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EVALUATION OF FLOW RATE OF 20-INCH-DIAMETER PERMEABILITY TEST SYSTEM

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16. ABSTRACT

Laboratory permeability tests on soils containing gravel that were performed using designation E-14 in the *Earth Manual* ("Permeability and Settlement of Soil Containing Gravel") showed what appeared to be inconsistent results when coefficients of hydraulic conductivity were determined at flow rates approaching the hydraulic conductivity limits of the test system. An evaluation of the flow rate of the test equipment showed a nonlinear flow rate with increasing hydraulic head. The evaluation identified inadequacies in the existing equipment and provided a method for evaluating the reliability of test results when the hydraulic conductivity of the soil approaches the hydraulic conductivity limit of the test system.

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by

Traver E. Metcalf, Jr.

Geotechnical Branch
Division of Research and Laboratory Services
Engineering and Research Center
Denver, Colorado

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

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INTRODUCTION

Laboratory permeability tests on soils containing gravel that were performed using designation E-14 in the *Earth Manual* [1]* (''Permeability and Settlement of Soil Containing Gravel'') showed what appeared to be inconsistent results when coefficients of hydraulic conductivity were determined at flow rates approaching the hydraulic conductivity limit of the test system. Although this behavior was noted before, the specific reasons for the inconsistency were not investigated or documented.

The primary problem with the test data appears in the form of decreasing calculated coefficients of hydraulic conductivity as the hydraulic gradient is increased. Although this appears unreasonable, it occurs because the test system operates at a flow rate where a linear flow rate versus hydraulic head relationship does not exist because of the test equipment configuration. To illustrate this behavior, a brief evaluation of the flow rate of the test equipment was performed, and the results were compared with results from an actual permeability test. This information was useful in identifying inadequacies in the existing test apparatus, and it provides the basis for guidelines used to evaluate the results of permeability tests.

CONCLUSIONS

The flow rate of the test apparatus defines the maximum coefficients of hydraulic conductivity that can be measured for any soil. Because the flow rate of the test equipment does not increase proportionally with increasing hydraulic gradient (hydraulic head), it is not possible to obtain consistent coefficients of hydraulic conductivity with increasing hydraulic gradients when the soil permeability exceeds the flow rate of the test system under the highest hydraulic gradient tested. Therefore, the flow rate of the test system under various hydraulic gradients can be used to (1) establish the validity of test data and (2) serve as an indicator if meaningful data will be provided by continuing the test.

The flow rate of the existing permeability test apparatus (using straight tees) allows measurement of coefficients of hydraulic conductivity up to approximately 30,000 ft/yr (3×10^{-2} cm/s). The test equipment, including the constant head supply tank, water supply system, and the permeameter cylinder, would have to be completely redesigned to accommodate flow rates for measuring significantly larger coefficients of hydraulic conductivity.

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* Numbers in brackets refer to entries in the bibliography.

DISCUSSION

Flow rate characteristics of the test apparatus were determined to identify (1) flow rates of the various components of the test apparatus and (2) the impact of flow rate on the coefficients of hydraulic conductivity calculated from the measured flow rates.

The 20-inch-diameter permeability equipment used in this study is shown on figure 1. The flow rate of the system was evaluated progressively, beginning with only the constant head water supply tank and a length of flexible tubing, and ending with the entire test system, including all tubing, fittings, and equipment involved in measuring the flow rate of a soil (using a spacing ring instead of a soil specimen). The components of the system were progressively tested in the configurations listed below:

1. Head tank plus 53½ inches of flexible tubing (½-inch i.d.)
2. Plus tee No. 1
3. Plus 36 inches of flexible tubing (½-inch i.d.)
4. Plus tee No. 2 and two pieces of flexible tubing, each 47 inches long (½-inch i.d.)
5. Plus permeameter cylinder
6. Plus pea gravel porous base
7. Plus top porous stone plus loading plate
   (Includes components 1 through 6 and 7)
8. Plus top porous gravel plus loading plate
   (Includes components 1 through 6 and 8)

The maximum hydraulic flow rate though the system was desired. Therefore, a pea gravel base was used instead of a porous stone base because gravel has greater conductivity.

The flow rate of the test system was measured progressively. Test data were recorded, and the flow rate was determined in milliliters per second.

The flow rate of the test system was measured at hydraulic heads of 0.75, 1.50, 2.25, and 3.0 feet; which correspond with hydraulic gradients of 1, 2, 3, and 4, assuming a 9-inch-high soil specimen is actually tested in the system.

The flow rate versus hydraulic gradient plots for configurations 1, 2, 3, 4, 5, 7, and 8 are shown on figure 2.

Results

The flow rate versus hydraulic gradient test data show a significant decrease in flow rate when the first tee is inserted into the system (configuration 2, fig. 2). Results also show additional decreases in the flow rate when the second tee, tubing, permeameter cylinder, porous media, and loading plate are added to the system. However, the impact of each of these items on the flow rate of the test system is very small compared with the decrease associated with the first tee.

When the head tank, plumbing components, and permeameter cylinders of all other test apparatus were inspected, it was discovered that these systems used a different type of tee from the one used in the apparatus being evaluated. The test apparatus being evaluated used plastic insert (tapered) tees that had an orifice of approximately ⅛ inch diameter (this tee is referred to as a reduction tee). However, the other apparatus used ½-inch-i.d. copper pipe tees with short sections of pipe soldered to each branch (this tee is referred to as a straight tee). The two types of tees are shown on figure 3.

The impact of the straight tee on the flow rate was determined by replacing the reduction tees in the original system with straight tees and again progressively measuring the flow rate of the system. The results of these tests (fig. 4) also show a reduction in flow rate upon addition of the first tee (configuration 2), but the magnitude of the reduction is significantly less. Additional decreases occur with the addition of the remaining tee, tubing, permeameter cylinder, porous media, and loading plates. Although each of these additional decreases is greater than the corresponding loss in the system with the reduction tee (because of higher flow rates and a correspondingly higher friction loss), the decrease in flow rate for a complete system (configurations 7 or 8) using the straight tees is significantly less than that for a complete system using reduction tees. The decreases in flow rates are shown on figure 5, for a partial system (configuration 2), and figure 6, for a complete system (configuration 8), and are summarized in table 1.

The flow rate of the test system decreased approximately 80 percent when the reduction tee was added to the head tank and flexible tubing. However, the flow rate of the test system decreased only about 20 percent when the straight tee was added to the system. Although adding components further decreased the flow rate of the system, the flow rate of the complete system

Table 1. – Flow rates, mL/s, for configurations 1, 2, and 8, using reduction tees and straight tees.

	Hydraulic gradient			
	1	2	3	4
Head tank plus tubing (configuration 1)	107.5	164.2	205.0	239.5
Head tank and tubing plus tee No. 1 (reduction) (configuration 2)	24.4 (22.7)*	33.7 (20.5)	43.4 (21.2)	51.7 (21.6)
Head tank plus complete system (reduction tee) (configuration 8)	17.5 (16.3)	27.5 (16.8)	34.6 (16.9)	39.6 (16.5)
Head tank and tubing plus tee No. 1 (straight) (configuration 2)	90.6 (84.3)	131.5 (80.1)	163.8 (79.9)	190.1 (79.4)
Head tank plus complete system (straight tee) (configuration 8)	50.0 (46.5)	76.0 (46.3)	101.4 (49.4)	121.4 (50.5)

* Numbers in parentheses indicate percent of configuration 1 flow.

using the straight tee was approximately 50 percent of initial capacity, much more than the approximately 17 percent for the complete system using the reduction tee.

The impact of the flow rate of the test system on calculated coefficients of hydraulic conductivity can be illustrated using actual test results.

A permeability test was performed on soil from Clark Canyon Dam using the same head tank, plumbing (with reduction tees), and permeameter cylinder used in the evaluation. A specimen from sample No. 20A-46 was placed in the cylinder on a porous gravel base and loaded using a porous stone attached to a loading plate. The results of this soil test are shown on figure 7 in the plot designated "test flow"; the plot of the equipment flow rate is designated "equipment flow." The line designated "theoretical flow" represents the flow rate required for a coefficient of hydraulic conductivity, at hydraulic gradients of 2 and 4, equivalent to that measured under the hydraulic gradient of 1.

Figure 7 clearly shows that the results obtained for the Clark Canyon Dam sample were influenced by the flow rate capacity of the test equipment. The results also show decreasing calculated coefficients of hydraulic conductivity with increasing hydraulic gradients. For these results, it is appropriate to report only the coefficient of hydraulic conductivity, 9,290 ft/yr obtained under the hydraulic gradient of 1, because under hydraulic gradients of 2 and 4, the measured coefficients of hydraulic conductivity were 7,020 and 4,920 ft/yr, respectively.

The decrease in the calculated coefficient of hydraulic conductivity with increasing hydraulic gradient results from the nonlinear flow rate of the test system caused by friction losses. Since the flow rate of the test system does not increase proportionally with the hydraulic gradient, the coefficient of hydraulic conductivity of the soil, as calculated using Darcy's law, decreases as shown below:

$$q = kia \tag{1}$$

where:

- q = flow rate (volume per time),
- k = coefficient of hydraulic conductivity (length per time),
- i = hydraulic gradient, and
- a = cross-sectional area through which flow occurs (length squared).

$$i = \frac{h}{l} \tag{2}$$

where:

- h = hydraulic head loss (length), and
- l = length of seepage path (length).

Thus, equation (1) may be rewritten:

$$q = k\left(\frac{h}{l}\right)a \tag{3}$$

Therefore:

$$k = \left(\frac{q}{h}\right)\left(\frac{l}{a}\right)$$

where $\frac{l}{a}$ is constant for a particular test configuration.

Since k is proportional to q/h, and q/h exhibits a decreasing slope with increasing h, calculated values of k decrease with increasing h. To provide guidelines for evaluating hydraulic conductivity coefficients determined using this equipment and to demonstrate the magnitude of restriction caused by the reduction fee, flow rates for the total test system (configuration 8 for both cases) are shown on figure 8. The calculated coefficient of hydraulic conductivity (expressed in ft/yr) for the system is shown in parentheses next to each maximum flow rate at each gradient. These results are summarized in table 2.

Table 2. – Equivalent coefficients of hydraulic conductivity.

Hydraulic gradient, *h/l*	Reduction tee, ft/yr	Straight tee, ft/yr
1.0	10,210	29,170
2.0	8,020	22,165
4.0	5,690	17,390

Using reduction tees in the water supply plumbing yielded a system flow rate that was approximately one-third that of the system with straight tees.

The flow rate of the system can be used as a guide to determine whether or not the hydraulic gradient should be increased after testing is completed under a hydraulic gradient of 1. If the coefficient of hydraulic conductivity measured under a hydraulic gradient of 1 approaches or equals that calculated for the equipment flow rate, there is no reason to continue testing using higher hydraulic gradients.

The flow rate of test equipment should be determined for each complete test system for all hydraulic gradients under which a specimen will be tested. This flow rate calibration should be performed whenever a component of the test system is changed, semiannually, or each time the permeability test is performed. It should guide the test operator in performing the test for proper duration and test conditions, as described in the previous paragraph.

Test Equipment Capacity

The maximum coefficient of hydraulic conductivity that can be measured using straight tees approaches 30,000 ft/yr (3.0×10^{-2} cm/s). This serves as the limit of measurable hydraulic conductivity with this equipment. To measure coefficients of hydraulic conductivity above 30,000 ft/yr, the water supply and test cylinder equipment would have to be redesigned.

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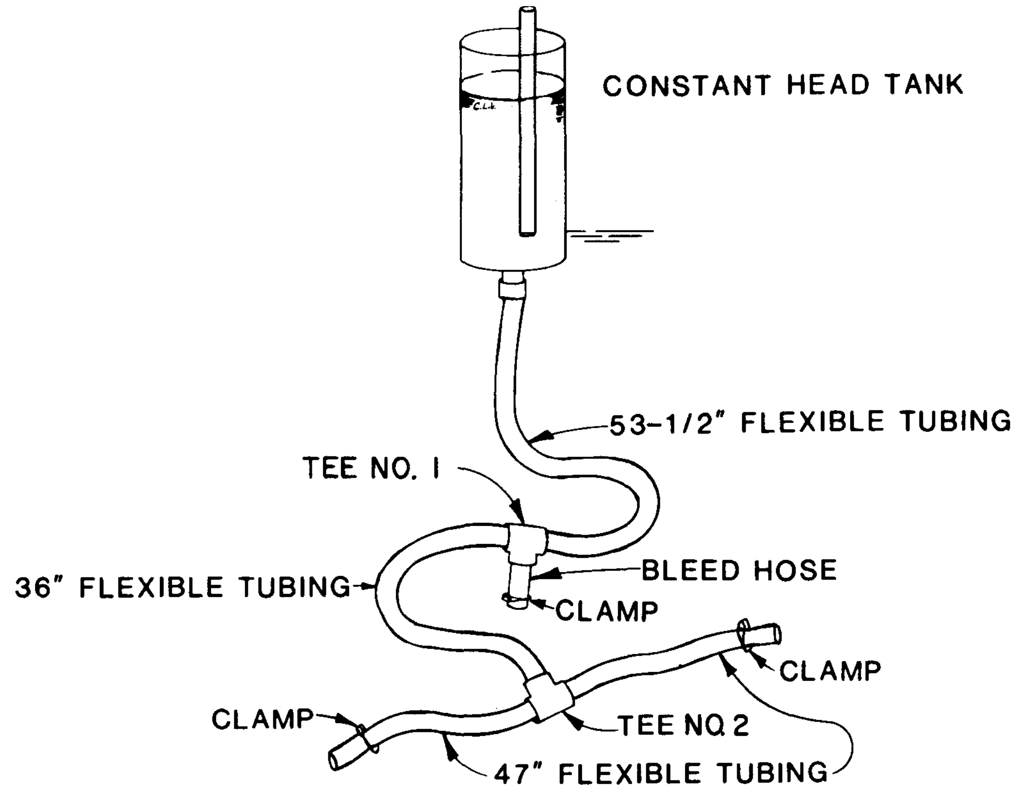
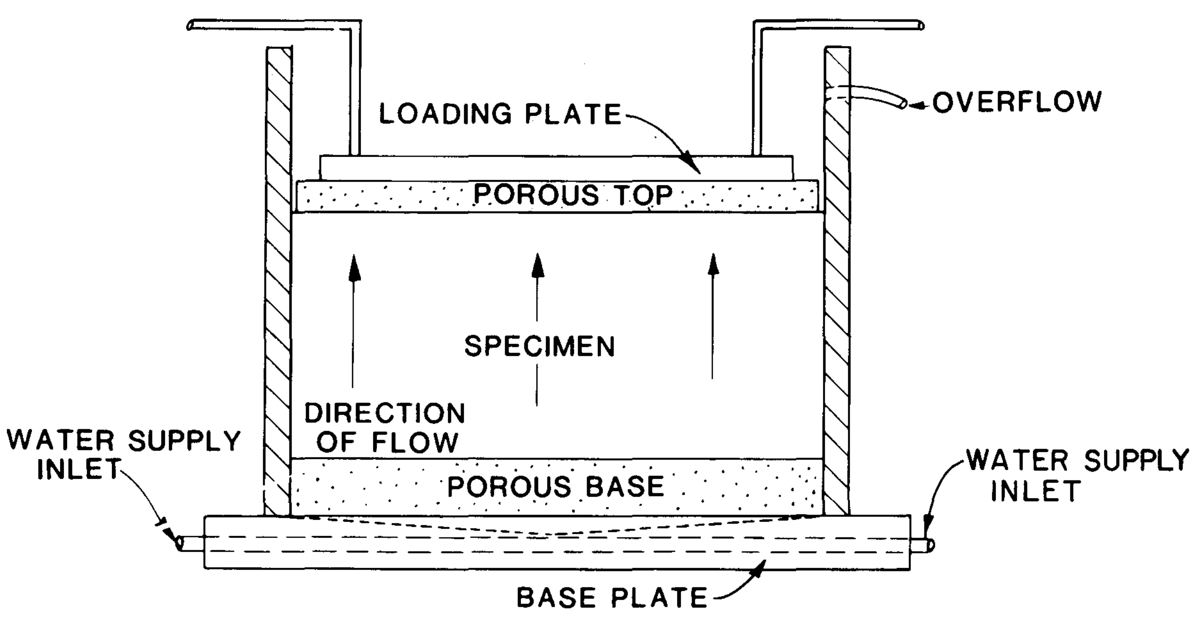


NOTE: ALL TUBING IS 1/2" ID

PERMEANT WATER SUPPLY SYSTEM



PERMEAMETER CYCLINDER

Figure 1. – Permeability test apparatus.

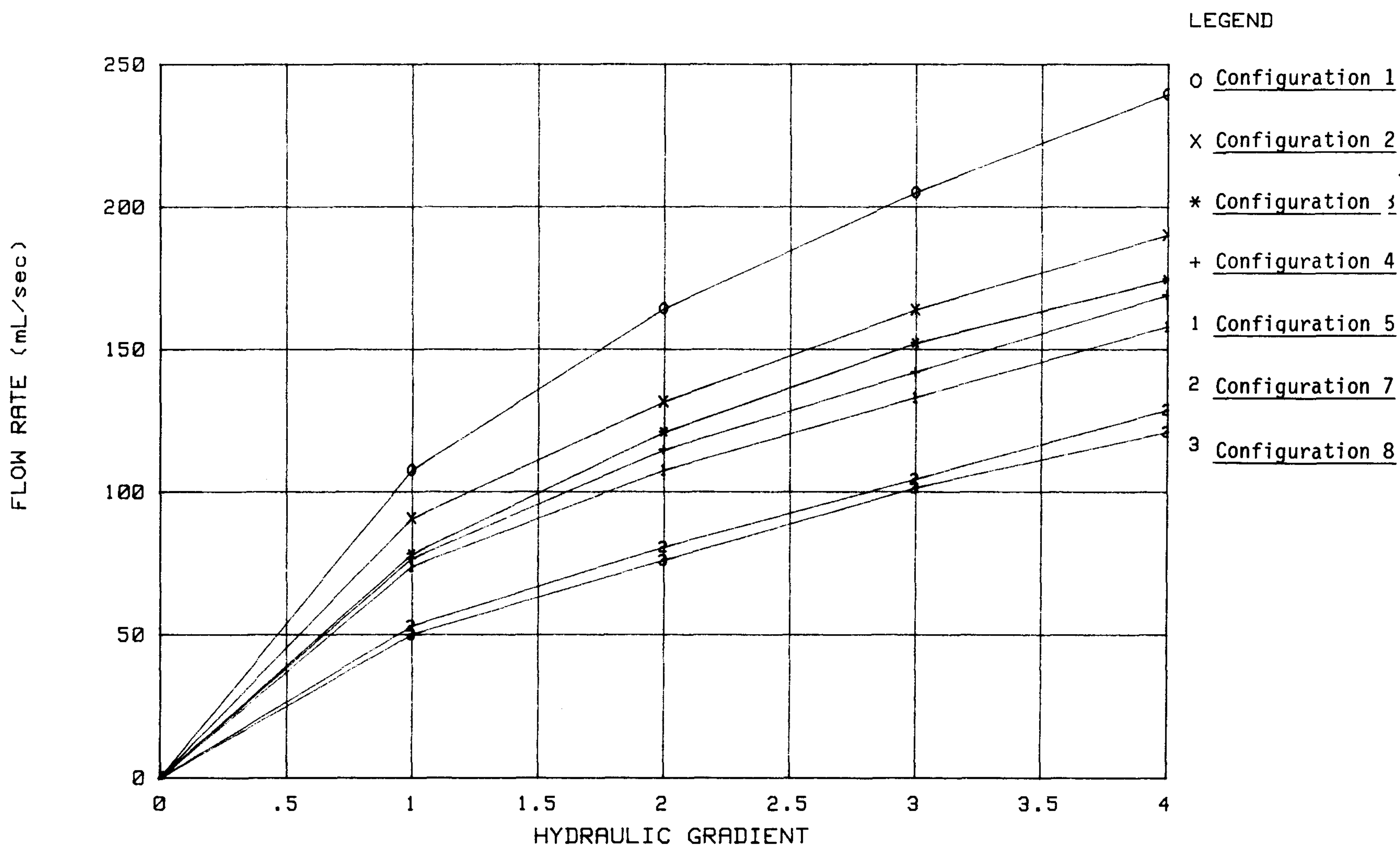


Figure 2. – Flow rate of 20-inch-diameter permeability test equipment (reduction tees).

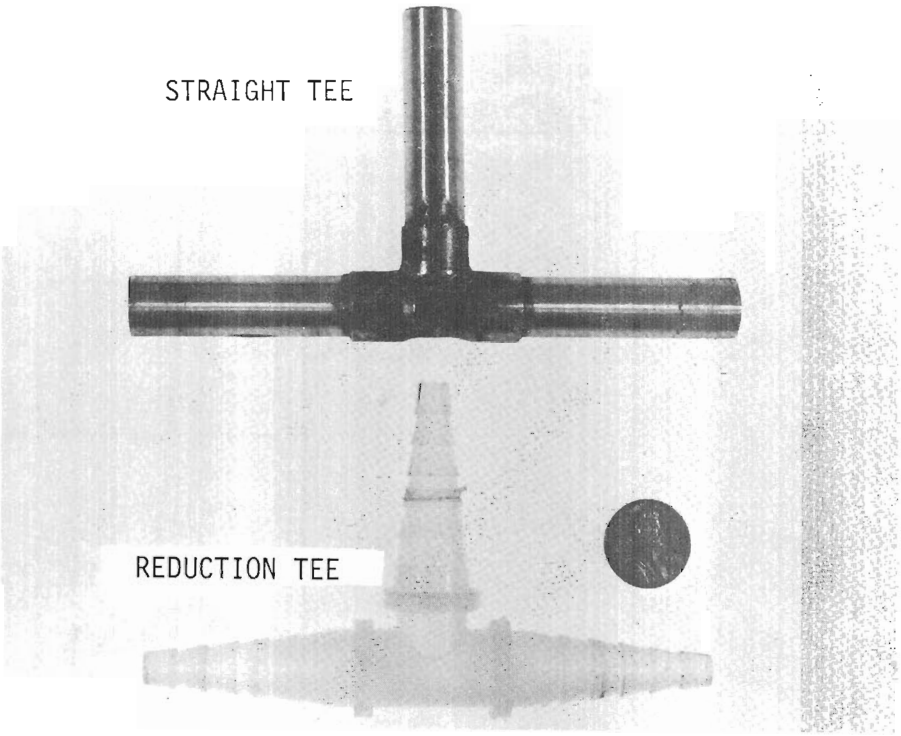


Figure 3. – Straight tee and reduction tee.

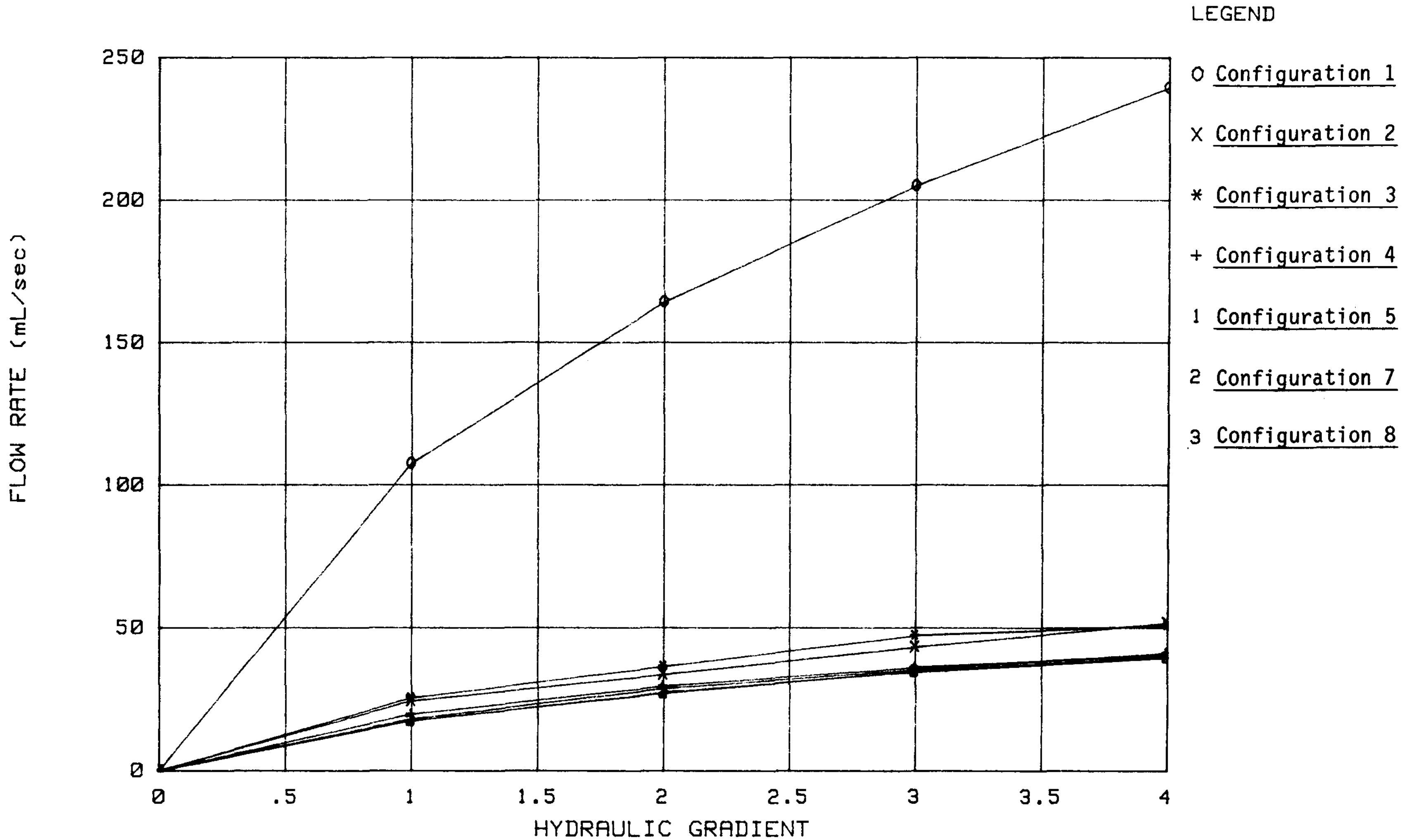


Figure 4. – Flow rate of 20-inch-diameter permeability test equipment (straight tees).

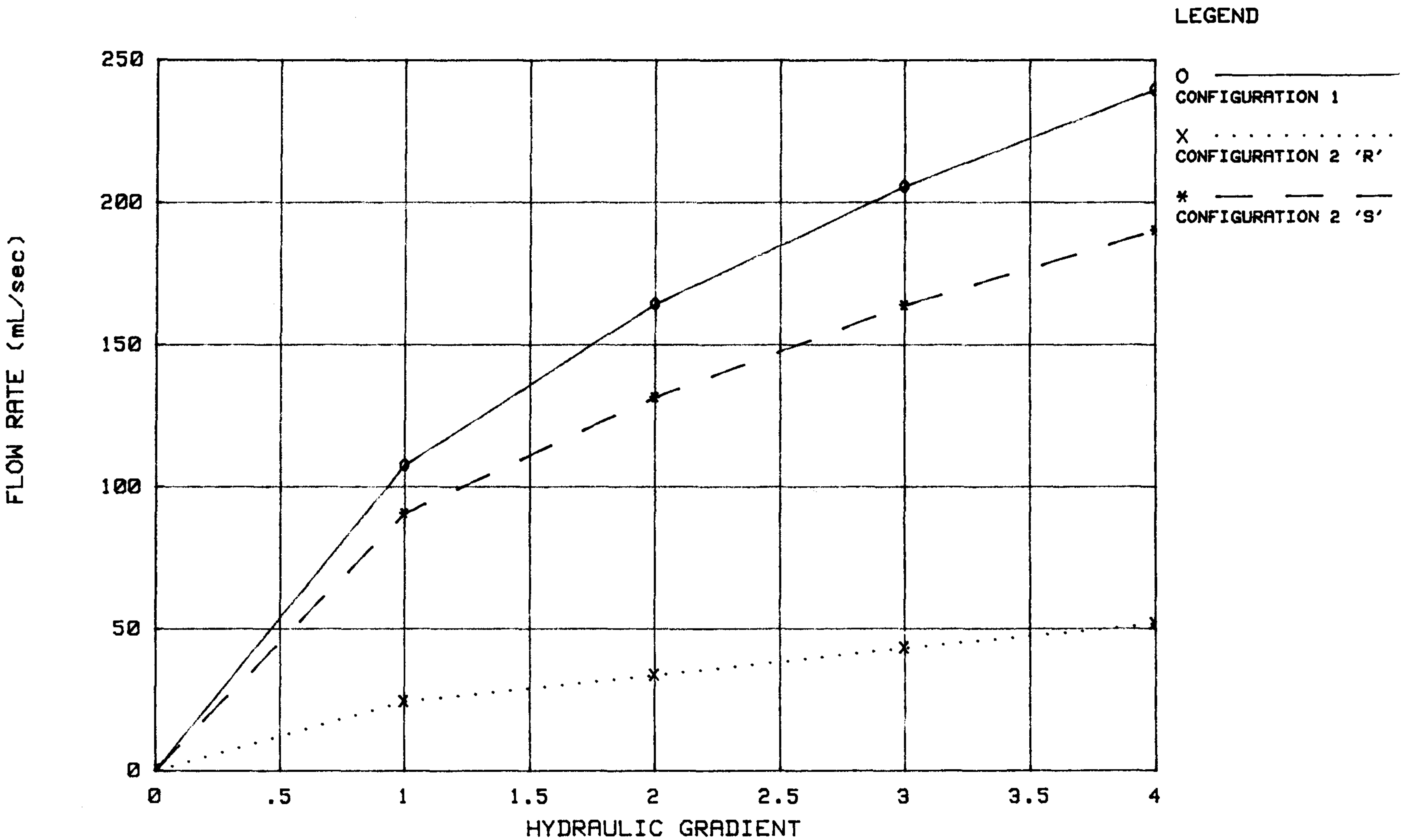


Figure 5. – Comparison of decreases in flow rates of partial systems (configuration 2) using reduction tees and straight tees.

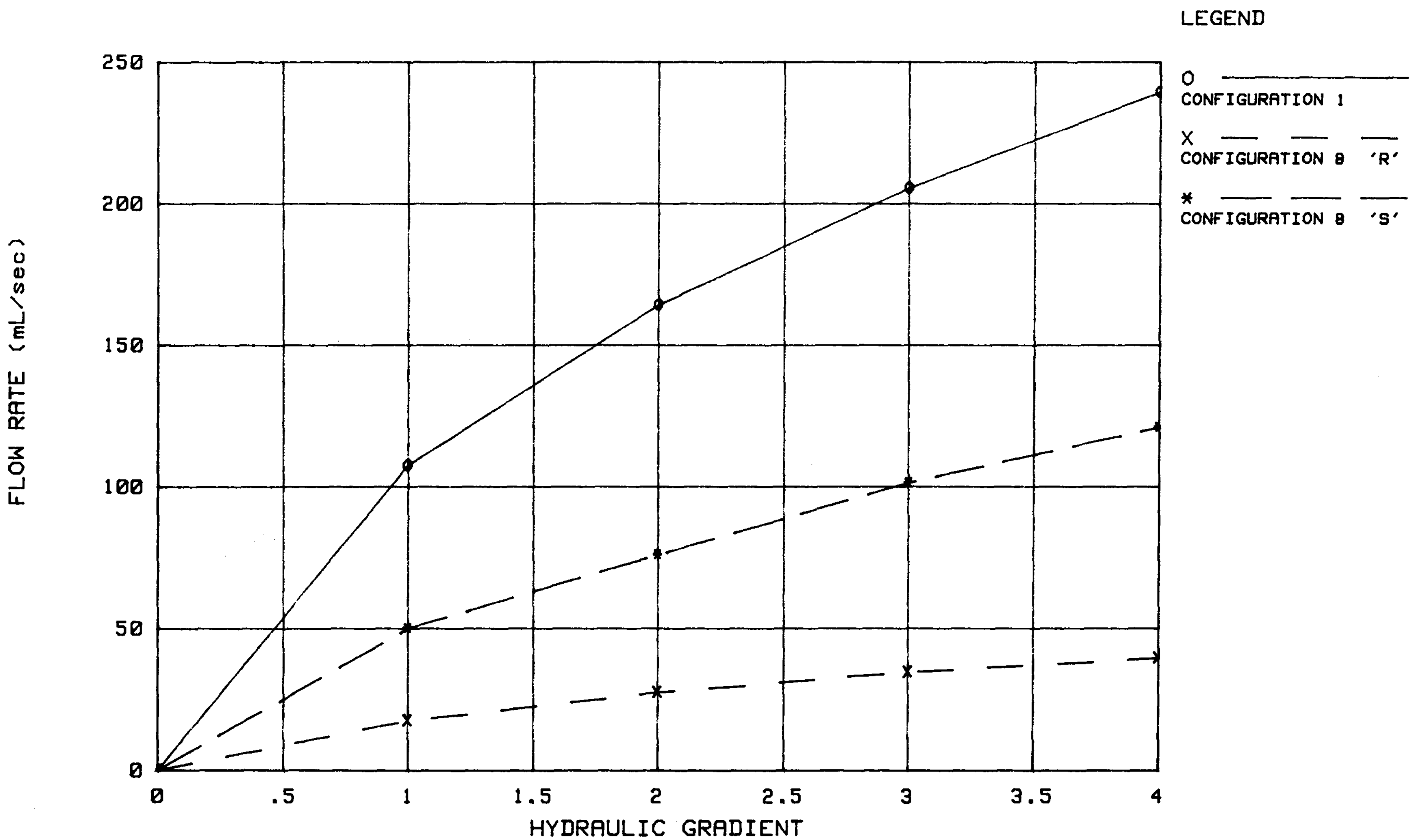
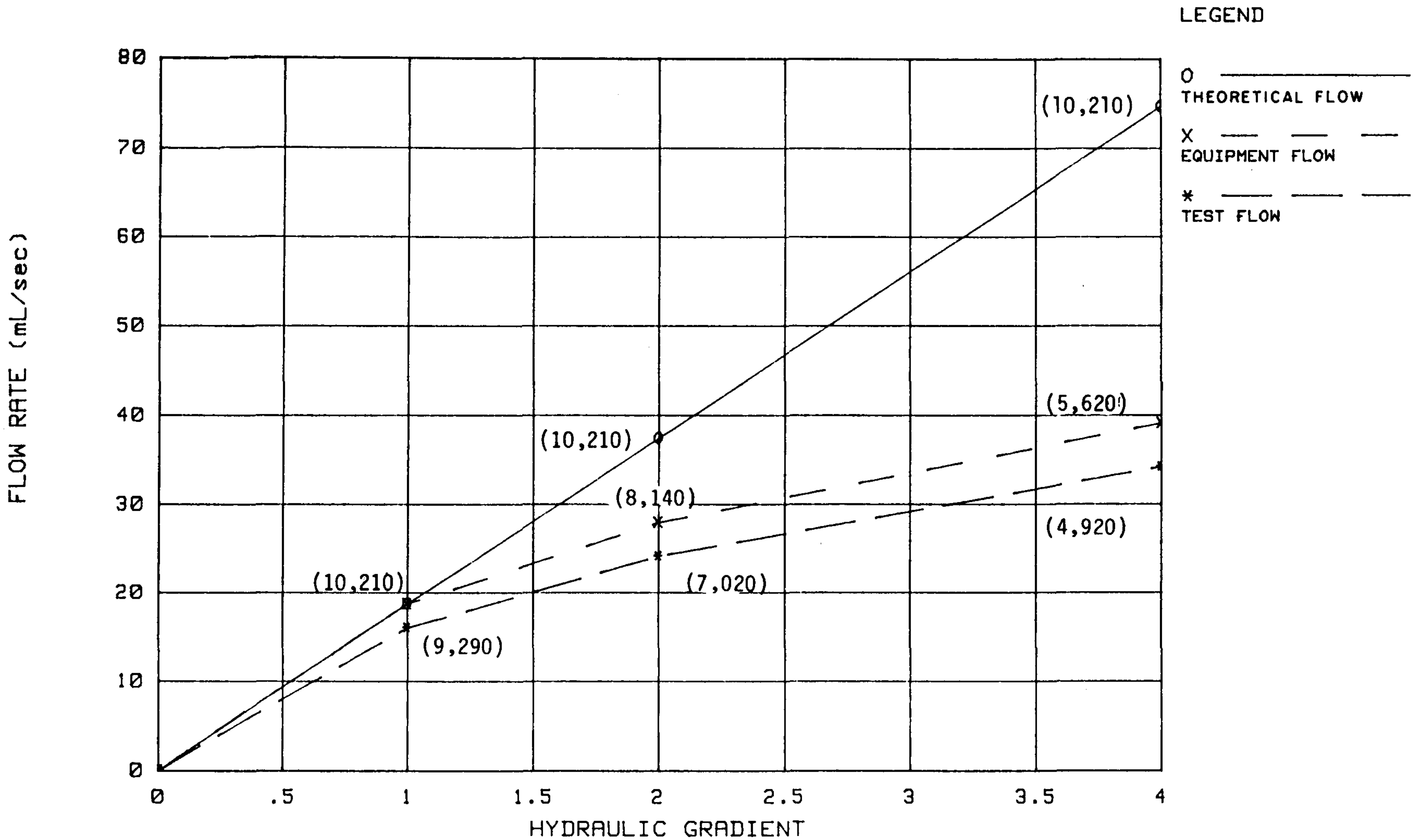
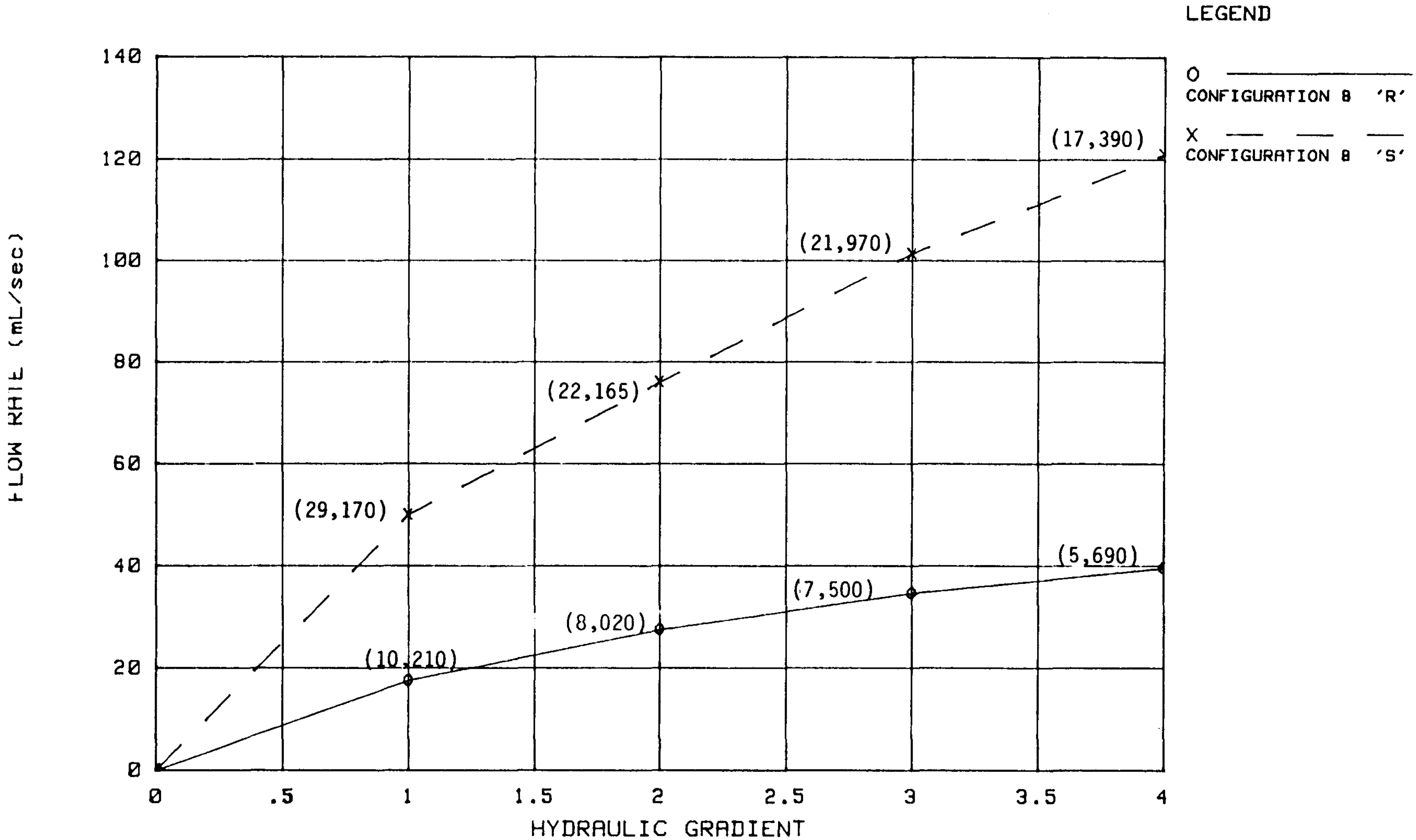


Figure 6. – Comparison of decreases in flow rate of complete systems (configuration 8) using reduction tees and straight tees.



NOTE: Numbers in parentheses are calculated coefficients of hydraulic conductivity in feet per year.

Figure 7. – Comparison of equipment flow rates with soil test results.



NOTE: Numbers in parentheses are calculated coefficients of hydraulic conductivity in feet per year.

Figure 8. – Comparison of flow rates of complete systems (configuration 8) using reduction tees and straight tees.

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