THE EFFECT OF POLYMER ADDITIVES
ON TRANSITION IN PIPE FLOW

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Summary
Small amounts of long chain water soluble polymers have a marked effect on turbulent flow resulting in an appreciable reduction of turbulent friction. The maximum reduction in pipe flow resistance is obtained at such low concentrations that the density and viscosity are not altered appreciably. The minimum friction curve varies as $Re^{-4}$ and appears to be the same for all effective additives tested. The transition process is affected by these additives. Quantitative results are presented showing a reduction in the intensity of the turbulent flashes and the fraction of the time the flow is turbulent at a given Reynolds number.

§ 1. Introduction
It has been known for some time that certain high molecular weight additives reduce turbulent friction appreciably [1] and this phenomenon has been utilized in practical applications such as hydraulic fracturing operations in the petroleum industry [2]. It was originally believed that the friction reduction was due to a non-Newtonian viscosity shear relation until Hoyt and Fabula [3] showed that appreciable friction reduction could be obtained with additive concentrations measured in parts per million. At these concentrations the viscosity and density of the solution does not differ measurably from those of the solvent so it is necessary to seek other explanations. There is considerable activity in this area but relatively little had been published when we began our work.

Previous investigations had shown that friction reducing additives must have a high molecular weight, long straight chain molecules and be soluble in the liquid. Molecules of this type are subject to shear degradation which results in a gradual loss of the friction re-

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ducing effect as the fluid is recirculated. The additives have little effect on laminar flow, though there is some evidence of a slight increase in friction. Also it appears that the friction reduction decreases at very high Reynolds number. Most of the previous experimental work has been in the intermediate Reynolds number range where the effect has a maximum. Friction reduction of up to 80% has been reported in a number of configurations. While several explanations have been suggested none were sufficiently developed for quantitative estimates.

We decided to study the effect of friction reducing additive on the transition process in pipe flow with the purpose of obtaining information about transition as well as friction reduction. It is well known that the flow in a pipe at a Reynolds number close to the critical value undergoes spontaneous transition from laminar to turbulent flow. This had been studied by Coles [4], Lindgren [5], and Rotta [6].

§ 2. Description of the apparatus

The apparatus used in our investigation is shown in fig. 1. It was designed to provide flow at constant head with a minimum of pressure fluctuations and without the use of pumps which might