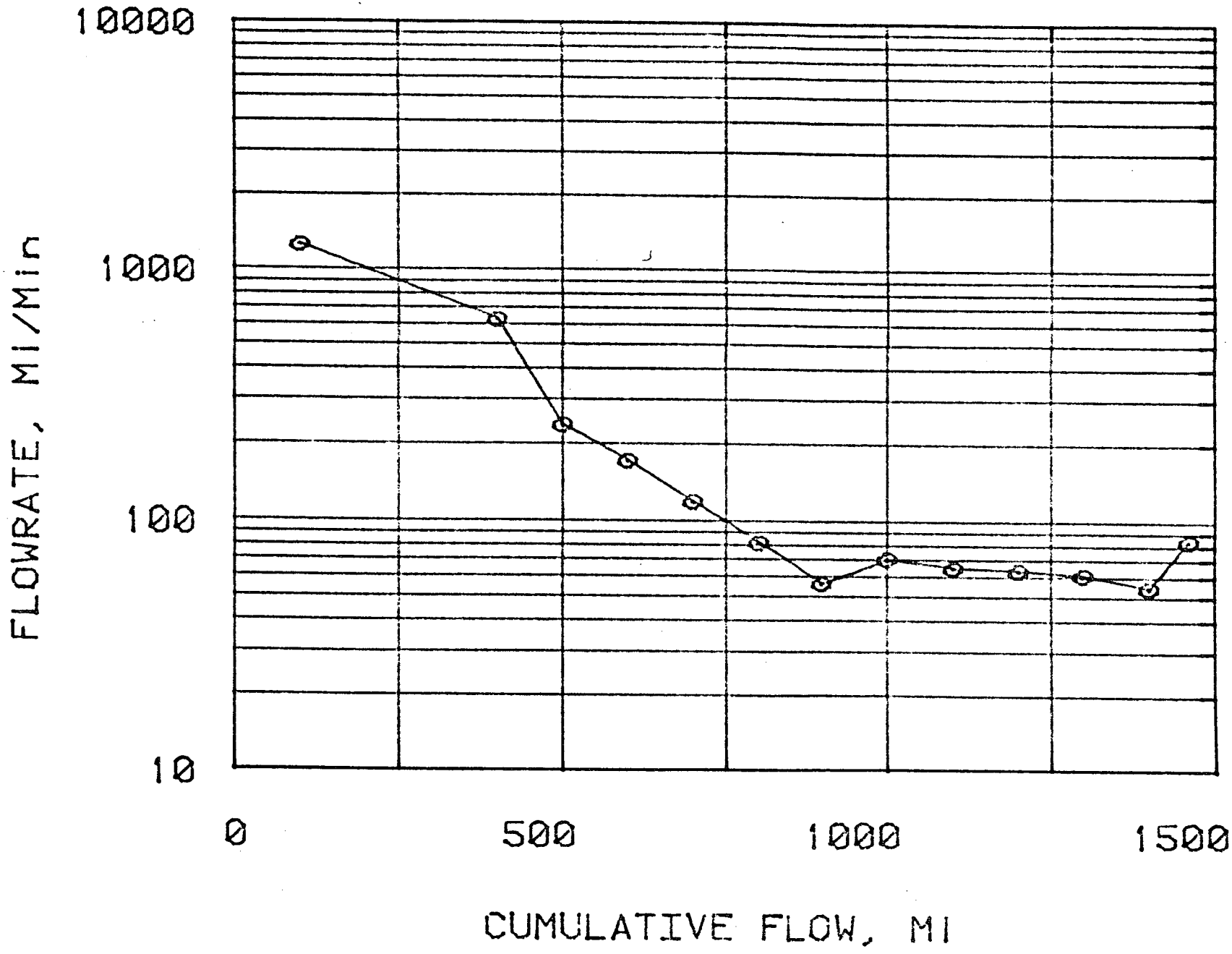
Source Press: 370 psig Run Press: 370 psig Differential Press: 50 psig

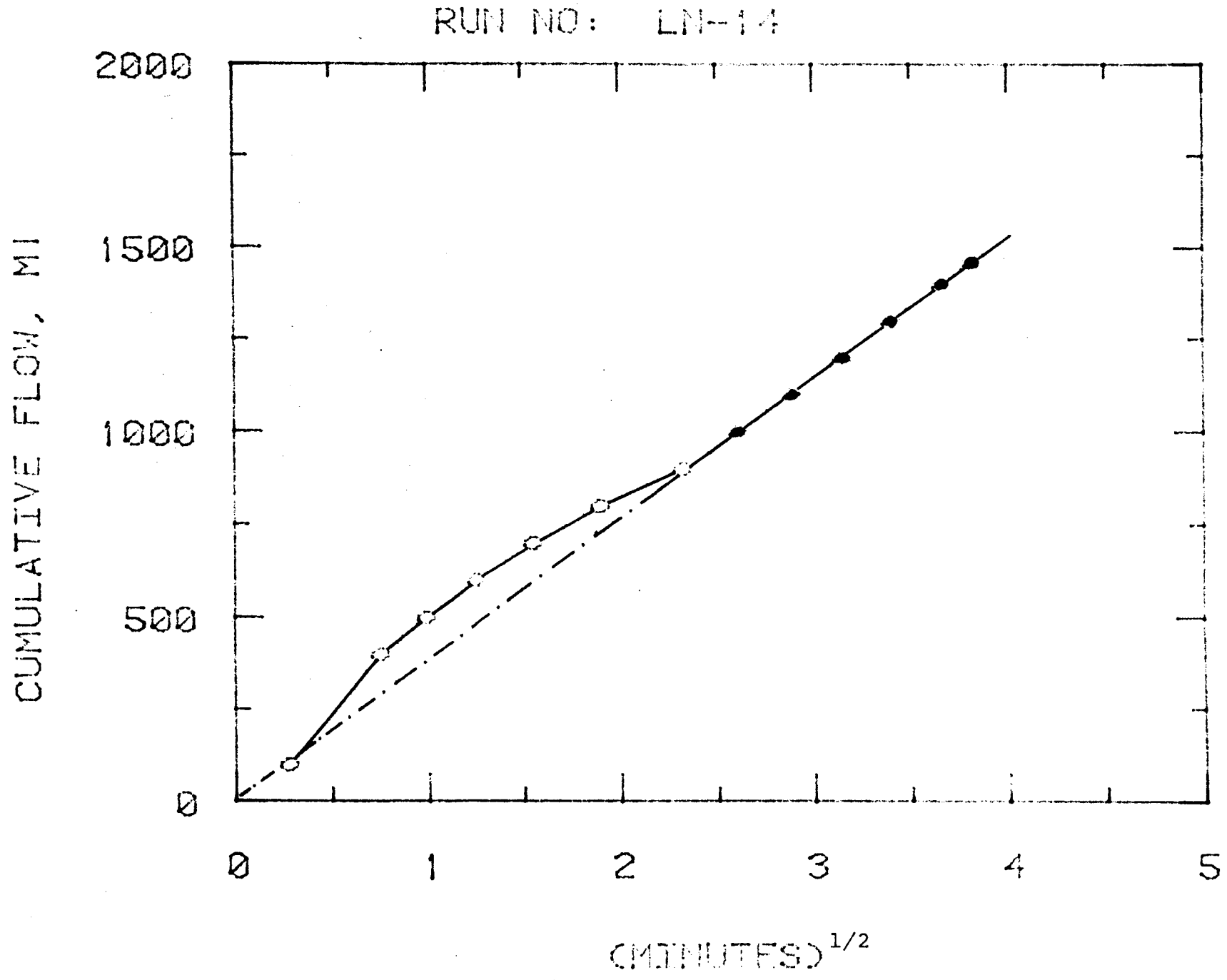
Source Temp: 130°C Run Temp: 119°C

Total Filtered Volume: 1620 ml Suspended Solids: 14.8 mg/l (13.5 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.52	0.72	100	192.3
2	1.19	1.09	200	149.3
3	2.00	1.41	300	123.5
4	2.71	1.65	400	140.9
5	3.52	1.88	500	123.5
6	4.33	2.08	600	123.5
7	5.36	2.32	700	97.1
8	6.42	2.53	800	94.3
9	7.40	2.72	900	102.0
10	8.47	2.91	1000	93.5
11	9.57	3.09	1100	90.9
12	10.86	3.30	1200	77.5
13	11.95	3.46	1300	91.7
14	13.15	3.63	1400	83.3
15	14.52	3.81	1500	73.0

RUN NO: LN-14


10000
1000
100
10
FLOWRATE, MI/Min
0
500
1000
1500
CUMULATIVE FLOW, MI


RUN NO: LN-14
2000
1500
1000
500
0
CUMULATIVE FLOW, MI
0
1
2
3
4
5
(MINUTES)^1/2

INJECTABILITY TEST DATA

Run: LN-14 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: No

Source Press:380 psig Run Press:380 psig Differential Press:50 psig

Source Temp:130°C Run Temp:112°C

Total Filtered Volume:1610 ml Suspended Solids: 9.9 mg/l (9 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.08	0.28	100	1250.0
2	0.56	0.75	400	625.0
3	0.98	0.99	500	238.1
4	1.56	1.25	600	172.4
5	2.40	1.55	700	119.1
6	3.62	1.90	800	82.0
7	5.40	2.32	900	56.2
8	6.82	2.61	1000	70.4
9	8.36	2.89	1100	64.9
10	9.94	3.15	1200	63.3
11	11.58	3.40	1300	61.0
12	13.41	3.66	1400	54.6
13	14.60	3.82	1460	84.0

INJECTABILITY TEST DATA

Run: LN-15 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: No

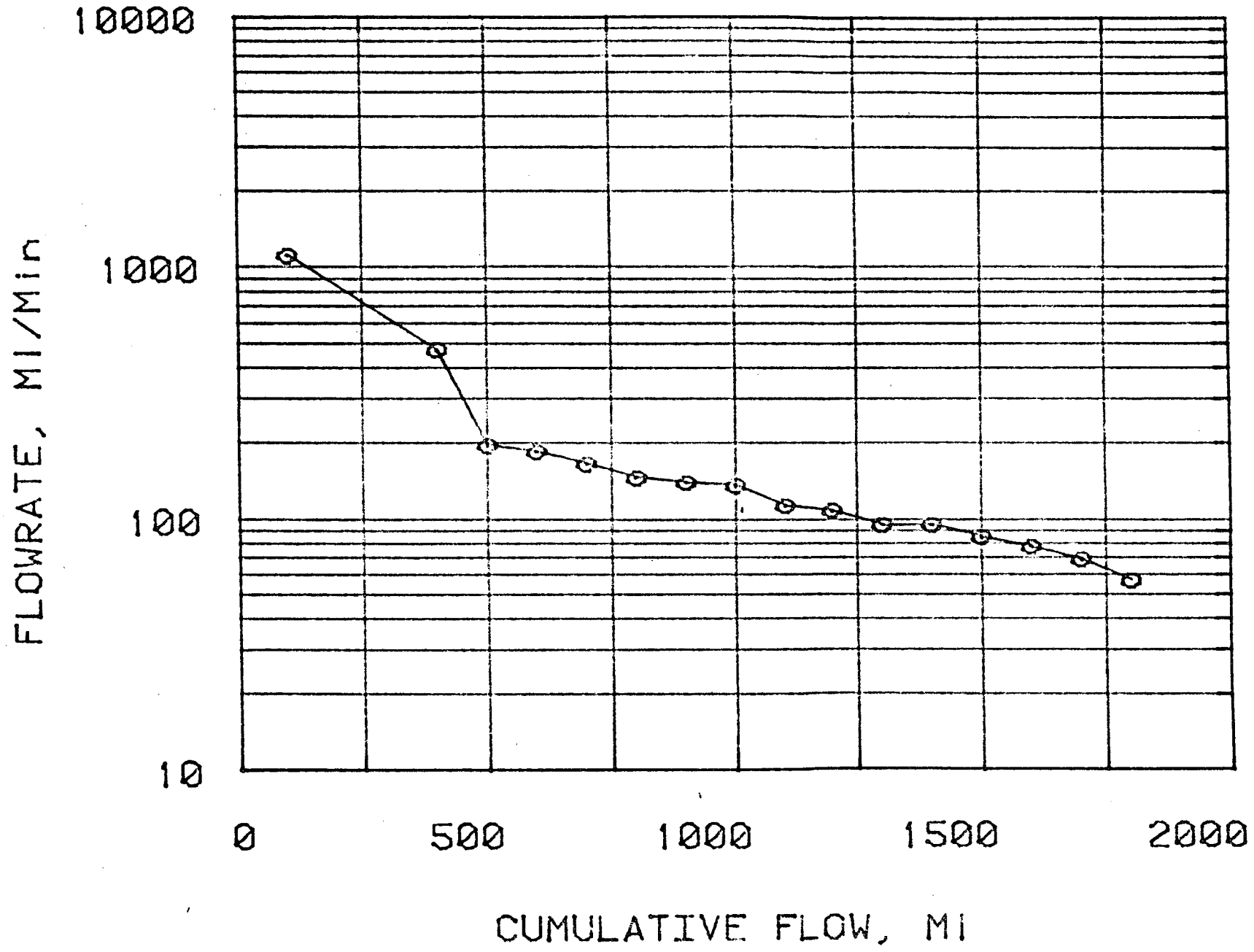
Source Press: 400 psig Run Press: 400 psig Differential Press: 50 psig

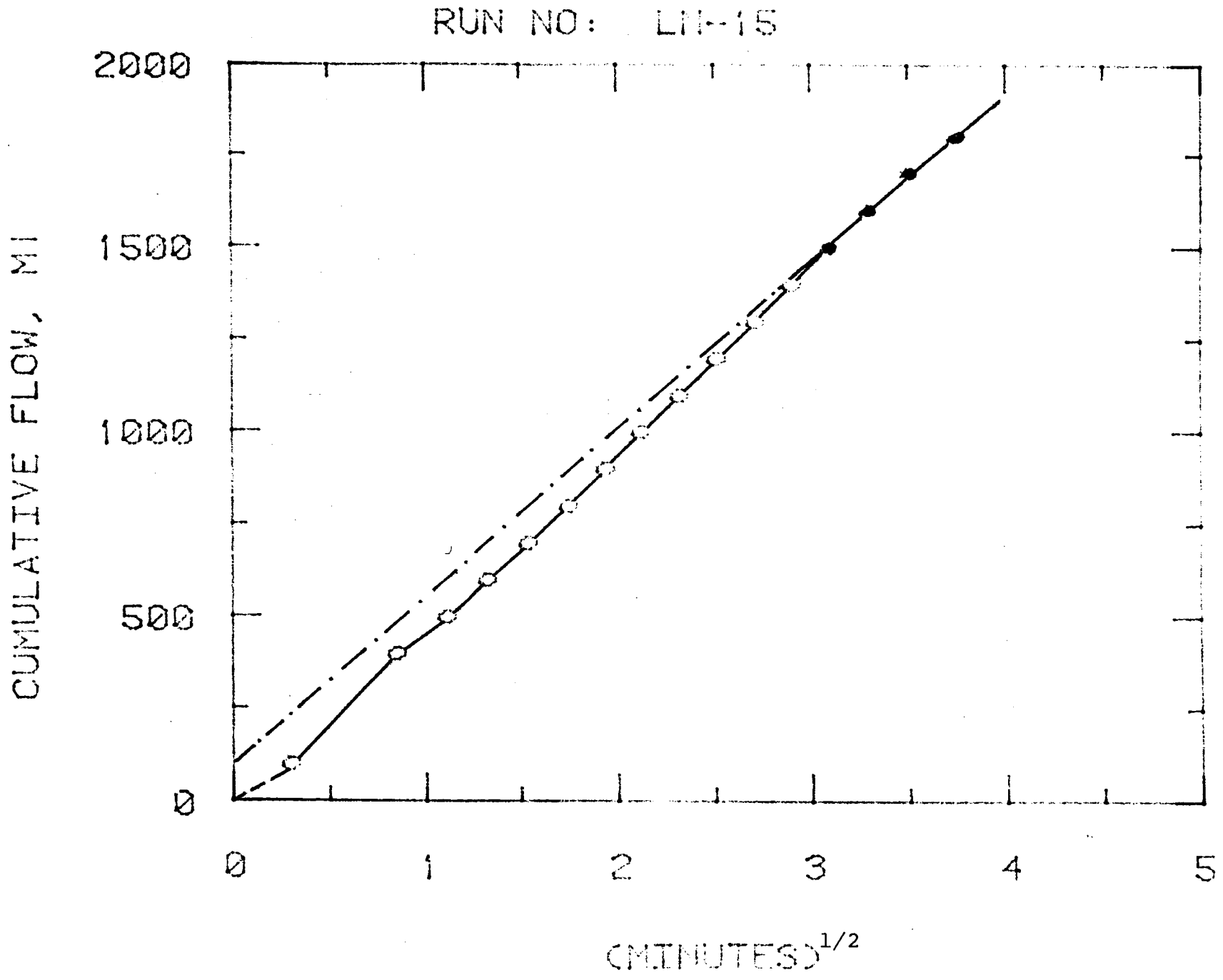
Source Temp: 130°C Run Temp: 115°C

Total Filtered Volume: 1960 ml Suspended Solids: 8.0 mg/l (7.3 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.09	0.3	100	1111.1
2	0.73	0.85	400	468.8
3	1.24	1.11	500	196.1
4	1.78	1.33	600	185.2
5	2.38	1.54	700	166.7
6	3.06	1.75	800	147.1
7	3.77	1.94	900	140.9
8	4.50	2.12	1000	137.0
9	5.38	2.32	1100	113.6
10	6.30	2.51	1200	108.7
11	7.35	2.71	1300	95.2
12	8.40	2.90	1400	95.2
13	9.58	3.10	1500	84.8
14	10.87	3.30	1600	77.5
15	12.32	3.51	1700	69.0
16	14.08	3.75	1800	56.8

RUN NO: LN-15


10000
1000
100
10
FLOWRATE, MI/Min
0
500
1000
1500
2000
CUMULATIVE FLOW, MI


RUN NO: LH-15
2000
1500
1000
500
0
CUMULATIVE FLOW, MI
0
1
2
3
4
5
(MINUTES)^1/2

INJECTABILITY TEST DATA

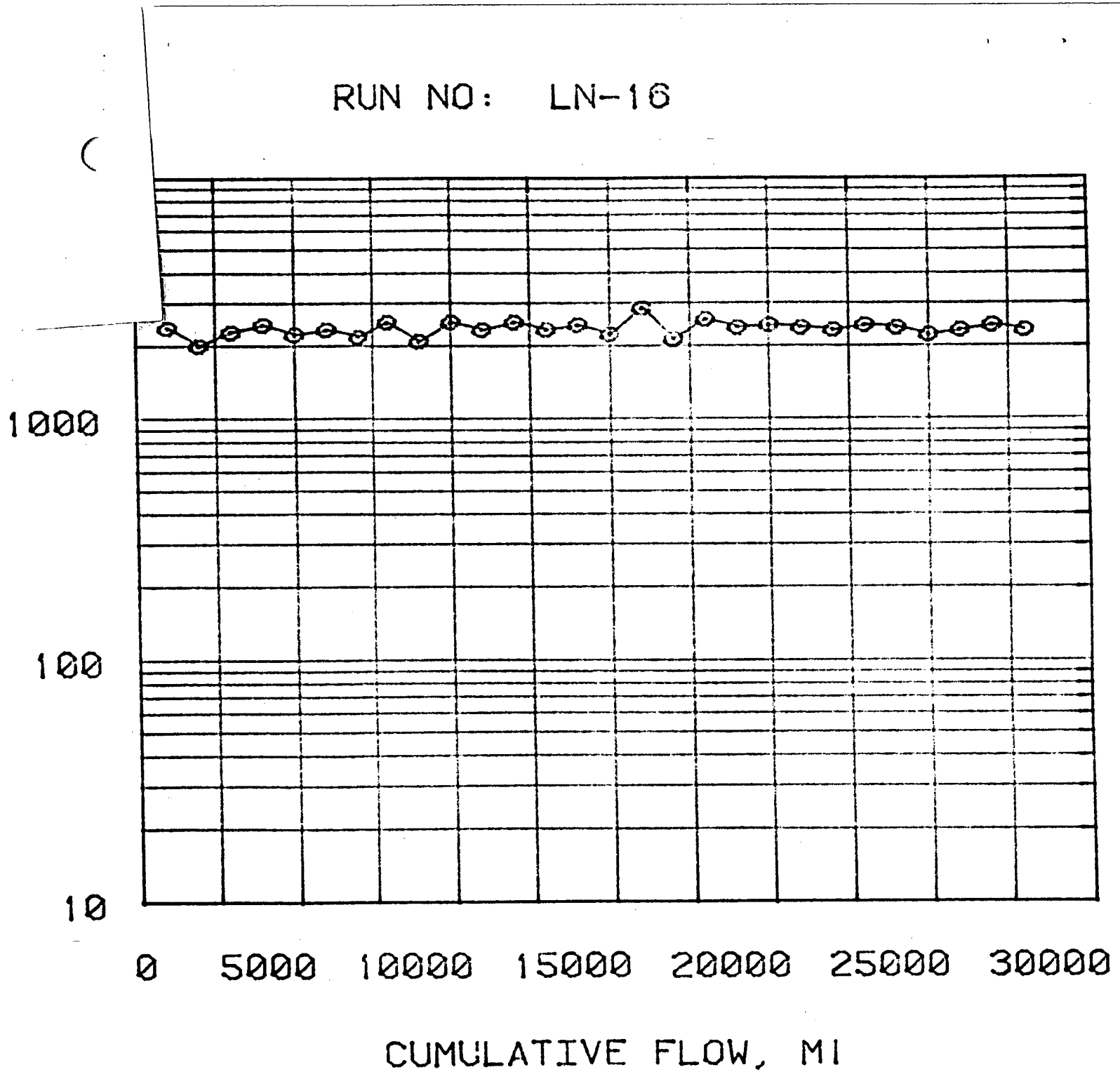
Run: LN-16 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: No

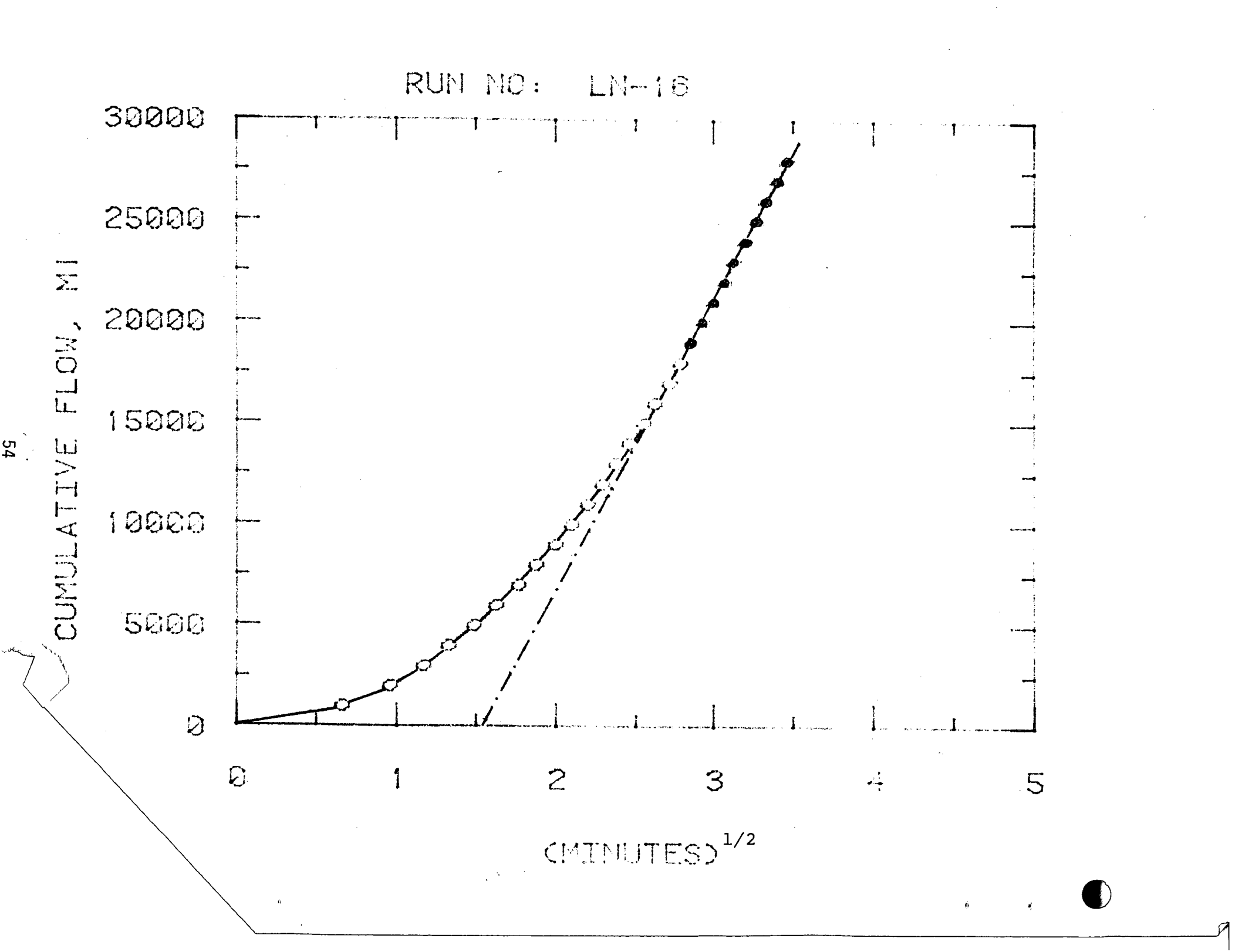
Source Press:400 psig Run Press:400 psig Differential Press:<0.1 psig

Source Temp:130°C Run Temp:130°C

Total Filtered Volume:28,310 ml Suspended Solids: 0.021 mg/l (0.019 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.43	0.66	1000	2368.4
2	0.93	0.96	2000	2000.0
3	1.37	1.17	3000	2272.7
4	1.78	1.33	4000	2439.0
5	2.23	1.49	5000	2222.2
6	2.66	1.63	6000	2325.6
7	3.12	1.77	7000	2173.9
8	3.52	1.88	8000	2500.0
9	4.00	2.00	9000	2083.3
10	4.40	2.10	10000	2500.0
11	4.83	2.20	11000	2325.6
12	5.23	2.29	12000	2500.0
13	5.66	2.38	13000	2325.6
14	6.07	2.46	14000	2439.0
15	6.52	2.55	15000	2222.2
16	6.87	2.62	16000	2857.1
17	7.34	2.71	17000	2127.7
18	7.73	2.78	18000	2564.1
19	8.15	2.85	19000	2381.0
20	8.56	2.93	20000	2439.0
21	8.98	3.00	21000	2381.0
22	9.41	3.07	22000	2325.6
23	9.82	3.13	23000	2439.0
24	10.24	3.20	24000	2381.0
25	10.69	3.27	25000	2222.2
26	11.12	3.33	26000	2325.6
27	11.53	3.40	27000	2439.0
28	11.96	3.46	28000	2325.6


RUN NO: LN-16
1000
100
10
FLOWRATE, MI/Min
0
5000
10000
15000
20000
25000
30000
CUMULATIVE FLOW, MI


RUN NO: LN-16
30000
25000
20000
15000
10000
5000
0
CUMULATIVE FLOW, MI
0
1
2
3
4
5
(MINUTES)^1/2

INJECTABILITY TEST DATA

Run: MN-1 Membrane Filter: 0.4-μm 1-μm Cuno Prefilter: No

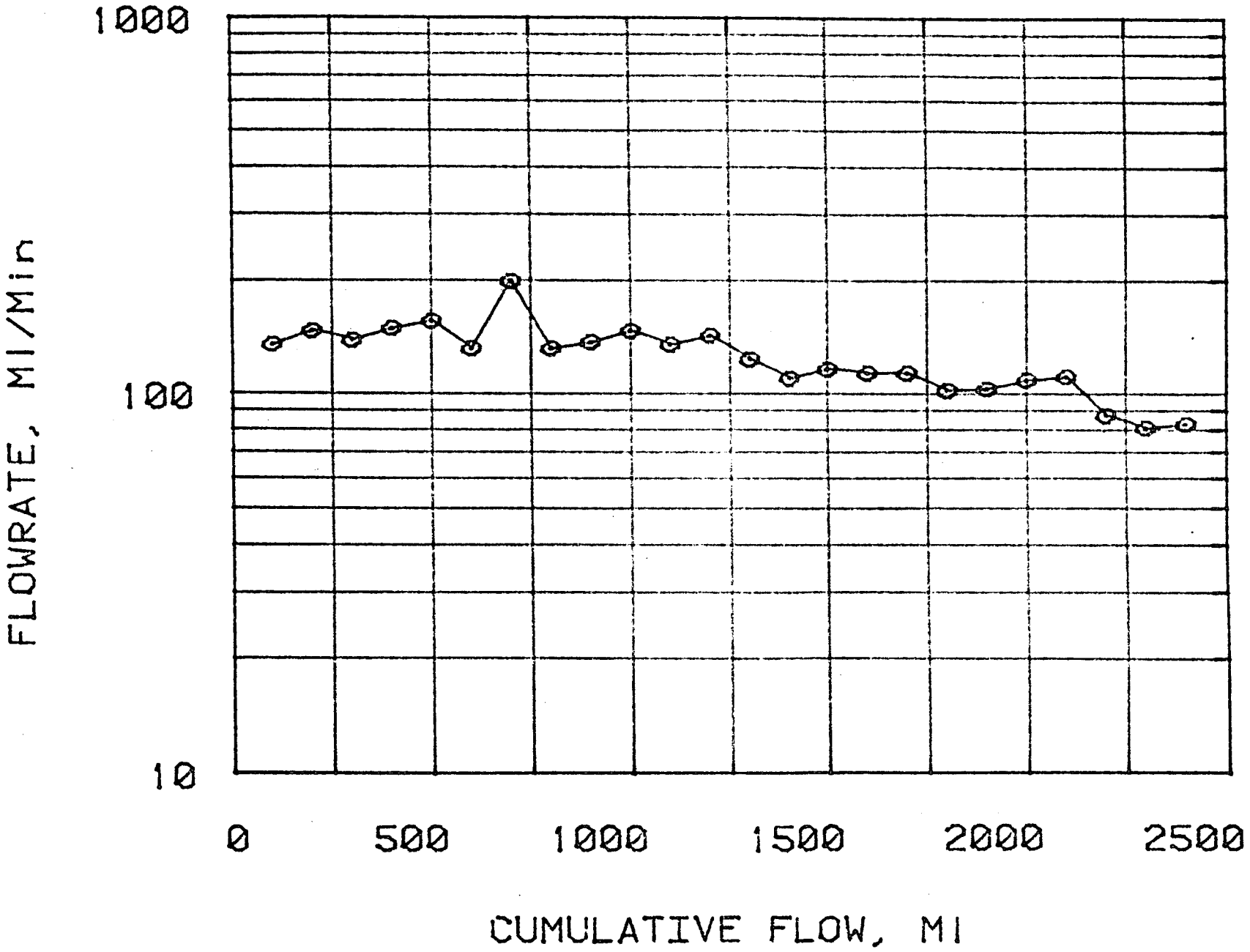
Source Press:800 psig Run Press:800 psig Differential Press:50 psig

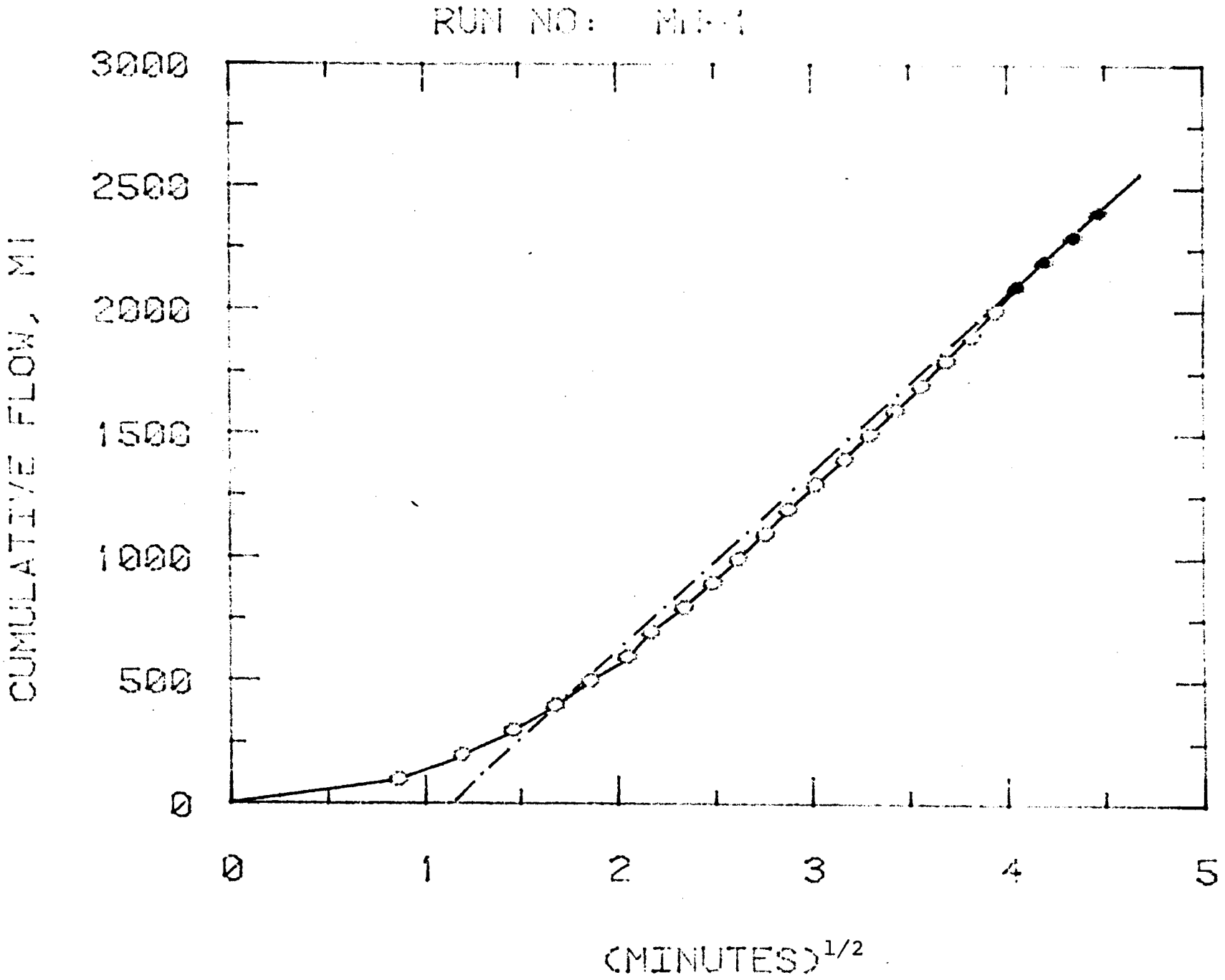
Source Temp:130°C Run Temp:112°C

Total Filtered Volume:2530 ml Suspended Solids: 13.5 mg/l (12.3 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.74	0.86	100	135.1
2	1.42	1.19	200	147.1
3	2.14	1.46	300	138.9
4	2.81	1.68	400	149.3
5	3.45	1.86	500	156.3
6	4.21	2.05	600	131.6
7	4.71	2.17	700	200.0
8	5.47	2.34	800	131.6
9	6.20	2.49	900	137.0
10	6.88	2.62	1000	147.1
11	7.62	2.76	1100	135.1
12	8.32	2.88	1200	142.9
13	9.13	3.02	1300	123.5
14	10.04	3.17	1400	109.9
15	10.90	3.30	1500	116.3
16	11.78	3.43	1600	113.6
17	12.66	3.56	1700	113.6
18	13.64	3.69	1800	102.0
19	14.61	3.82	1900	103.1
20	15.53	3.94	2000	108.7
21	16.43	4.05	2100	111.1
22	17.57	4.19	2200	87.7
23	18.80	4.34	2300	81.3
24	20.00	4.47	2400	83.3

RUN NO: MN-1


1000
100
10
FLOWRATE, MI/Min
0
500
1000
1500
2000
2500
CUMULATIVE FLOW, MI


RUN NO: M1-1
3000
2500
2000
1500
1000
500
0
CUMULATIVE FLOW, MI
0
1
2
3
4
5
(MINUTES)1/2

INJECTABILITY TEST DATA

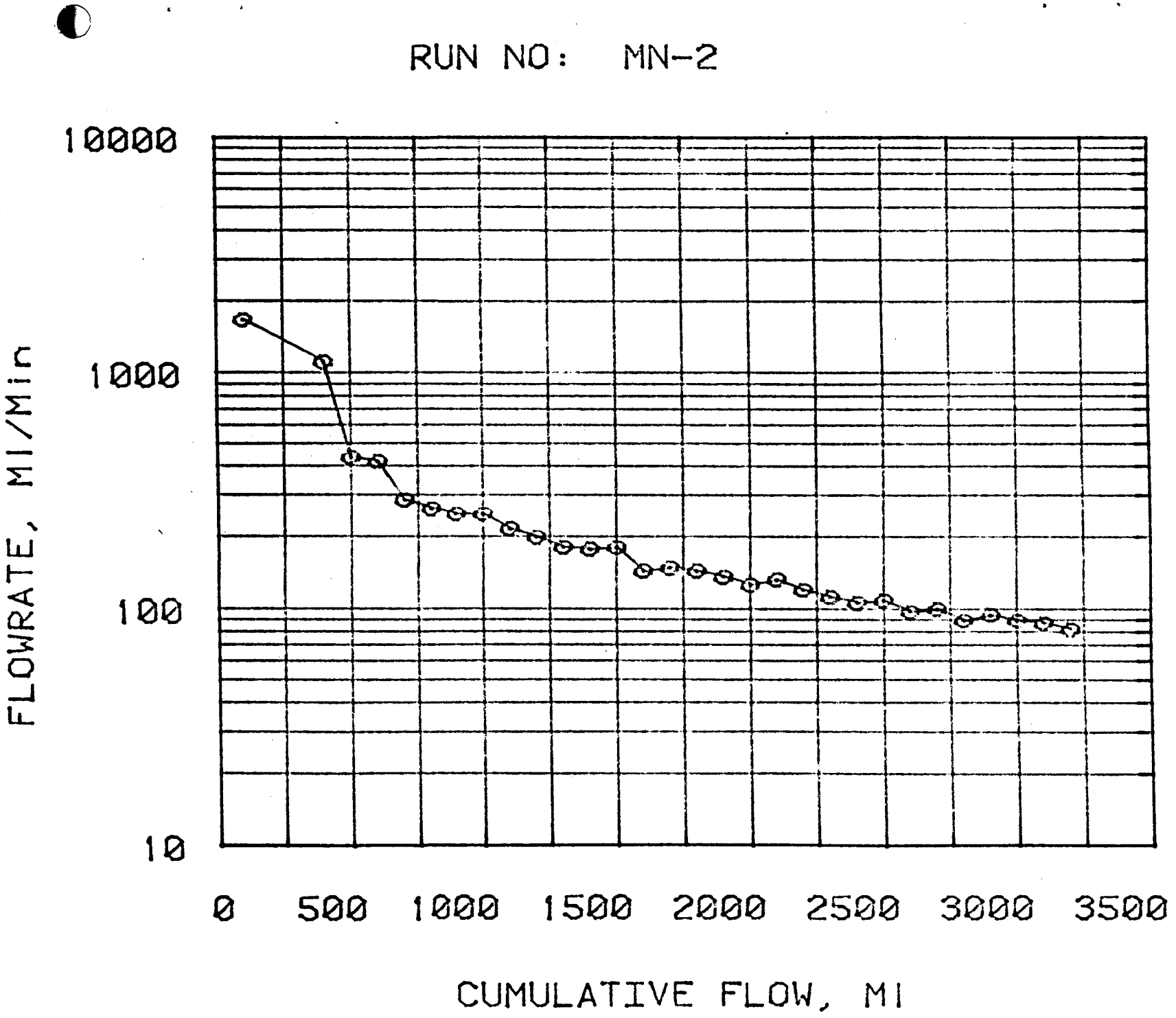
Run: MN-2 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: No

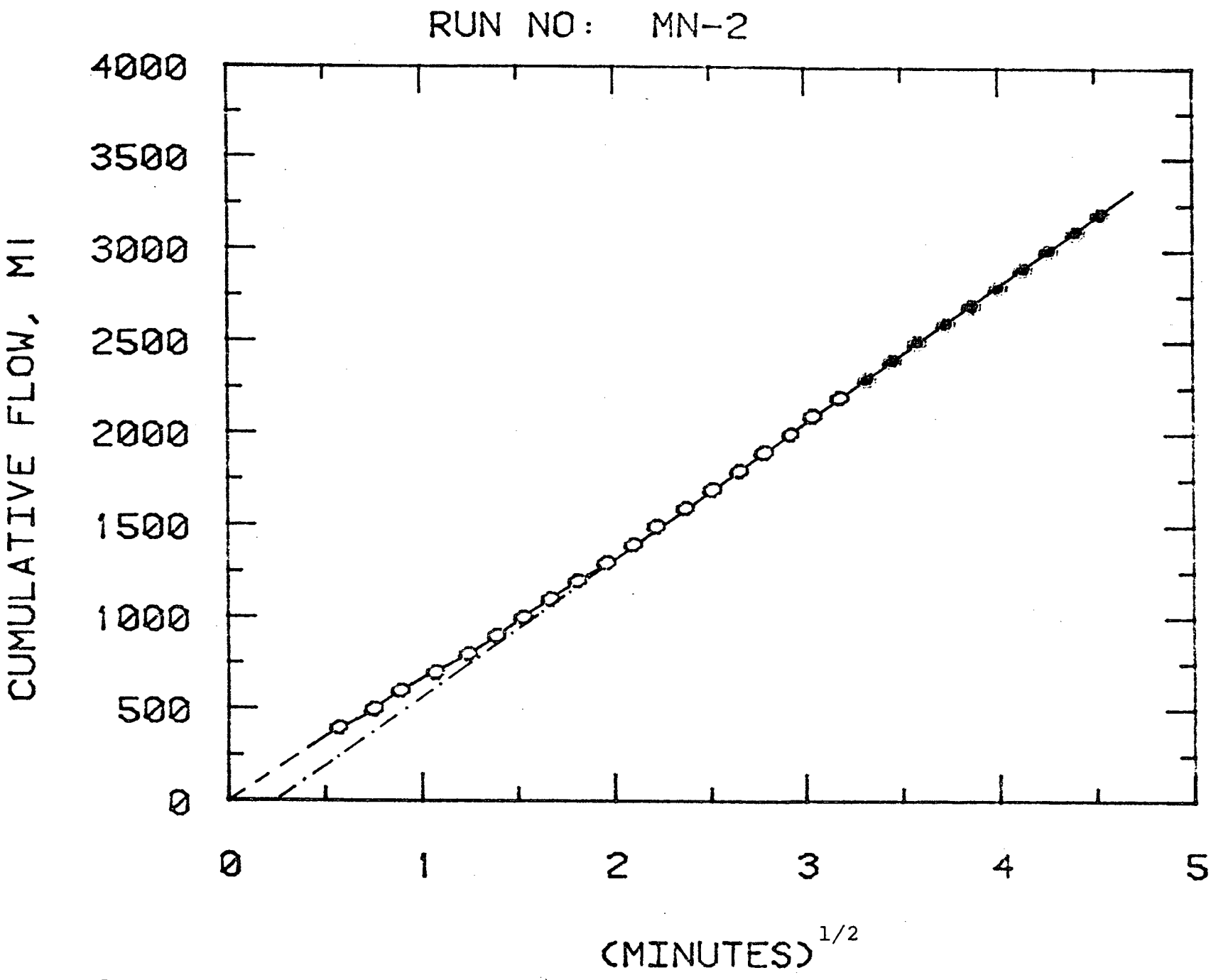
Source Press:800 psig Run Press:800 psig Differential Press:50 psig

Source Temp:130°C Run Temp:120°C

Total Filtered Volume:3340 ml Suspended Solids: 11.8 mg/l (10.7 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.06	0.24	100	1666.7
2	0.33	0.57	400	1111.1
3	0.56	0.75	500	434.8
4	0.80	0.89	600	416.7
5	1.15	1.07	700	285.7
6	1.53	1.24	800	263.2
7	1.93	1.39	900	250.0
8	2.33	1.53	1000	250.0
9	2.79	1.67	1100	217.4
10	3.29	1.81	1200	200.0
11	3.84	1.96	1300	181.8
12	4.40	2.10	1400	178.6
13	4.95	2.22	1500	181.8
14	5.64	2.37	1600	144.9
15	6.31	2.51	1700	149.3
16	7.00	2.65	1800	144.9
17	7.73	2.78	1900	137.0
18	8.52	2.92	2000	126.6
19	9.27	3.04	2100	133.3
20	10.10	3.18	2200	120.5
21	10.99	3.32	2300	112.4
22	11.93	3.45	2400	106.4
23	12.85	3.58	2500	108.7
24	13.88	3.73	2600	97.1
25	14.88	3.86	2700	100.0
26	16.00	4.00	2800	89.3
27	17.06	4.13	2900	94.3
28	18.18	4.26	3000	89.3
29	19.33	4.40	3100	87.0
30	20.55	4.53	3200	82.0


RUN NO: MN-2
10000
1000
100
10
FLOWRATE, MI/Min
0
500
1000
1500
2000
2500
3000
3500
CUMULATIVE FLOW, MI


RUN NO: MN-2
CUMULATIVE FLOW, MI
4000
3500
3000
2500
2000
1500
1000
500
0
0
1
2
3
4
5
(MINUTES)^1/2

INJECTABILITY TEST DATA

Run: MN-3 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: Yes

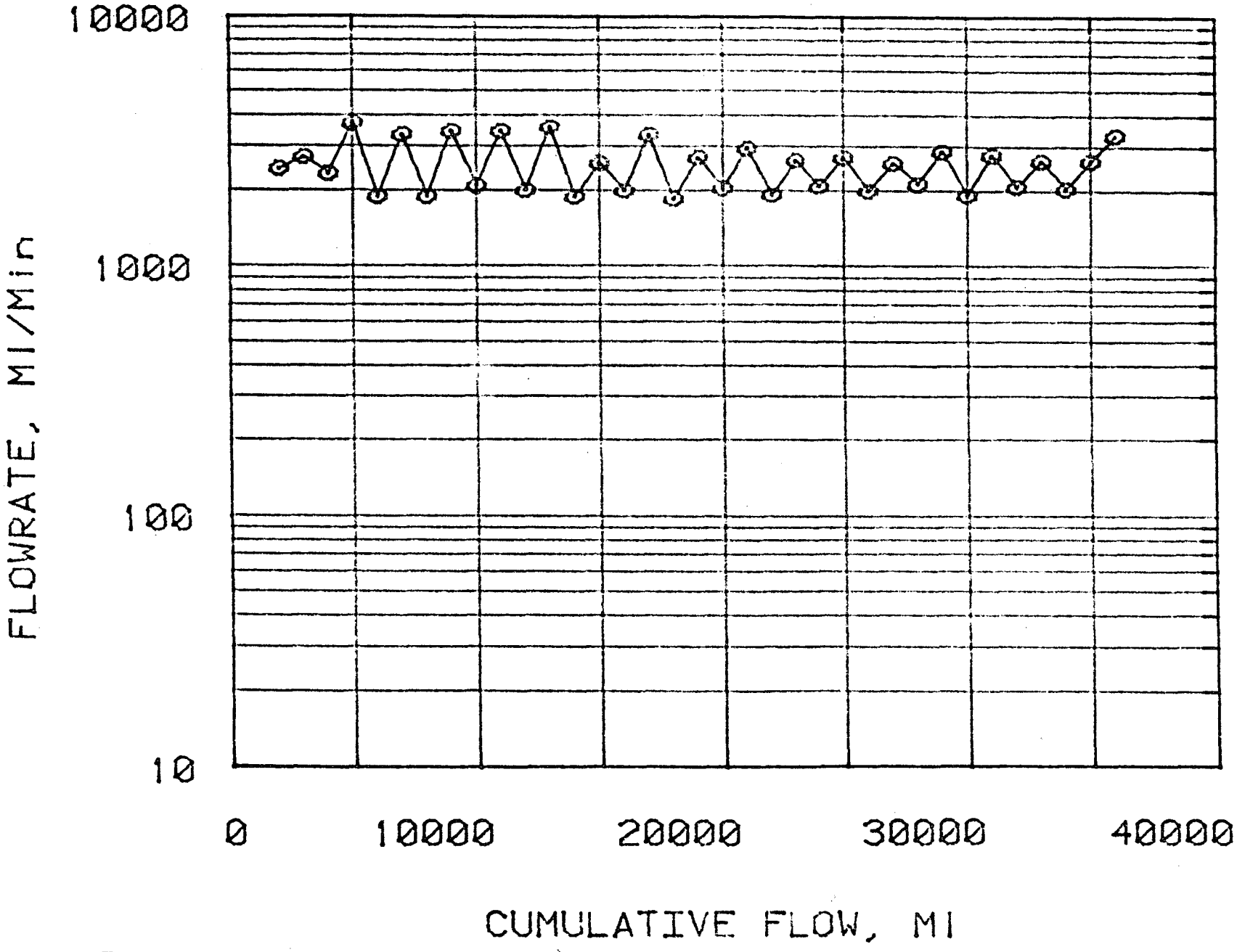
Source Press: 750 psig Run Press: 750 psig Differential Press: <0.1 psig

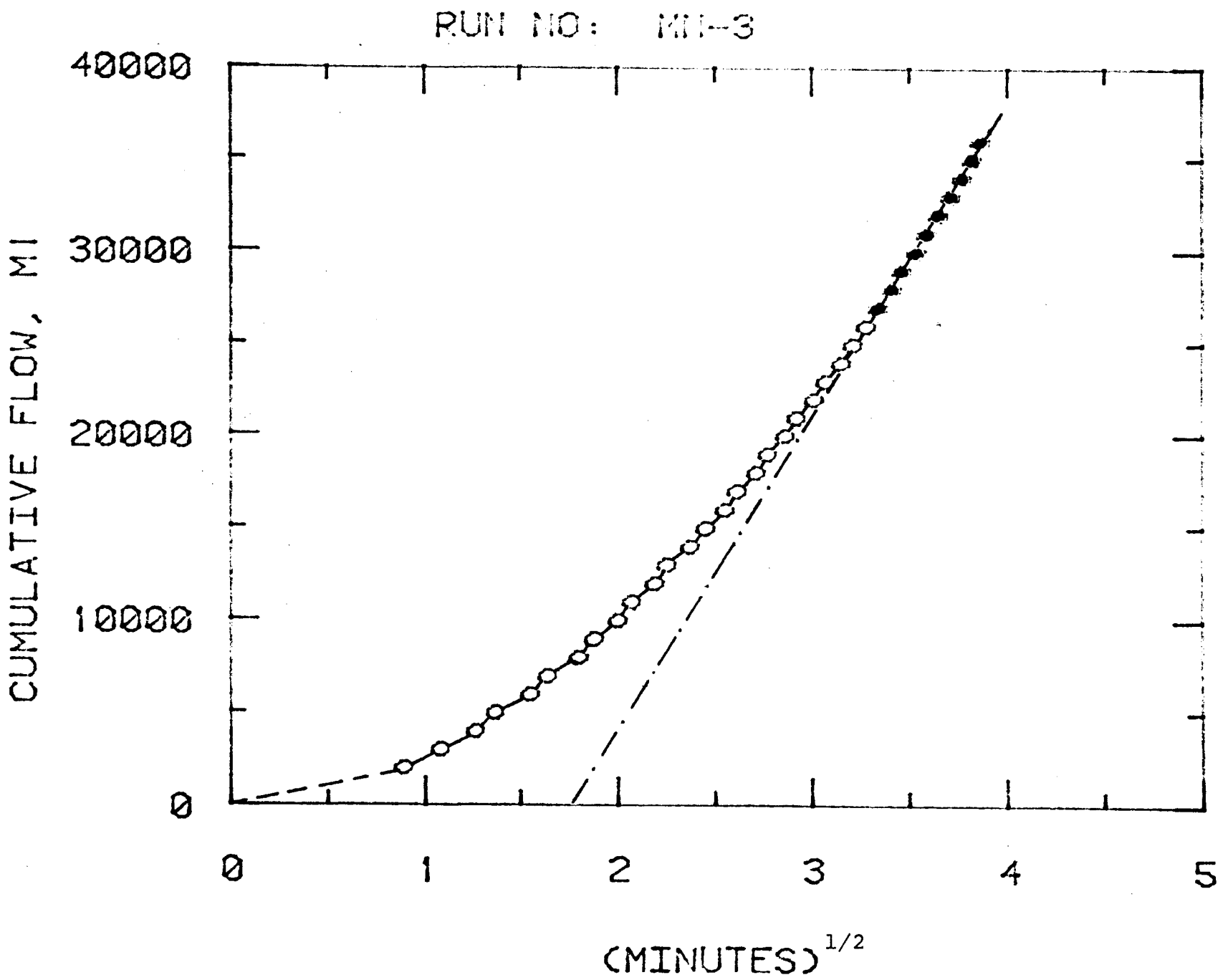
Source Temp: 130°C Run Temp: 129°C

Total Filtered Volume: 36,000 ml Suspended Solids: 0.031 mg/l (0.028 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.08	0.28	100	1250.0
2	0.80	0.89	2000	2435.9
3	1.17	1.08	3000	2702.7
4	1.60	1.26	4000	2325.6
5	1.87	1.37	5000	3703.7
6	2.40	1.55	6000	1886.8
7	2.70	1.64	7000	3333.3
8	3.23	1.80	8000	1886.8
9	3.52	1.88	9000	3448.3
10	4.00	2.00	10000	2083.3
11	4.29	2.07	11000	3448.3
12	4.79	2.19	12000	2000.0
13	5.07	2.25	13000	3571.4
14	5.60	2.37	14000	1886.8
15	5.99	2.45	15000	2564.1
16	6.49	2.55	16000	2000.0
17	6.79	2.61	17000	3333.3
18	7.33	2.71	18000	1851.9
19	7.70	2.77	19000	2702.7
20	8.19	2.86	20000	2040.8
21	8.53	2.92	21000	2941.2
22	9.05	3.01	22000	1923.1
23	9.43	3.07	23000	2631.6
24	9.91	3.15	24000	2083.3
25	10.28	3.21	25000	2702.7
26	10.78	3.28	26000	2000.0
27	11.17	3.34	27000	2564.1
28	11.64	3.41	28000	2127.7
29	11.99	3.46	29000	2857.1
30	12.51	3.54	30000	1923.1
31	12.87	3.59	31000	2777.8
32	13.35	3.65	32000	2083.3
33	13.73	3.71	33000	2631.6
34	14.22	3.77	34000	2040.8
35	14.60	3.82	35000	2631.6
36	14.90	3.86	36000	3333.3

RUN NO: MN-3


10000
1000
100
10
FLOWRATE, MI/Min
0
10000
20000
30000
40000
CUMULATIVE FLOW, MI


RUN NO: MII-3
40000
30000
20000
10000
0
CUMULATIVE FLOW, MI
0
1
2
3
4
5
(MINUTES)^1/2

INJECTABILITY TEST DATA

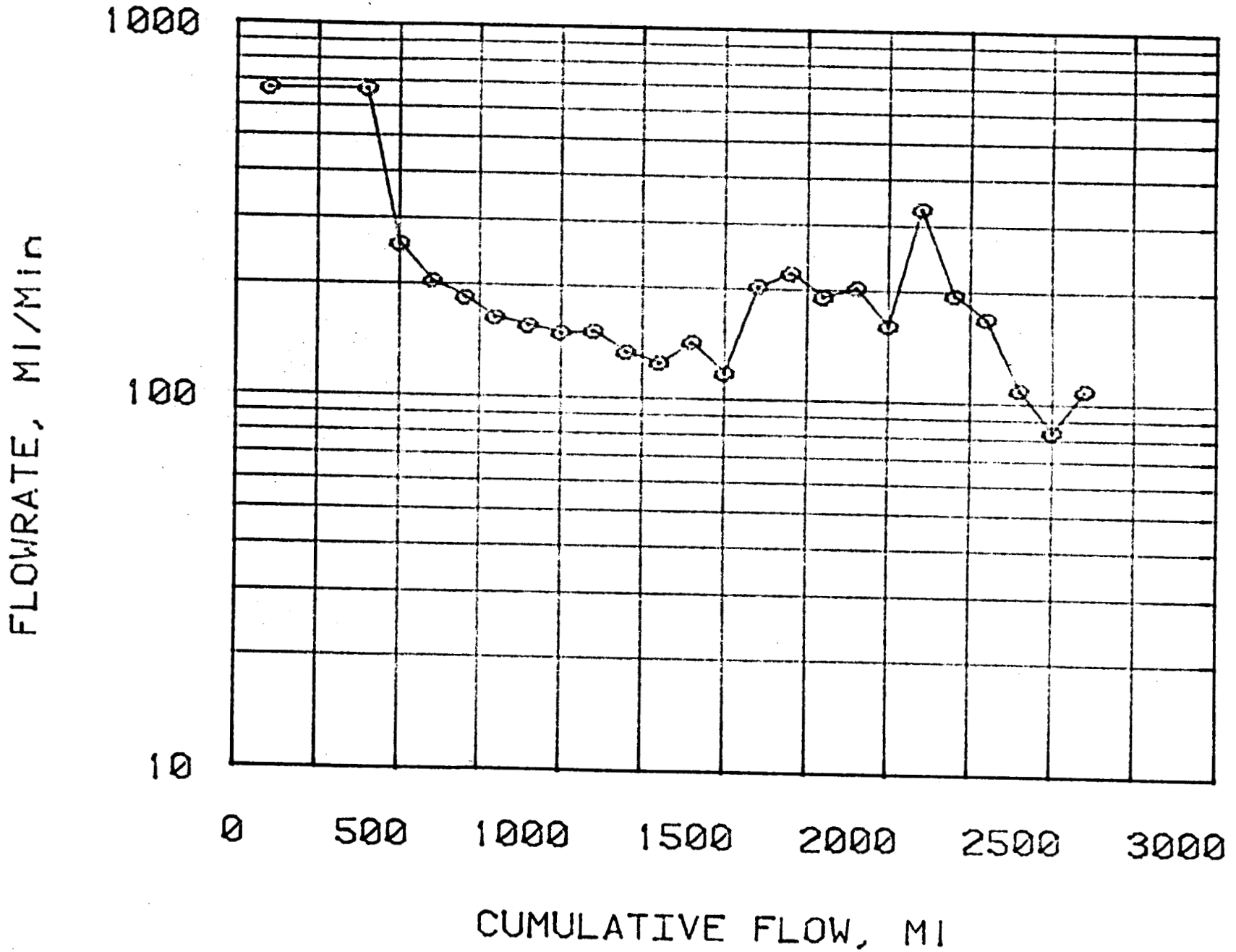
Run: HN-1 Membrane Filter: 0.4-μm 1-μm Cuno Prefilter: No

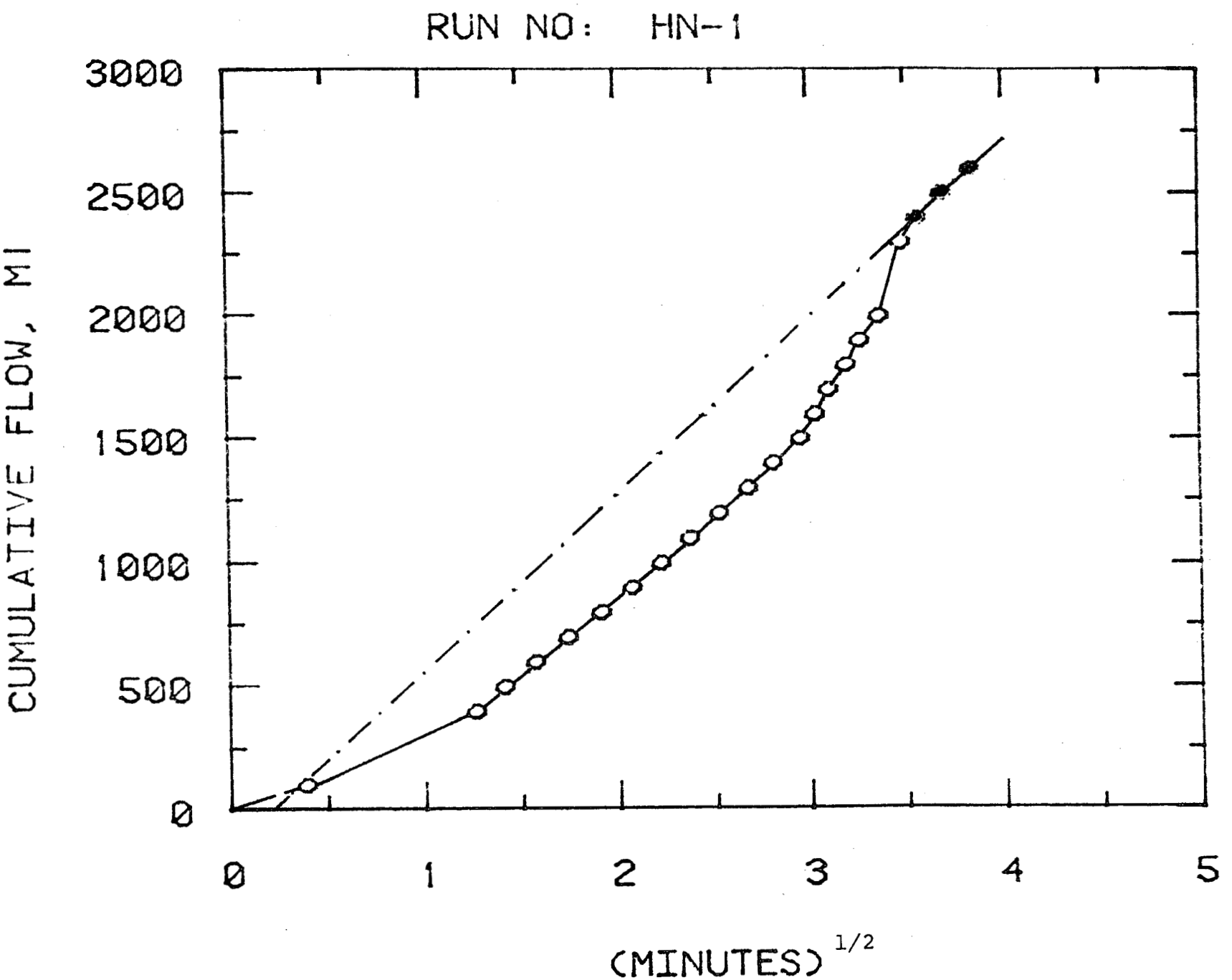
Source Press: 3800 psig Run Press: 400 psig Differential Press: 50 psig

Source Temp: 130°C Run Temp: 120°C

Total Filtered Volume: 2630 ml Suspended Solids: 1.4 mg/l (1.3 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.15	0.39	100	666.7
2	1.60	1.26	400	666.7
3	1.99	1.41	500	256.5
4	2.48	1.57	600	204.1
5	3.02	1.74	700	185.2
6	3.63	1.91	800	163.9
7	4.27	2.07	900	156.3
8	4.94	2.22	1000	149.3
9	5.60	2.37	1100	151.5
10	6.35	2.52	1200	133.3
11	7.15	2.67	1300	125.0
12	7.85	2.80	1400	142.9
13	8.70	2.95	1500	117.7
14	9.19	3.03	1600	204.1
15	9.64	3.10	1700	222.2
16	10.16	3.19	1800	192.3
17	10.65	3.26	1900	204.1
18	11.27	3.36	2000	161.3
19	11.57	3.40	2100	333.3
20	12.08	3.48	2200	196.1
21	12.67	3.56	2300	169.5
22	13.59	3.69	2400	108.7
23	14.78	3.84	2500	84.0
24	15.70	3.96	2600	108.7


RUN NO: HN-1
1000
100
10
FLOWRATE, Ml/Min
0
500
1000
1500
2000
2500
3000
CUMULATIVE FLOW, Ml


RUN NO: HN-1
CUMULATIVE FLOW, MI
3000
2500
2000
1500
1000
500
0
0
1
2
3
4
5
(MINUTES) 1/2

INJECTABILITY TEST DATA

Run: HN-2 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: No

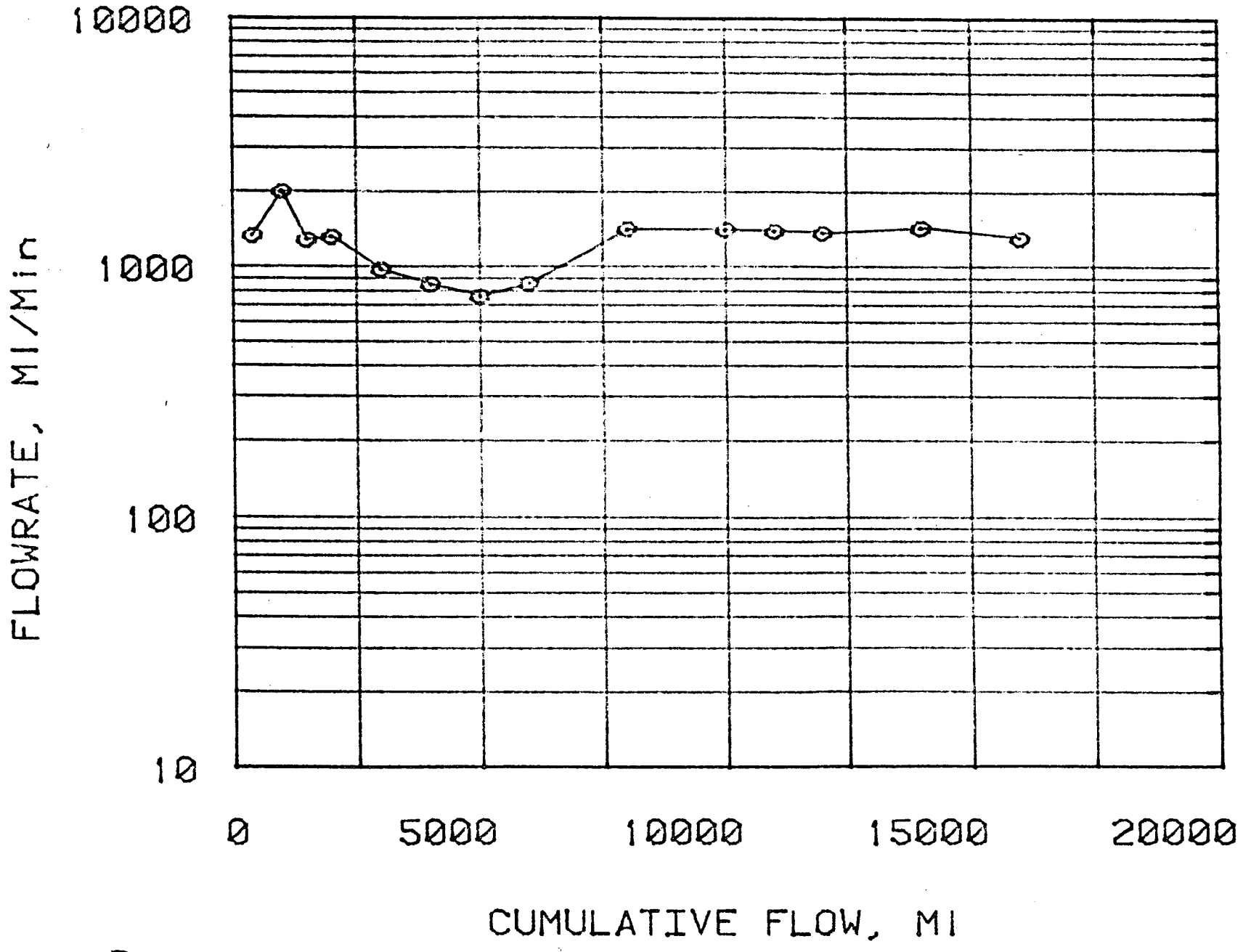
Source Press:3800 psig Run Press:400 psig Differential Press:5 psig

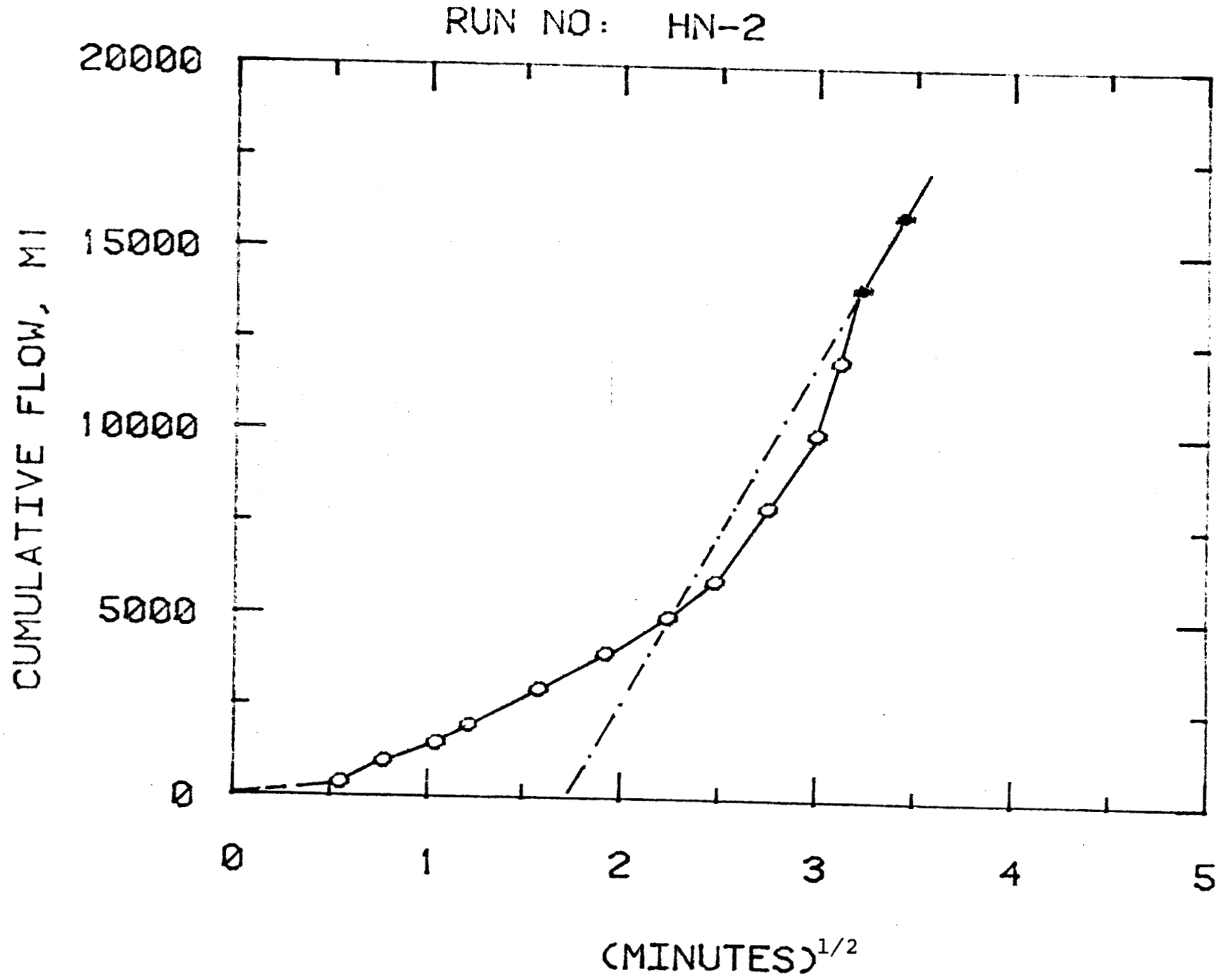
Source Temp:130°C Run Temp:128°C

Total Filtered Volume:19,300 ml Suspended Solids: 0.067 mg/l (0.061 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	.30	0.55	400	1333.3
2	.60	0.77	1000	2000.0
3	1.09	1.04	1500	1282.1
4	1.47	1.21	2000	1315.8
5	2.50	1.58	3000	970.9
6	3.68	1.92	4000	847.5
7	5.00	2.24	5000	757.6
8	6.17	2.48	6000	854.7
9	7.58	2.75	8000	1418.4
10	9.00	3.00	10000	1408.5
11	9.72	3.12	11000	1388.9
12	10.45	3.23	12000	1369.9
13	11.84	3.44	14000	1438.9
14	13.37	3.66	16000	1307.2

RUN NO: HN-2


10000
1000
100
10
FLOWRATE, MI/Min
0
5000
10000
15000
20000
CUMULATIVE FLOW, MI


RUN NO: HN-2
20000
15000
10000
5000
0
CUMULATIVE FLOW, MI
0
1
2
3
4
5
(MINUTES)^1/2

INJECTABILITY TEST DATA

Run: HN-3 Membrane Filter: 0.4-μm 1-μm Cuno Prefilter: No

Source Press: 3800 psig Run Press: 1000 psig Differential Press: 70 psig

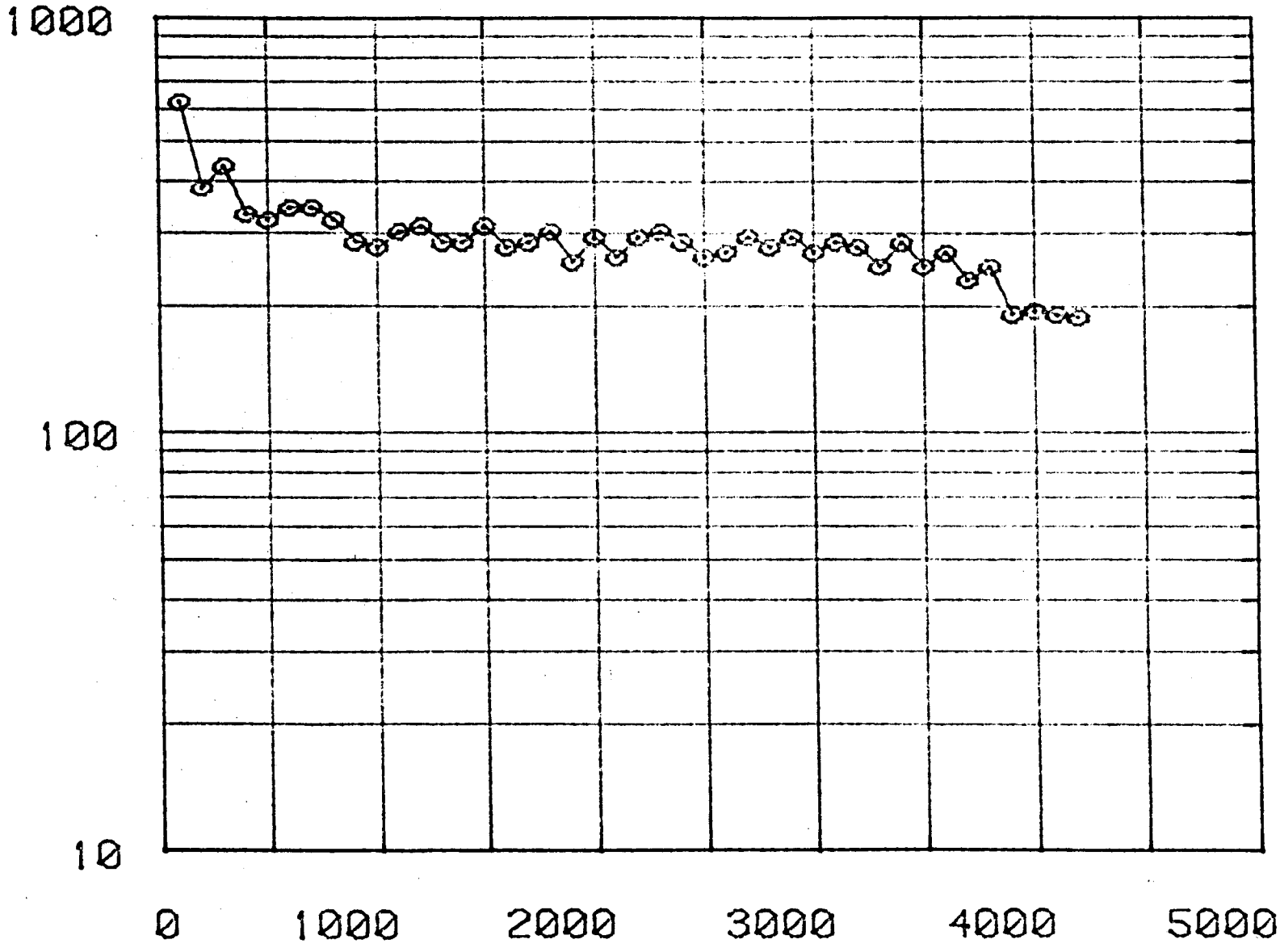
Source Temp: 130°C Run Temp: 119°C

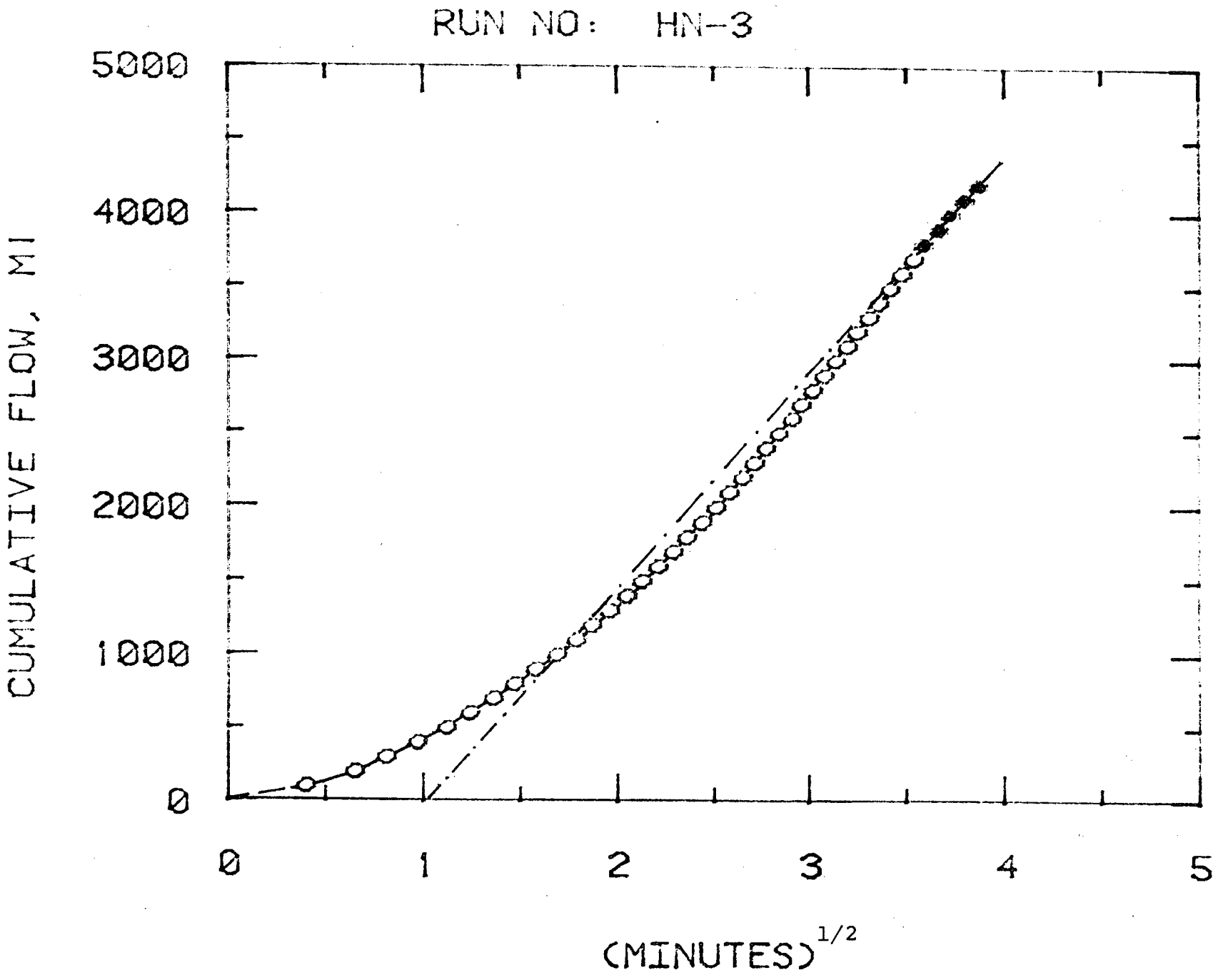
Total Filtered Volume: 4320 ml Suspended Solids: 0.69 mg/l (0.63 μg/g)

ITEM	Time(min)	√Min	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.16	0.40	100	625.0
2	0.42	0.65	200	384.6
3	0.65	0.81	300	434.8
4	0.95	0.97	400	333.3
5	1.26	1.12	500	322.6
6	1.55	1.24	600	344.8
7	1.84	1.36	700	344.8
8	2.15	1.47	800	322.6
9	2.50	1.58	900	285.7
10	2.86	1.69	1000	277.8
11	3.19	1.79	1100	303.0
12	3.51	1.87	1200	312.5
13	3.86	1.96	1300	285.7
14	4.21	2.05	1400	285.7
15	4.53	2.13	1500	312.5
16	4.89	2.21	1600	277.8
17	5.24	2.29	1700	285.7
18	5.57	2.36	1800	303.0
19	5.96	2.44	1900	256.4
20	6.30	2.51	2000	294.1
21	6.68	2.58	21000	263.2

ITEM	Time(min)	√Min	Cumulative Volume(ml)	Flow Rate (ml/min)
22	7.02	2.65	2200	294.1
23	7.35	2.71	2300	303.0
24	7.70	2.77	2400	285.7
25	8.08	2.84	2500	263.2
26	8.45	2.91	2600	270.3
27	8.79	2.96	2700	294.1
28	9.15	3.02	2800	277.8
29	9.49	3.08	2900	294.1
30	9.86	3.14	3000	270.3
31	10.21	3.20	3100	285.7
32	10.57	3.25	3200	277.8
33	10.97	3.31	3300	250.0
34	11.32	3.36	3400	285.7
35	11.72	3.42	3500	250.0
36	12.09	3.48	3600	270.3
37	12.52	3.54	3700	232.6
38	12.92	3.59	3800	250.0
39	13.44	3.67	3900	192.3
40	13.95	3.73	4000	196.1
41	14.47	3.80	4100	192.3
42	15.00	3.87	4200	188.7

RUN NO: HN-3


1000
100
10
FLOWRATE, MI/Min
0
1000
2000
3000
4000
5000
CUMULATIVE FLOW, MI


RUN NO: HN-3
5000
4000
3000
2000
1000
0
CUMULATIVE FLOW, MI
0
1
2
3
4
5
(MINUTES)^1/2

INJECTABILITY TEST DATA

Run: HN-4 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: No

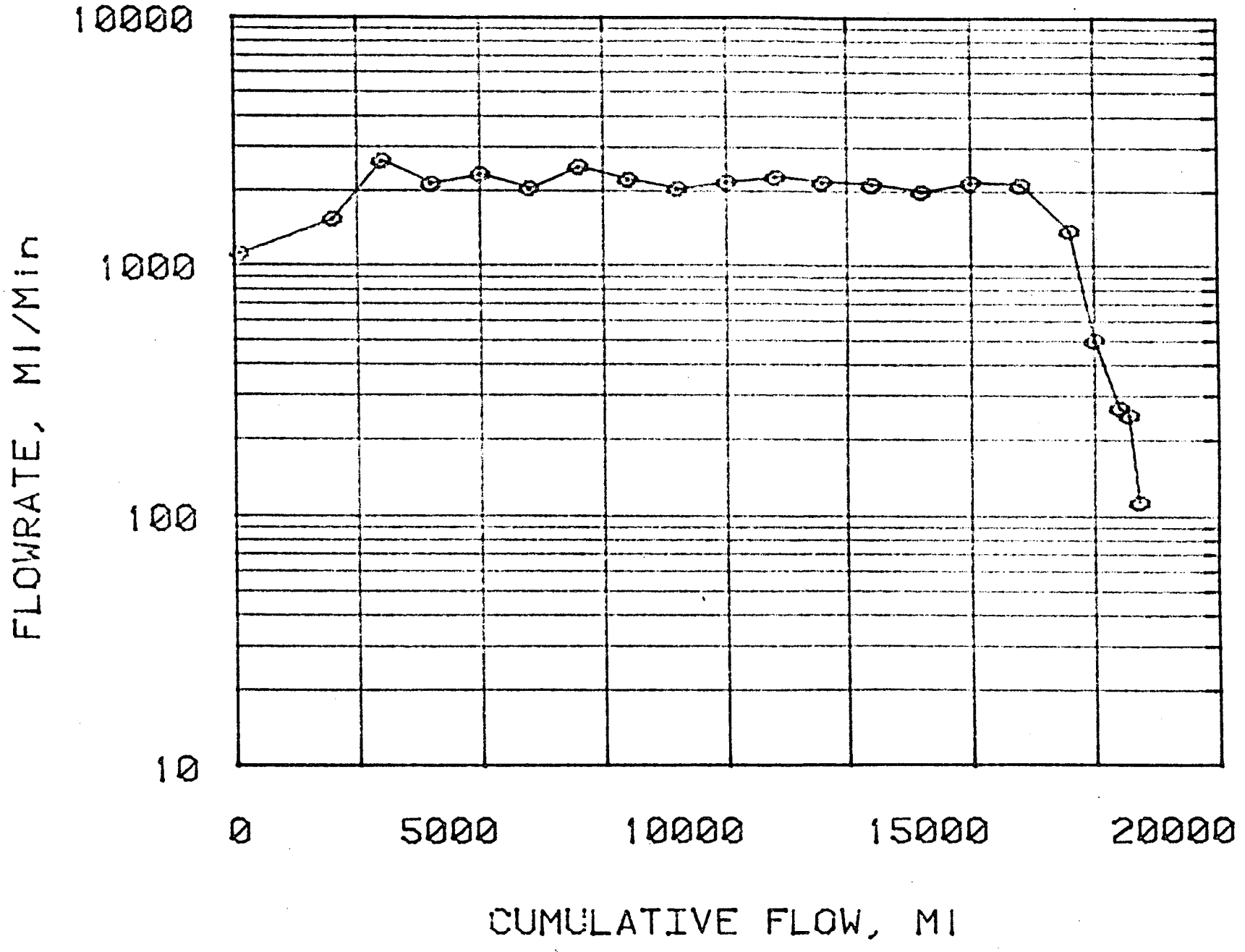
Source Press: 3800 psig Run Press: 1000 psig Differential Press: 0.1 psig

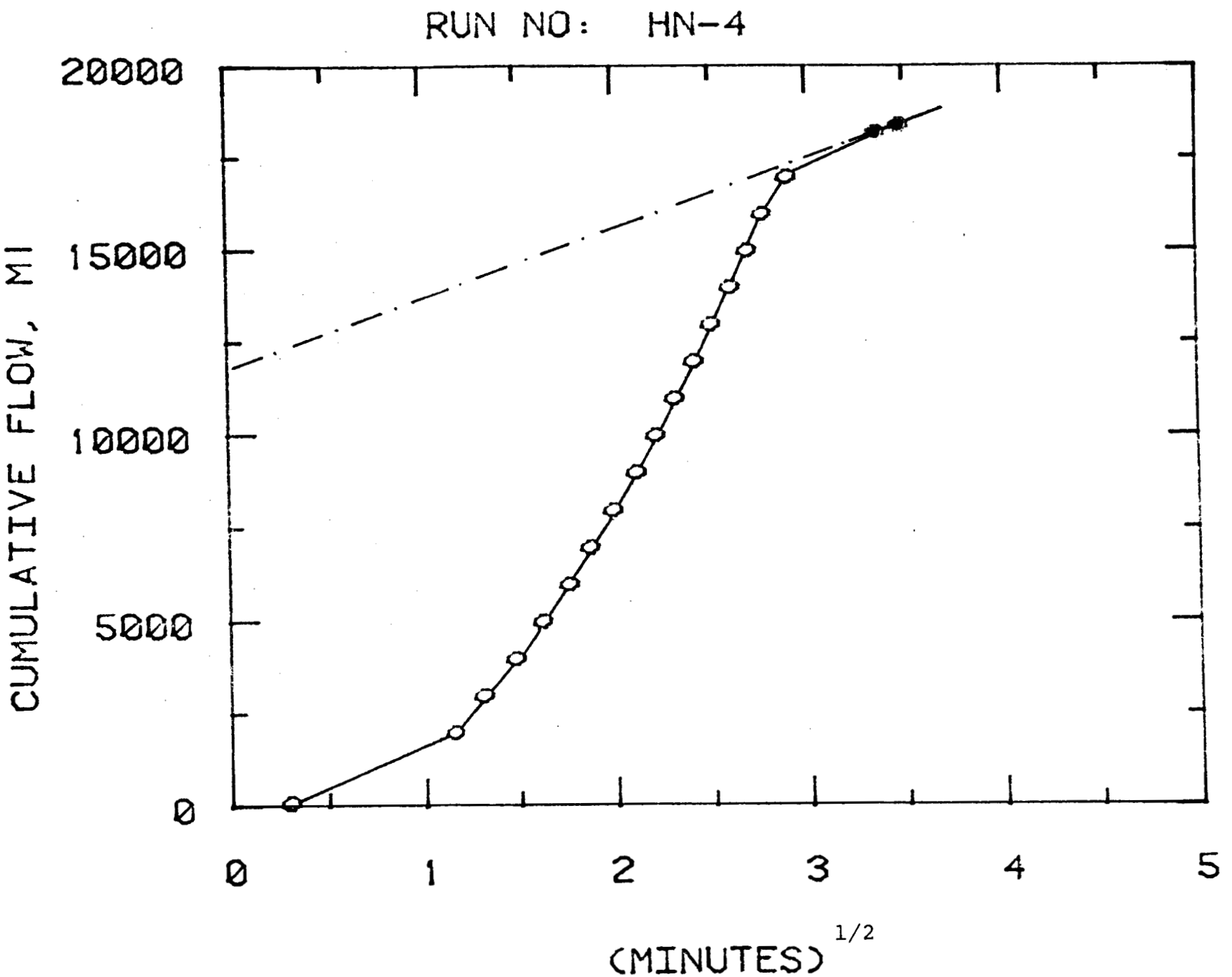
Source Temp: 130°C Run Temp: 130°C

Total Filtered Volume: 13,540 ml Suspended Solids: 0.27 mg/l (0.25 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.09	0.30	100	1111.1
2	1.33	1.15	2000	1532.3
3	1.71	1.31	3000	2631.6
4	2.18	1.48	4000	2127.7
5	2.61	1.62	5000	2325.6
6	3.10	1.76	6000	2040.8
7	3.50	1.87	7000	2500.0
8	3.95	1.99	8000	2222.2
9	4.44	2.11	9000	2040.8
10	4.90	2.21	10000	2173.9
11	5.34	2.31	11000	2272.7
12	5.80	2.41	12000	2173.9
13	6.27	2.50	13000	2127.7
14	6.77	2.60	14000	2000.0
15	7.23	2.69	15000	2173.9
16	7.70	2.77	16000	2127.7
17	8.42	2.90	17000	1388.9
18	9.42	3.07	17500	500.0
19	11.28	3.36	18000	268.8
20	12.08	3.48	18200	250.0
21	13.84	3.72	18400	113.6

RUN NO: HN-4


10000
1000
100
10
FLOWRATE, MI/Min
0
5000
10000
15000
20000
CUMULATIVE FLOW, MI


RUN NO: HN-4
20000
15000
10000
5000
0
CUMULATIVE FLOW, MI
0
1
2
3
4
5
(MINUTES)^1/2

INJECTABILITY TEST DATA

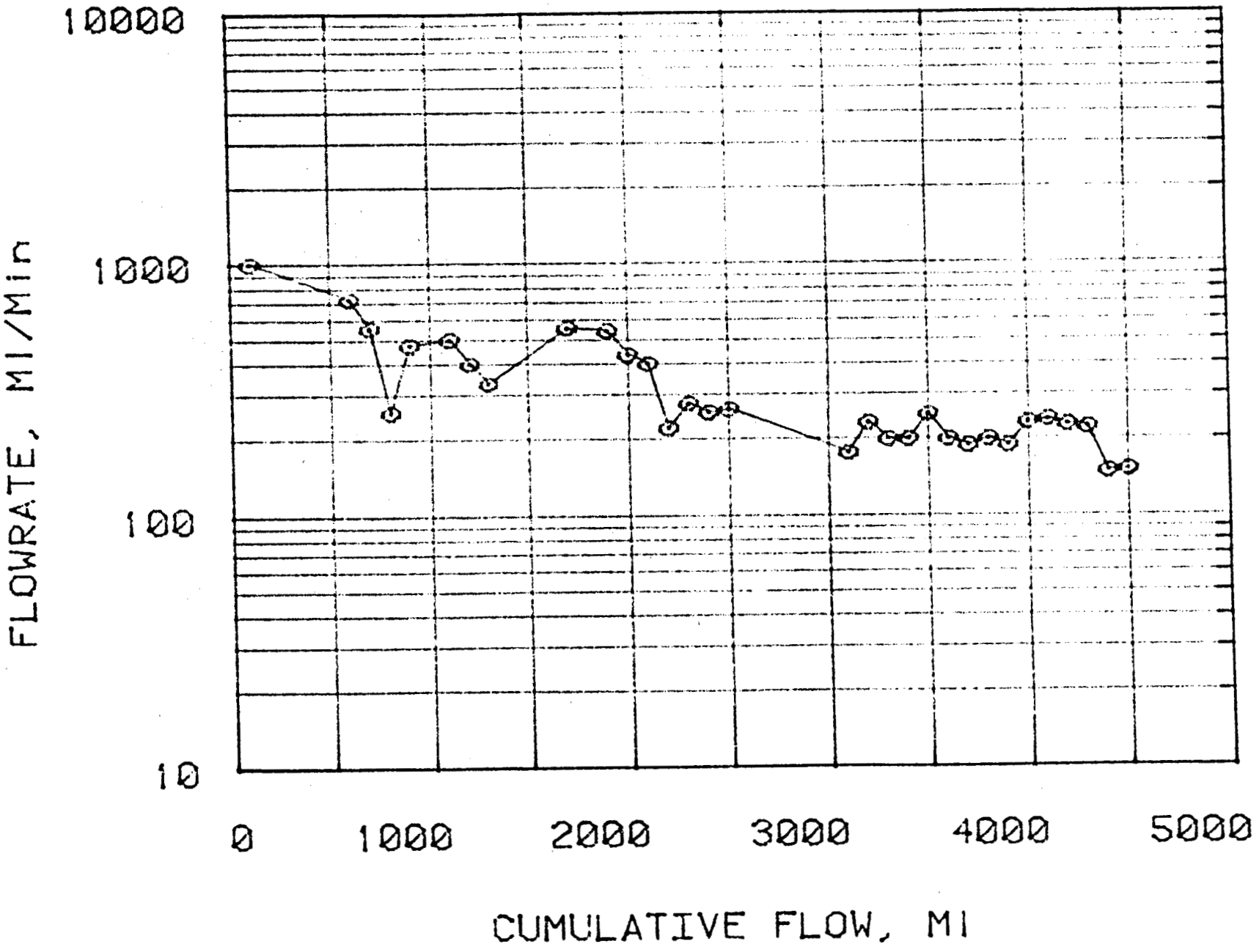
Run: HN-5 Membrane Filter: 0.4-μm 1-μm Cuno Prefilter: No

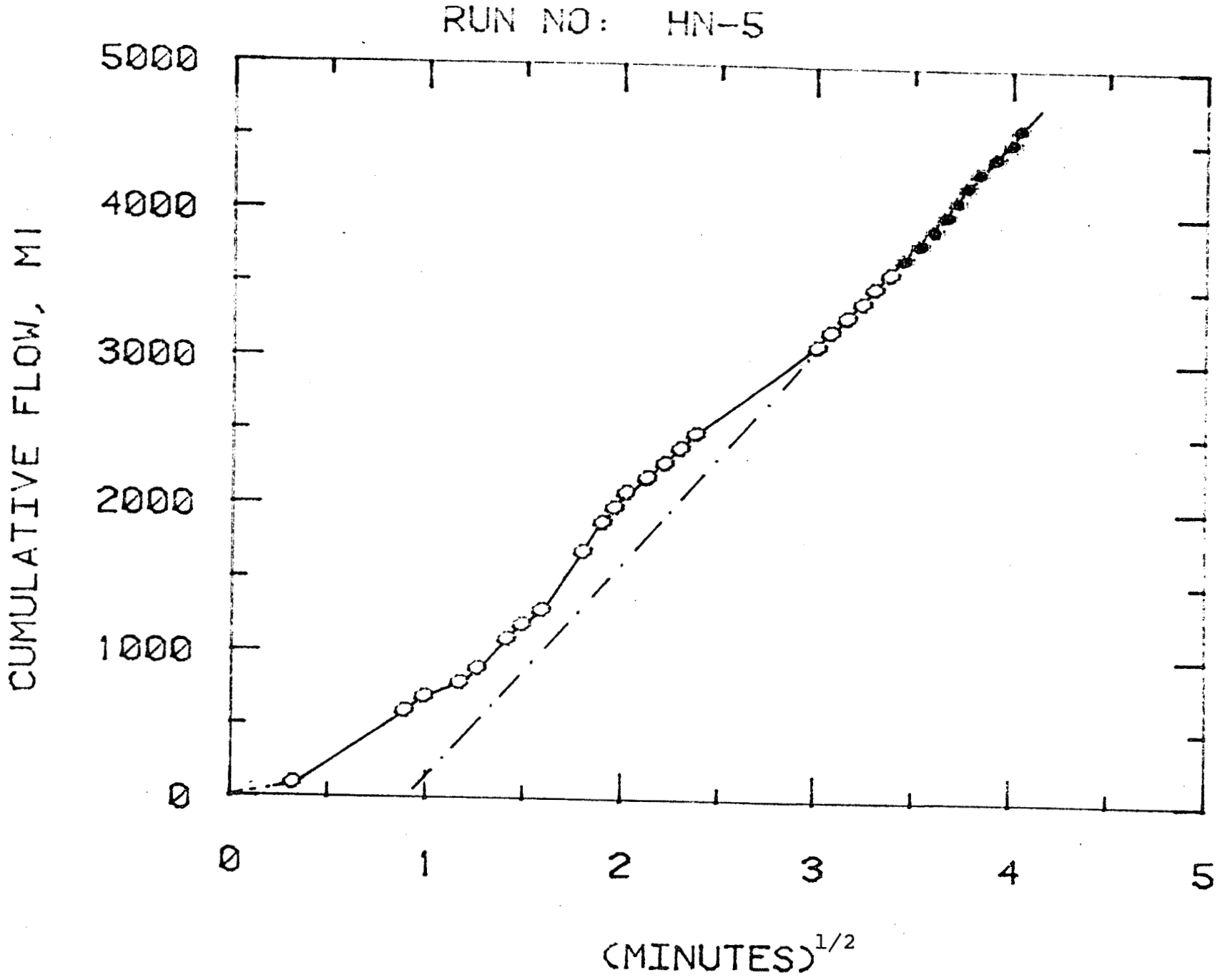
Source Press:3800 psig Run Press:1800 psig Differential Press:50 psig

Source Temp:130°C Run Temp:120°C

Total Filtered Volume:4620 ml Suspended Solids: 1.3 mg/l (1.2 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.10	0.32	100	1000.0
2	0.79	0.89	600	724.6
3	0.98	0.99	700	555.6
4	1.37	1.17	800	256.4
5	1.58	1.26	900	476.2
6	1.98	1.41	1100	500.0
7	2.23	1.49	1200	400.0
8	2.53	1.59	1300	333.3
9	3.25	1.80	1700	555.6
10	3.62	1.90	1900	540.5
11	3.85	1.96	2000	434.8
12	4.10	2.02	2100	400.0
13	4.55	2.13	2200	222.2
14	4.91	2.22	2300	277.8
15	5.30	2.30	2400	256.4
16	5.68	2.38	2500	263.2
17	9.07	3.01	3100	177.0
18	9.50	3.08	3200	232.6
19	10.00	3.16	3300	200.0
20	10.50	3.24	3400	200.0
21	10.90	3.30	3500	250.0
22	11.40	3.38	3600	200.0
23	11.93	3.45	3700	188.7
24	12.43	3.53	3800	200.0
25	12.96	3.60	3900	188.7
26	13.39	3.66	4000	232.6
27	13.81	3.72	4100	238.1
28	14.25	3.77	4200	227.3
29	14.70	3.83	4300	222.2
30	15.37	3.92	4400	149.3
31	16.03	4.00	4500	151.5
32	16.35	4.04	4600	312.5


RUN NO: HN-5
10000
1000
100
10
FLOWRATE, MI/Min
0
1000
2000
3000
4000
5000
CUMULATIVE FLOW, MI


RUN NO: HN-5
CUMULATIVE FLOW, MI
5000
4000
3000
2000
1000
0
0
1
2
3
4
5
(MINUTES)^1/2

INJECTABILITY TEST DATA

Run: HN-6 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: No

Source Press: 3800 psig Run Press: 1800 psig Differential Press: 1 psig

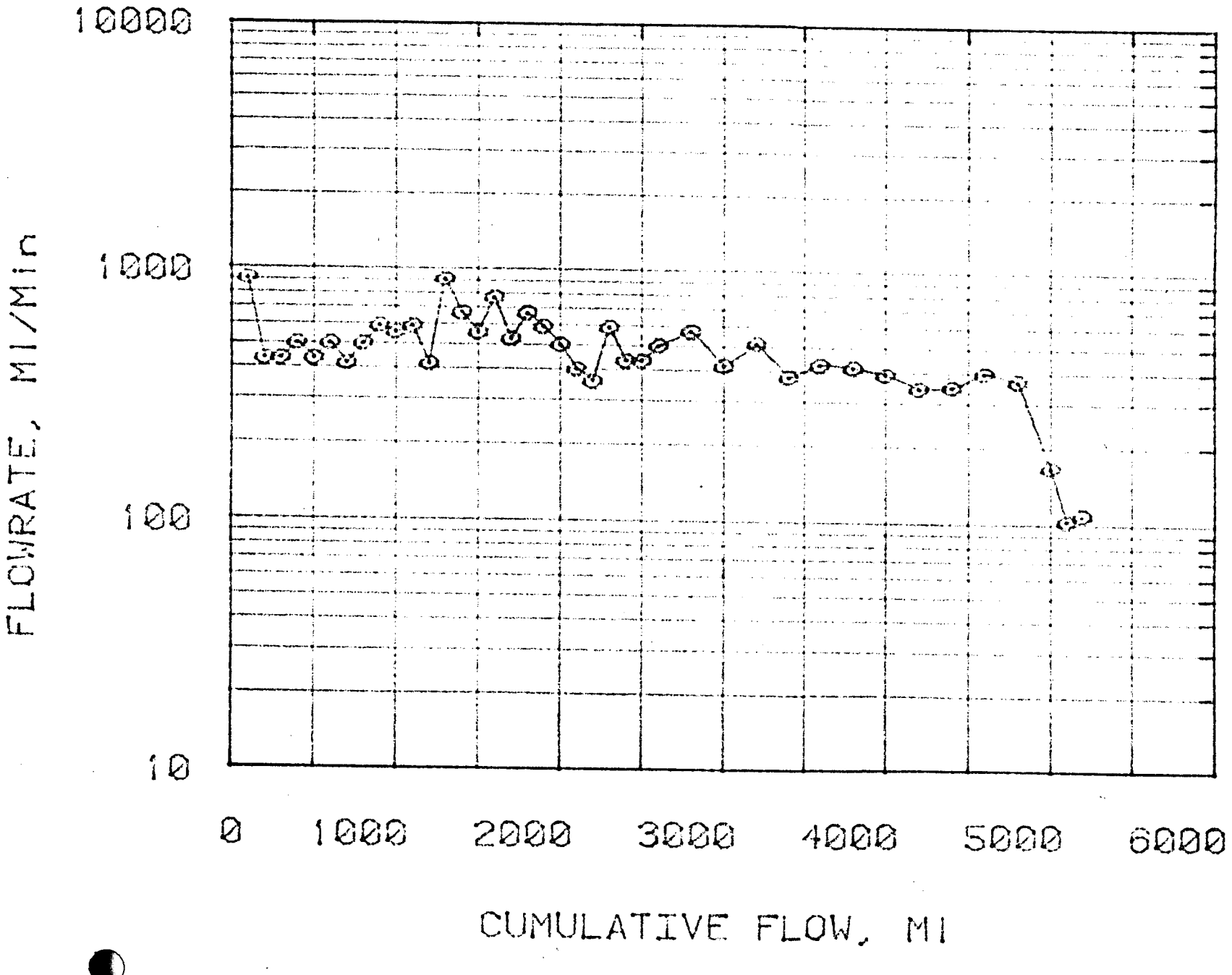
Source Temp: 130°C Run Temp: 123°C

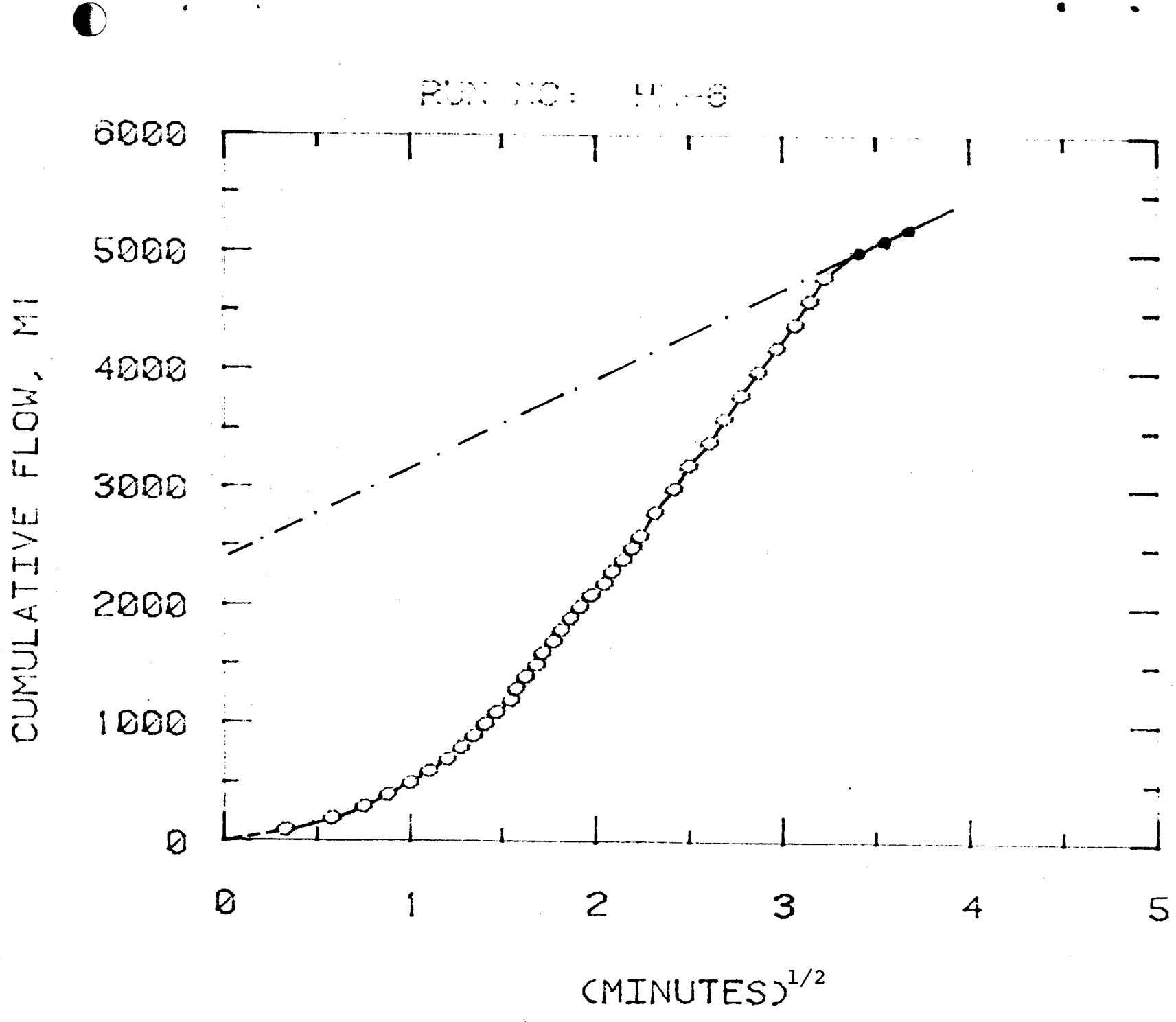
Total Filtered Volume: 5360 ml Suspended Solids: 1.3 mg/l (1.2 μg/g)

ITEM	Time(min)	√Min	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.11	0.33	100	909.1
2	0.34	0.58	200	434.8
3	0.57	0.75	300	434.8
4	0.77	0.88	400	500.0
5	1.00	1.00	500	434.8
6	1.20	1.10	600	500.0
7	1.44	1.20	700	416.7
8	1.64	1.28	800	500.0
9	1.81	1.35	900	588.2
10	1.99	1.41	1000	555.6
11	2.16	1.47	1100	588.2
12	2.40	1.55	1200	416.7
13	2.51	1.58	1300	909.1
14	2.66	1.63	1400	666.7
15	2.84	1.69	1500	555.6
16	2.97	1.72	1600	769.2
17	3.16	1.78	1700	526.3
18	3.31	1.82	1800	666.7
19	3.48	1.87	1900	588.2
20	3.68	1.92	2000	500.0

ITEM	Time(min)	√Min	Cumulative Volume(ml)	Flow Rat (ml/min)
21	3.93	1.98	2100	400.0
22	4.21	2.05	2200	357.1
23	4.38	2.09	2300	588.2
24	4.61	2.15	2400	434.8
25	4.84	2.20	2500	434.8
26	5.04	2.24	2600	500.0
27	5.39	2.32	2800	571.4
28	5.87	2.42	3000	416.7
29	6.26	2.50	3200	512.8
30	6.79	2.61	3400	377.4
31	7.26	2.69	3600	425.5
32	7.74	2.78	3800	416.7
33	8.25	2.87	4000	392.2
34	8.83	2.97	4200	344.8
35	9.40	3.07	4400	350.9
36	9.90	3.15	4600	400.0
37	10.44	3.23	4800	370.4
38	11.63	3.41	5000	168.1
39	12.60	3.55	5100	103.1
40	13.52	3.68	5200	108.7

RUN NO: HN-6


10000
1000
100
10
FLOWRATE, Ml/Min
0
1000
2000
3000
4000
5000
6000
CUMULATIVE FLOW, Ml


RUN NO: M1-6
6000
5000
4000
3000
2000
1000
0
CUMULATIVE FLOW, Ml
0
1
2
3
4
5
(MINUTES)1/2

INJECTABILITY TEST DATA

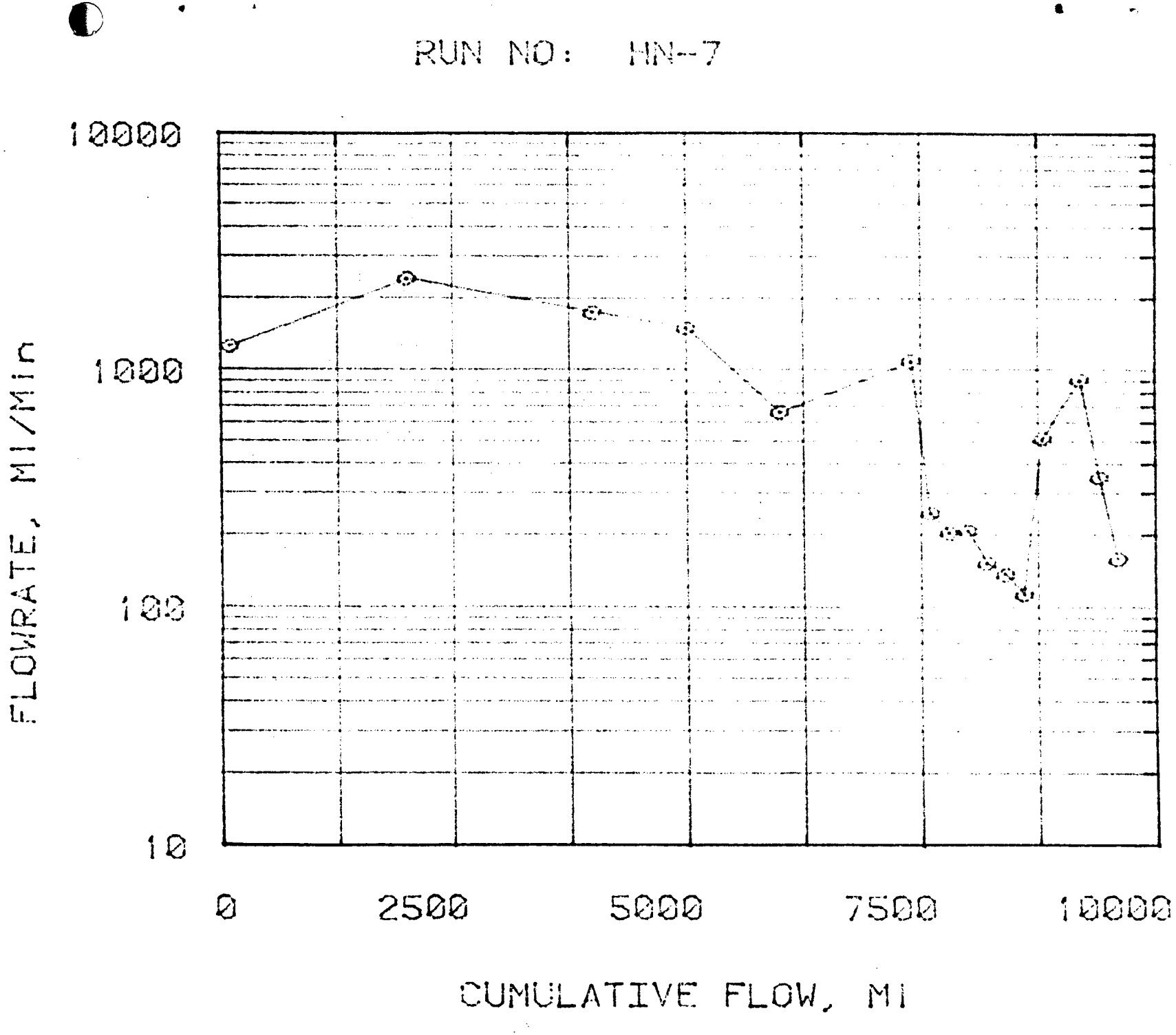
Run: HN-7 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: No

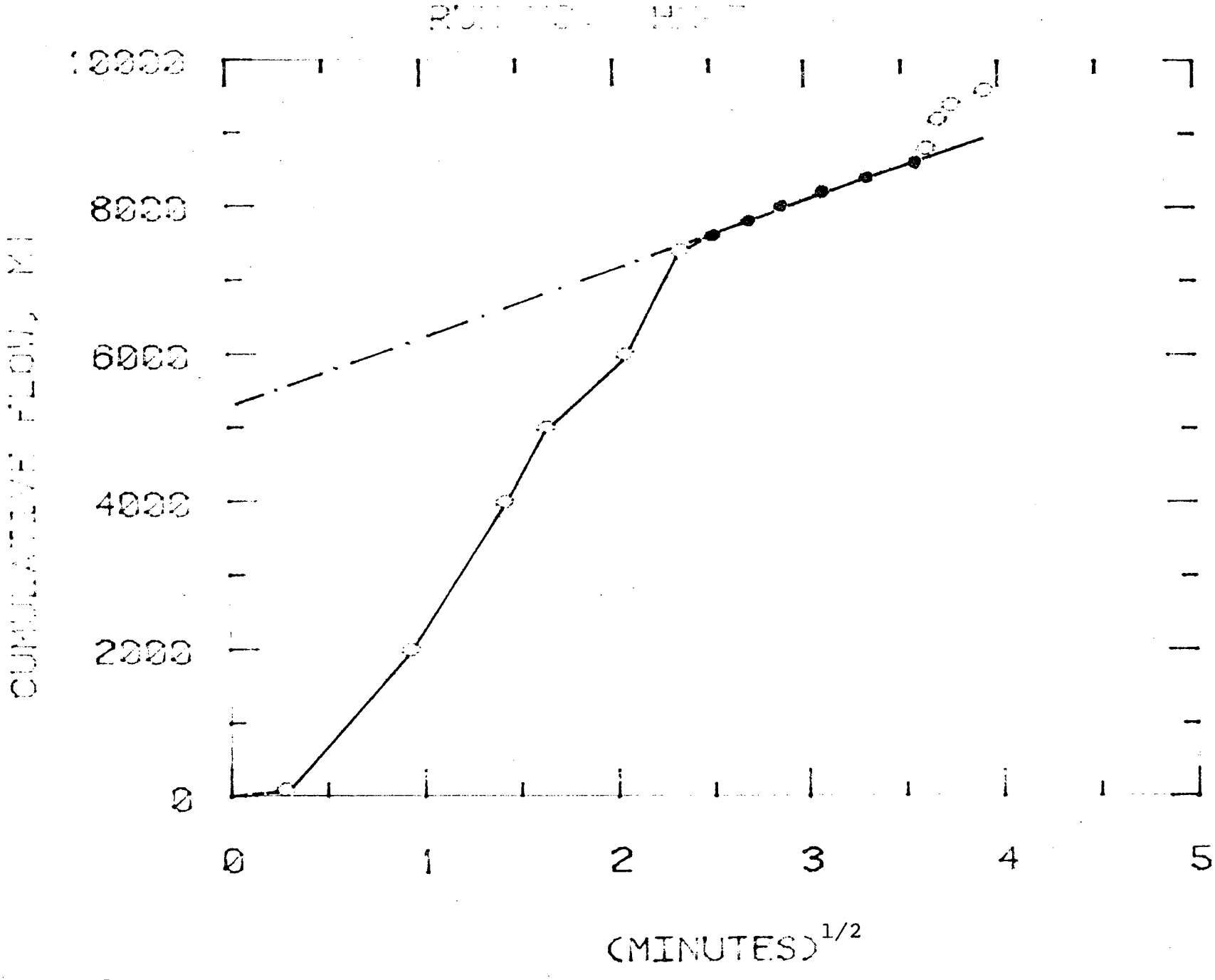
Source Press:3800 psig Run Press:1500 psig Differential Press:20 psig

Source Temp:130°C Run Temp:125°C

Total Filtered Volume:10,110 ml Suspended Solids: 0.41 mg/l (0.37 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.08	0.28	100	1250.0
2	0.87	0.93	2000	2405.1
3	2.02	1.42	4000	1739.1
4	2.69	1.64	5000	1492.5
5	4.20	2.05	6000	662.3
6	5.48	2.34	7400	1093.8
7	6.29	2.51	7600	246.9
8	7.27	2.70	7800	204.1
9	8.23	2.87	8000	208.3
10	9.54	3.09	8200	152.7
11	11.00	3.32	8400	137.0
12	12.77	3.57	8600	113.0
13	13.16	3.63	8800	512.8
14	13.60	3.69	9200	909.1
15	14.17	3.76	9400	350.9
16	15.43	3.93	9600	158.7


RUN NO: HN-7
10000
1000
100
10
FLOWRATE, Ml/Min
0
2500
5000
7500
10000
CUMULATIVE FLOW, Ml


10000
8000
6000
4000
2000
0
0
1
2
3
4
5
(MINUTES)^1/2

INJECTABILITY TEST DATA

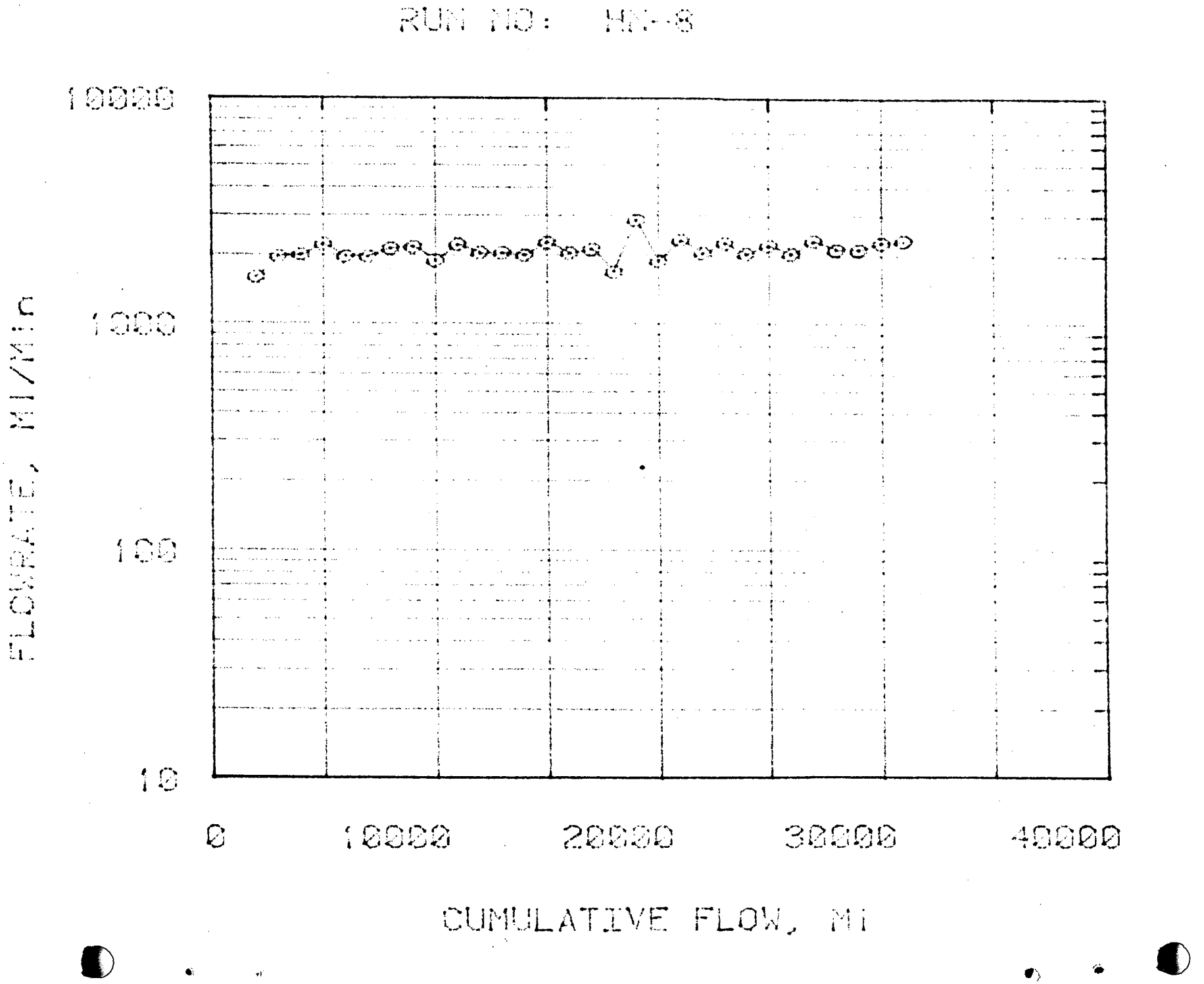
Run: HN-8 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: No

Source Press: 3800 psig Run Press: 1000 psig Differential Press: <0.1 psig

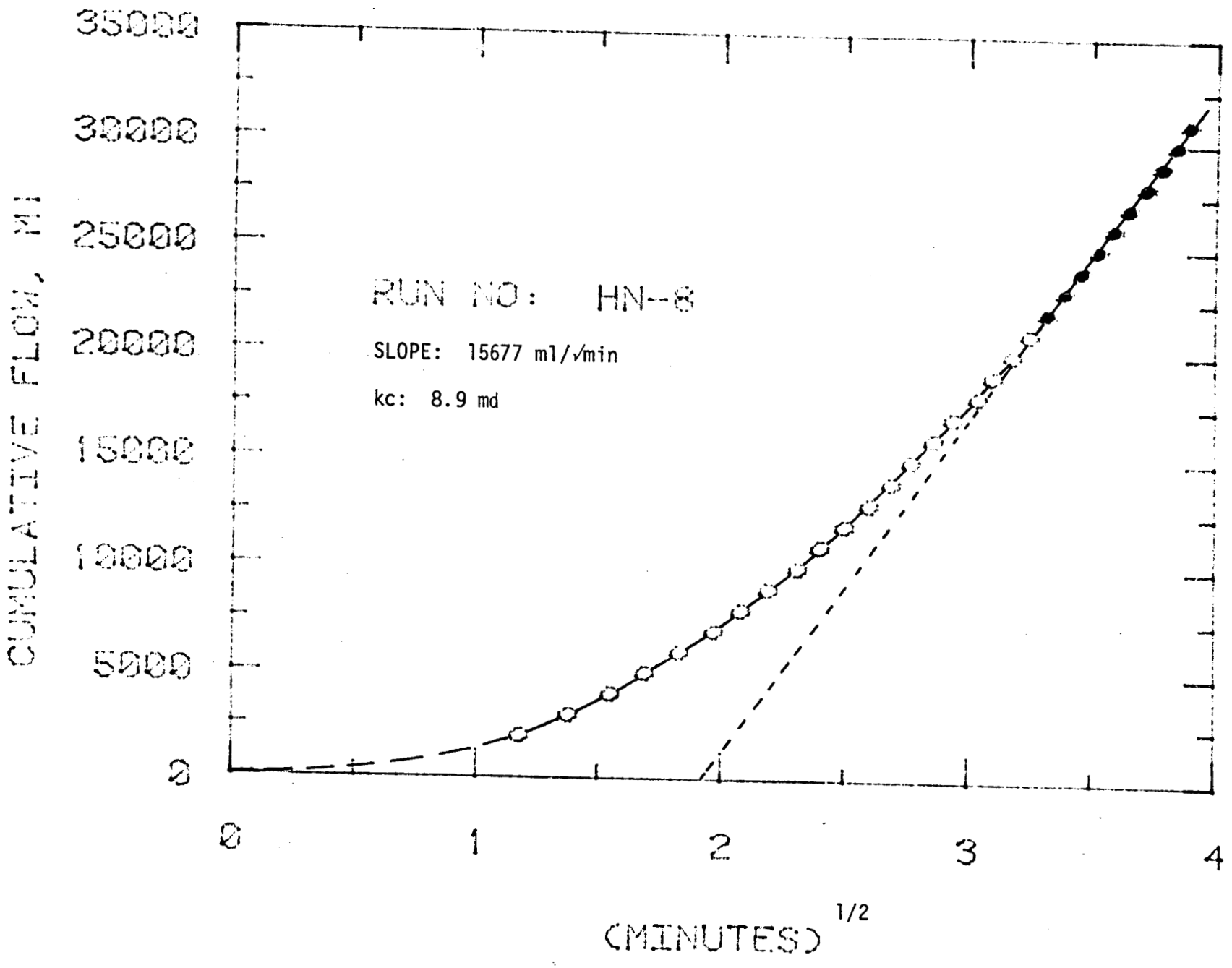
Source Temp: 130°C Run Temp: 129°C

Total Filtered Volume: 31,000 ml Suspended Solids: 0.026 mg/l (0.024 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	1.39	1.18	2000	1596.6
2	1.90	1.38	3000	1960.8
3	2.40	1.55	4000	2000.0
4	2.85	1.69	5000	2222.2
5	3.36	1.83	6000	1960.8
6	3.87	1.97	7000	1960.8
7	4.34	2.08	8000	2127.7
8	4.80	2.19	9000	2173.9
9	5.33	2.31	10000	1886.8
10	5.78	2.40	11000	2222.2
11	6.27	2.50	12000	2040.8
12	6.76	2.60	13000	2040.8
13	7.26	2.69	14000	2000.0
14	7.70	2.77	15000	2272.7
15	8.19	2.86	16000	2040.8
16	8.66	2.94	17000	2127.7
17	9.25	3.04	18000	1694.9
18	9.60	3.10	19000	2857.1
19	10.13	3.18	20000	1886.8
20	10.56	3.25	21000	2325.6
21	11.05	3.32	22000	2040.8
22	11.49	3.39	23000	2272.7
23	11.98	3.46	24000	2040.8
24	12.43	3.53	25000	2222.2
25	12.92	3.59	26000	2040.8
26	13.35	3.65	27000	2325.6
27	13.82	3.72	28000	2127.7
28	14.29	3.78	29000	2127.7
29	14.73	3.84	30000	2272.7
30	15.16	3.89	31000	2325.6


RUN NO: HN-8
10000
1000
100
10
FLOWRATE, Ml/Min
0
10000
20000
30000
40000
CUMULATIVE FLOW, Ml

FILTRATION CURVE WITHOUT INVASION



INJECTABILITY TEST DATA

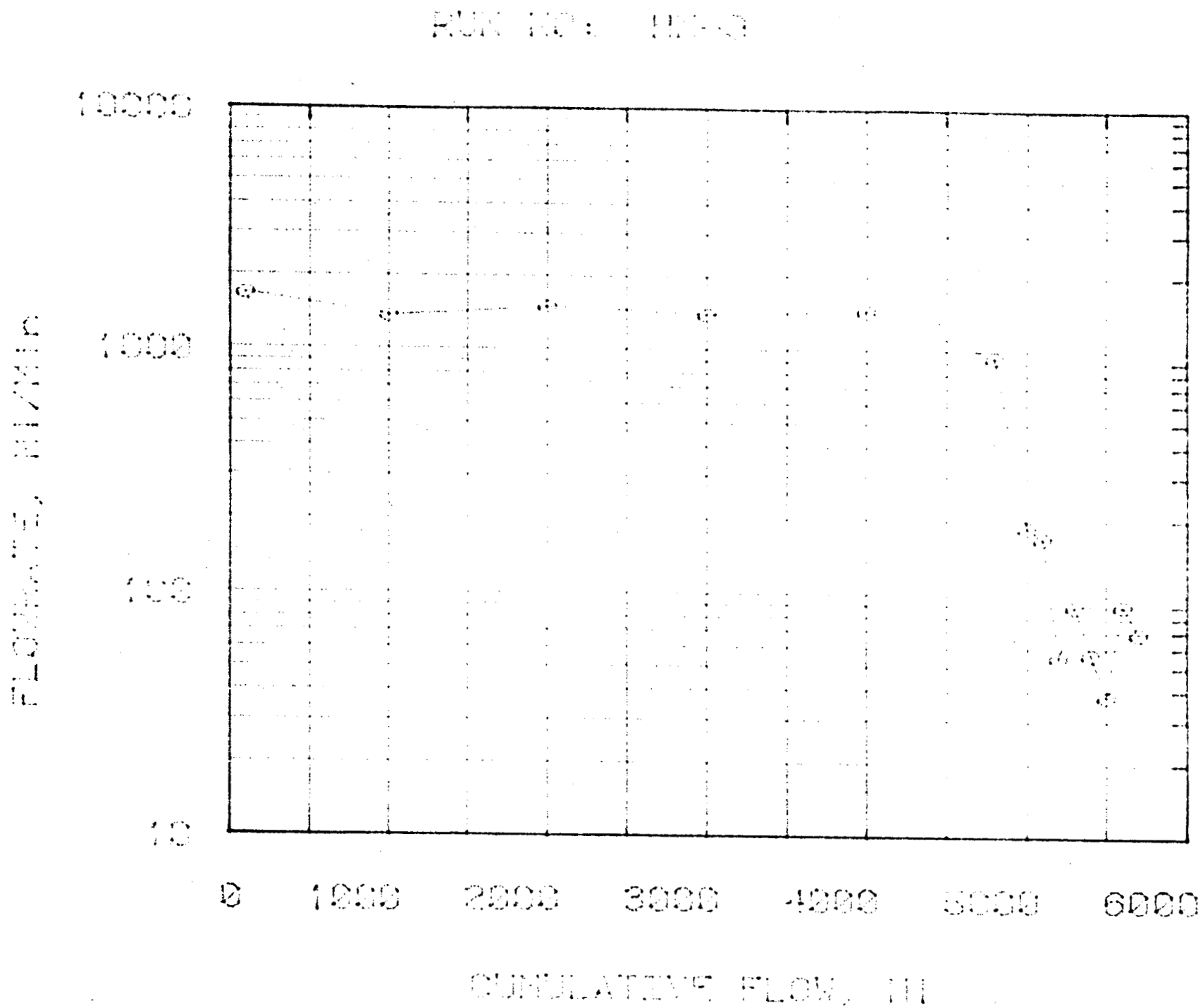
Run: HN-9 Membrane Filter: 10.0-μm 1-μm Cuno Prefilter: No

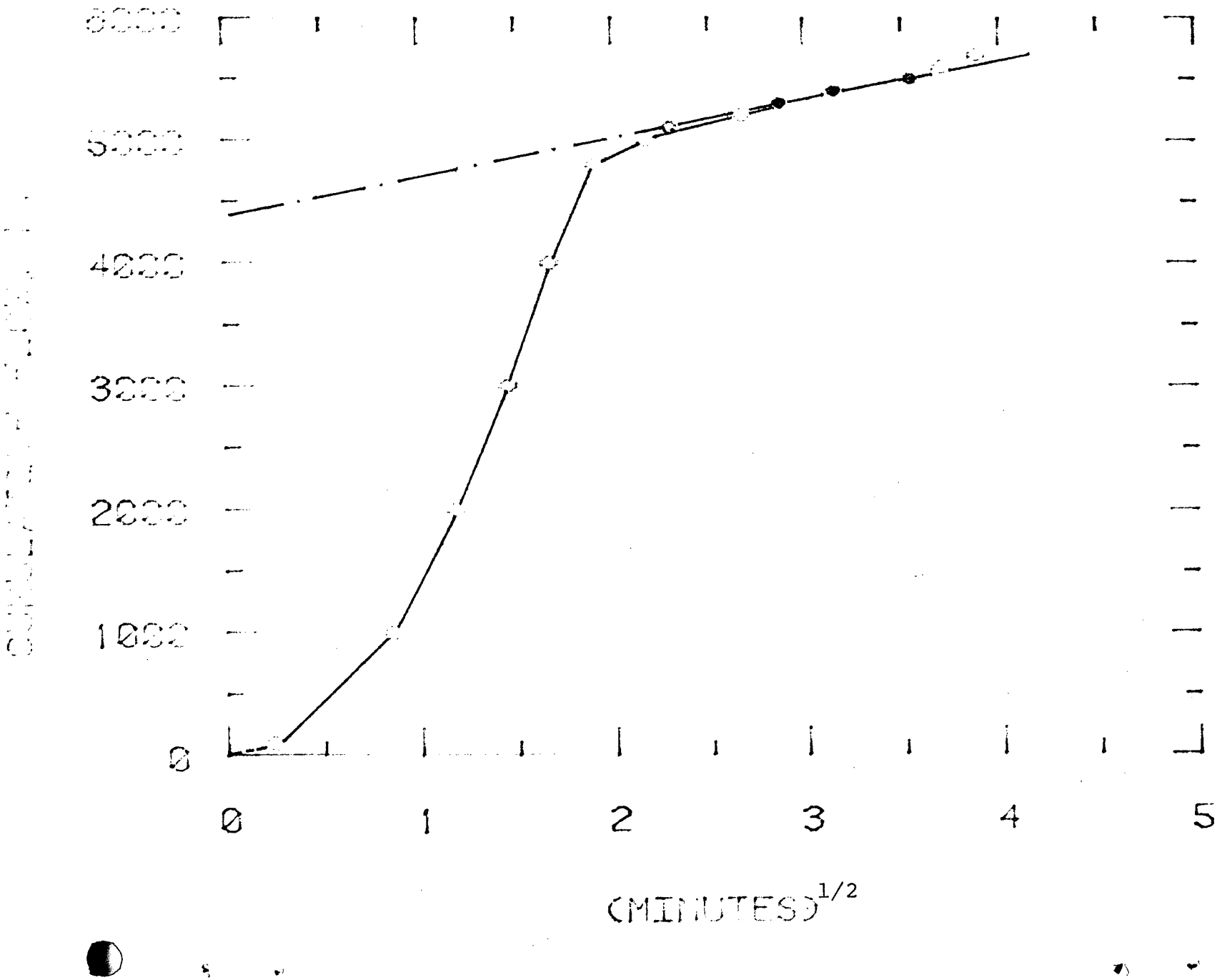
Source Press: 3800 psig Run Press: 1000 psig Differential Press: 1 psig

Source Temp: 130°C Run Temp: 127°C

Total Filtered Volume: 5850 ml Suspended Solids: 0.48 mg/l (0.44 μg/g)

ITEM	Time(min)	$\sqrt{\text{Min}}$	Cumulative Volume(ml)	Flow Rate (ml/min)
1	0.06	0.24	100	1666.7
2	0.72	0.85	1000	1363.6
3	1.39	1.18	2000	1492.5
4	2.11	1.45	3000	1388.9
5	2.80	1.67	4000	1449.3
6	3.65	1.91	4800	941.2
7	4.72	2.17	5000	186.9
8	5.31	2.30	5100	169.5
9	7.12	2.67	5200	55.3
10	8.24	2.87	5300	89.3
11	10.00	3.16	5400	56.8
12	12.62	3.55	5500	38.2
13	13.73	3.71	5600	90.1
14	15.17	3.89	5700	69.4


10000
1000
100
10
0
1000
2000
3000
4000
5000
6000


5000
4000
3000
2000
1000
0
0
1
2
3
4
5
(MINUTES)^1/2

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