These tubes were used in the 19-tube module.

3.9 Performance of Multi-Tube Module

3.9.1 Multi-Tube Baseline Data

Nineteen of the above tubes that met the separation criteria and were in the A/F range of 20-28 ft^2/lbmol/hr were selected and assembled in the multi-tube module. Each tube was sealed in the module and the module was checked for external leaks and tested with pure He and CO_2 to ensure that there were no internal leaks. The He and CO_2 permeances were close to those for the individual tubes.

The multi-tube module was tested with the FCC gas mix at 3.0 and 7.0 atm feed pressures and a permeate pressure of ~1.05 atm. The membrane was fed from the bottom and the sweep was countercurrent, with the permeate collected at the bottom and the non-permeate stream collected at the top of the module. The membrane performance data is shown in **Figures 28-35**. Along with the multi-tube module data is the data for the individual tubes assembled in the bundle. The data show the following :

(i) The separation property of the bundle is an average of the individual tubes, with the overall performance at target separation for all the gas components.

(ii) The A/F for the multi-tube module is higher by 20-30% vs individual tubes. The reasons for this are not clear but may be related to either incomplete utilization of the membrane tube area (the sweep gas is introduced a few cm below the top end of the tube) or due to gas maldistribution in the module.

(iii) With the FCC mix, the membrane separation performance is not changed significantly at the higher feed pressure (note that the ethane and ethylene rejections are lower and CH_4 rejection is higher at 7.0 atm vs at 3.0 atm). The overall H_2 purity in the high pressure effluent stream is unaffected.

(iv) The membrane A/F decreases from ~30 ft^2/lbmol/hr at 3.0 atm to ~10ft^2/lbmol/hr at 7.0 atm, thus profoundly reducing the membrane area required to handle a fixed feed flow rate at the higher feed pressure.

3.9.2 Stability of SSF Membrane

The SSF membrane was continuously tested for a 2-month period and the recovery-reject data generated over this period. The feed gas was pretreated to remove moisture and C_5+ hydrocarbons. These data are also included in **Figures 28-35**. The relatively tight scatter in the data indicates that membrane performance did not deteriorate during this test period and that the membrane is stable.

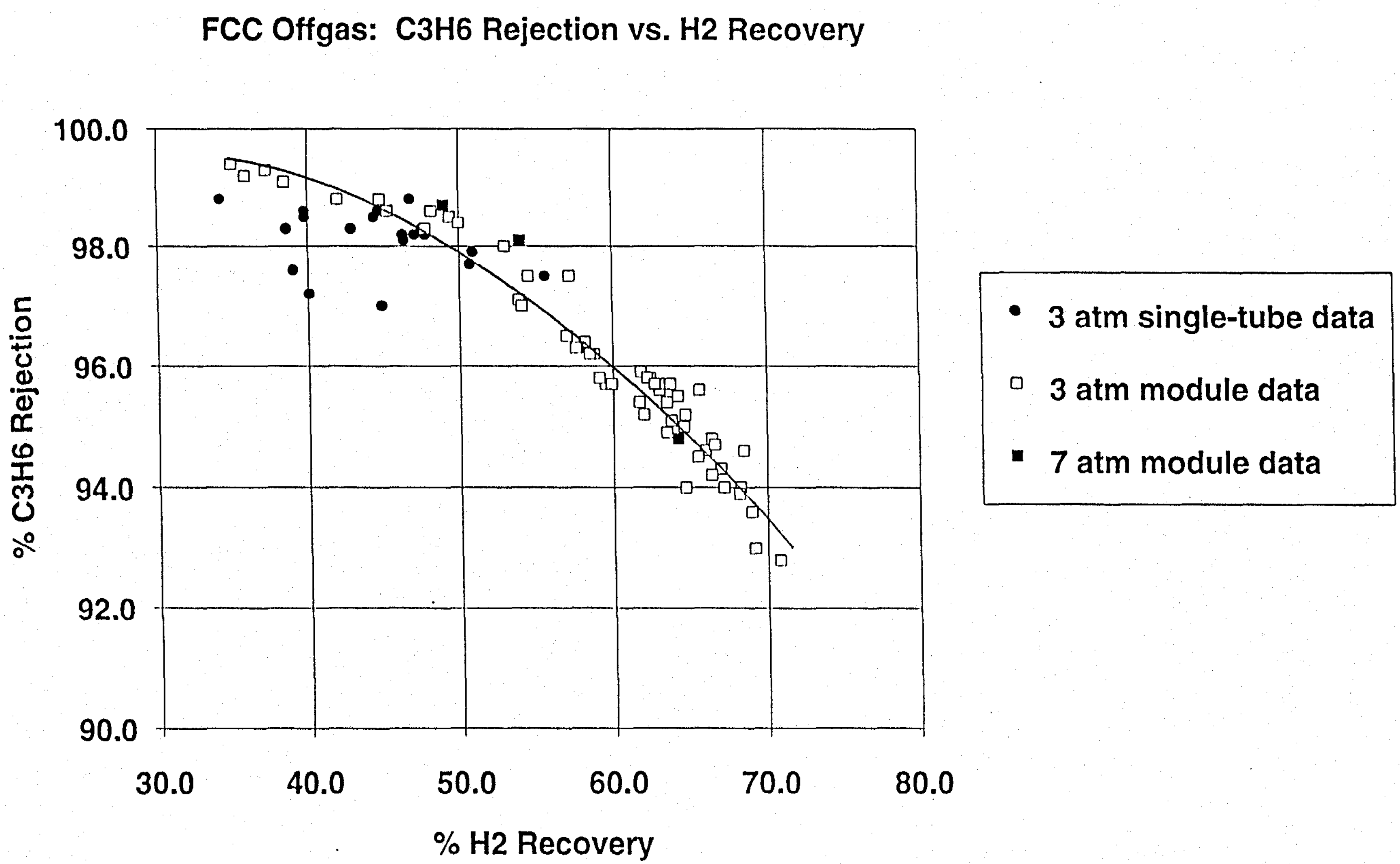

Figure 28. Performance of Multi-tube Module at 3 and 7 atm Feed Pressure: H_2 Recovery vs Propylene Rejection

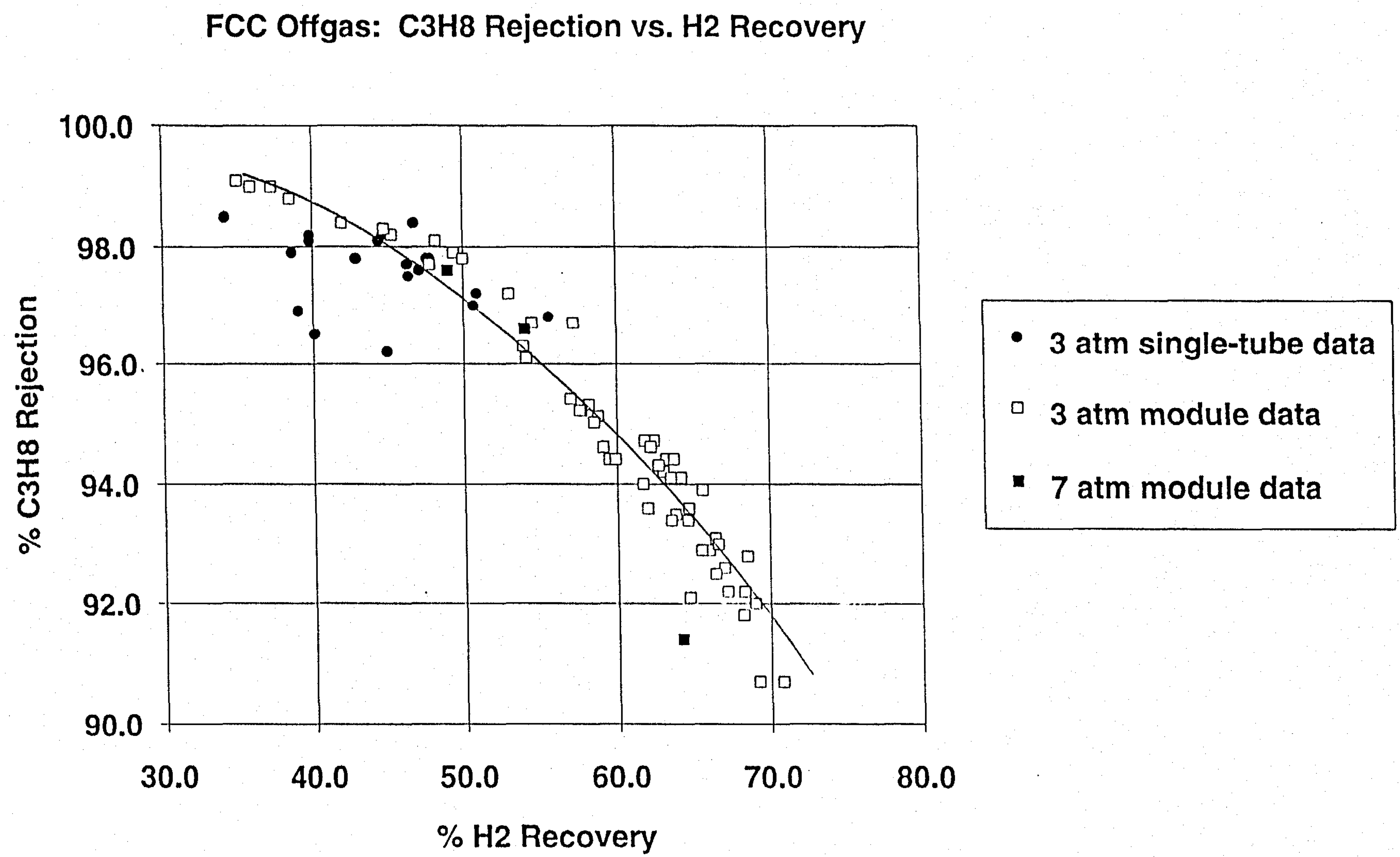

Figure 29. Performance of Multi-tube Module at 3 and 7 atm Feed Pressure H_2 Recovery vs Propane Rejection

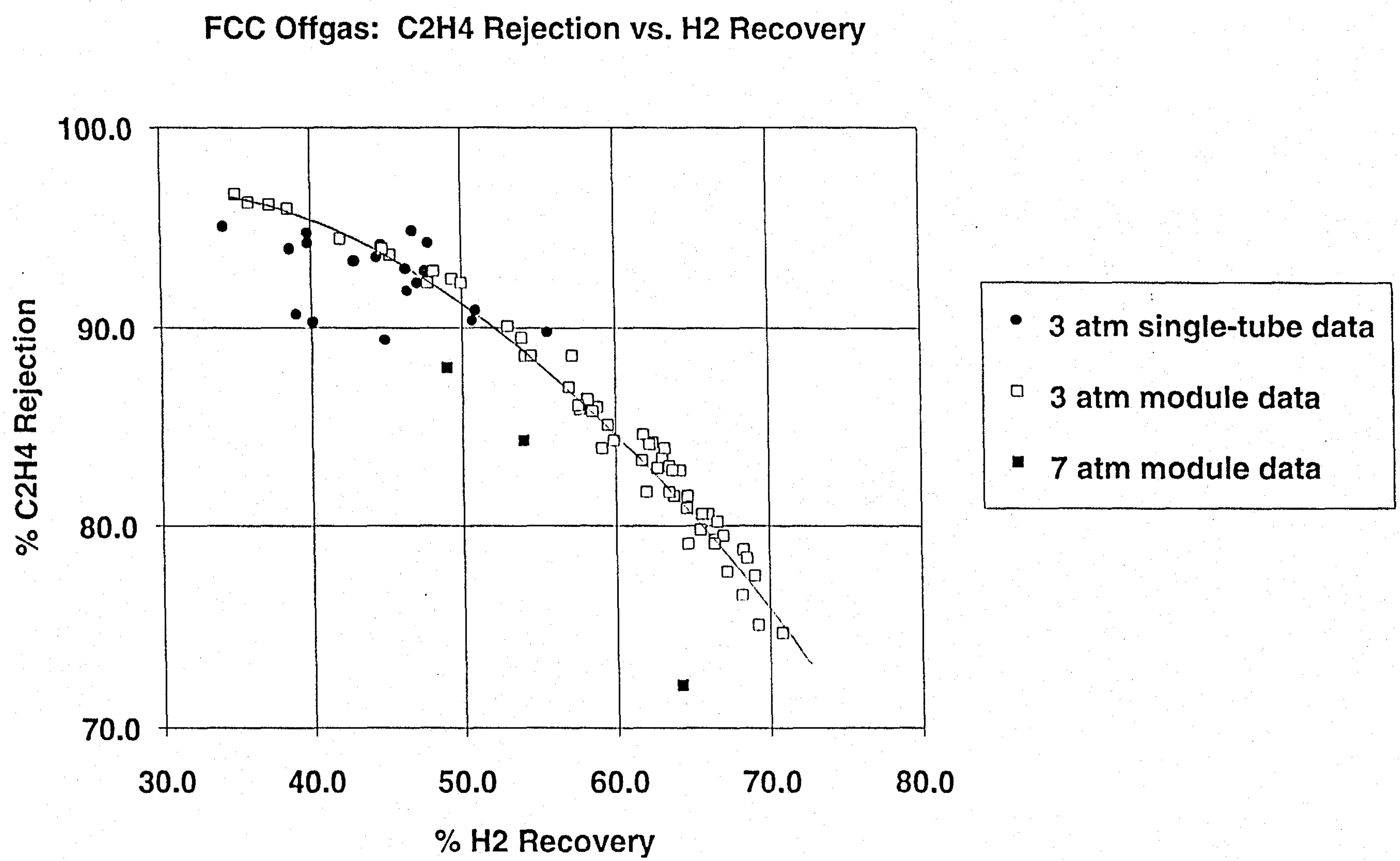

Figure 30. Performance of Multi-tube Module at 3 and 7 atm Feed Pressure H_2 Recovery vs Ethylene Rejection

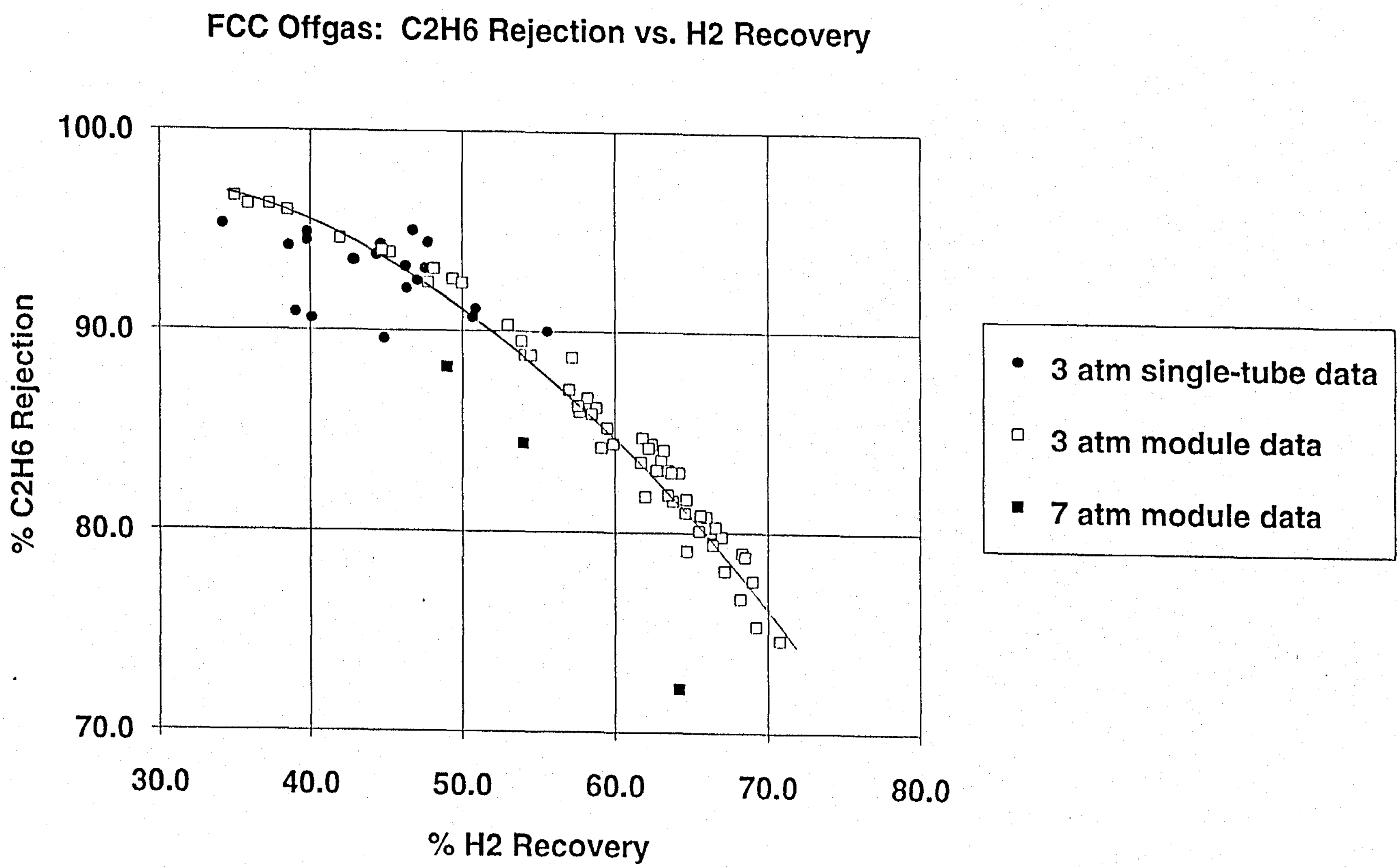

Figure 31. Performance of Multi-tube Module at 3 and 7 atm Feed Pressure H_2 Recovery vs Ethane Rejection

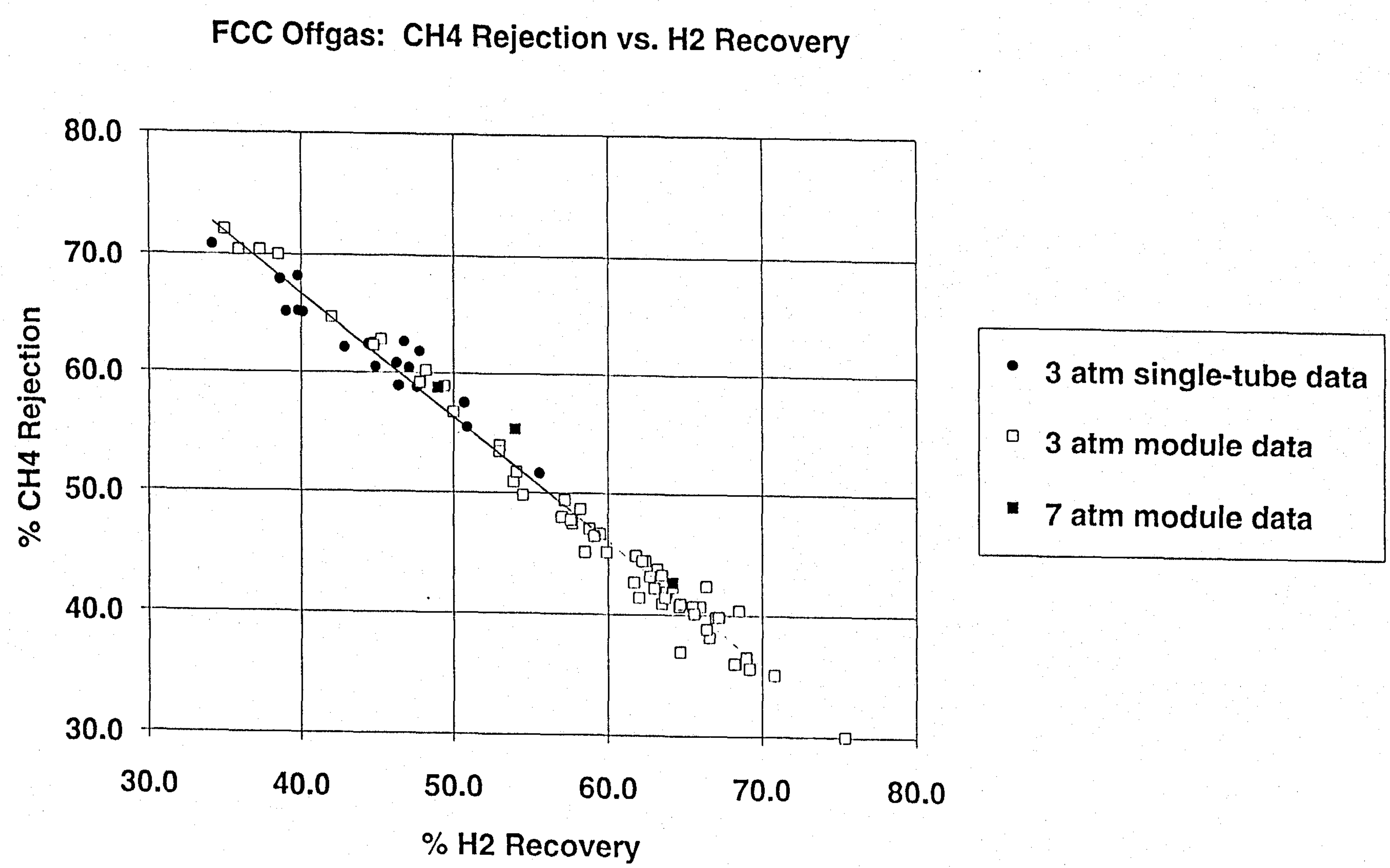

Figure 32. Performance of Multi-tube Module at 3 and 7 atm Feed Pressure H_2 Recovery vs Methane Rejection

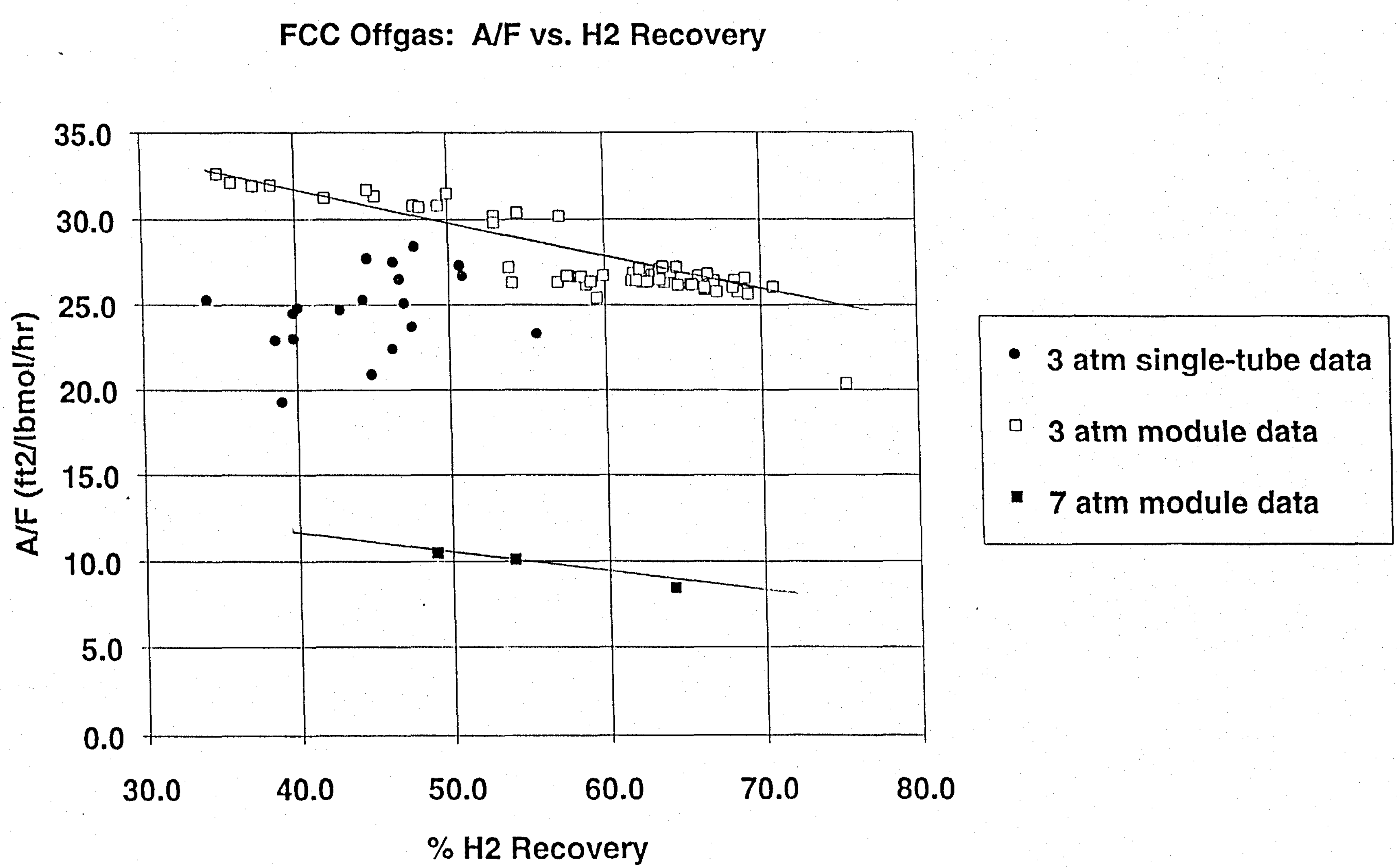

Figure 33. Performance of Multi-tube Module at 3 and 7 atm Feed Pressure H_2 Recovery vs A/F

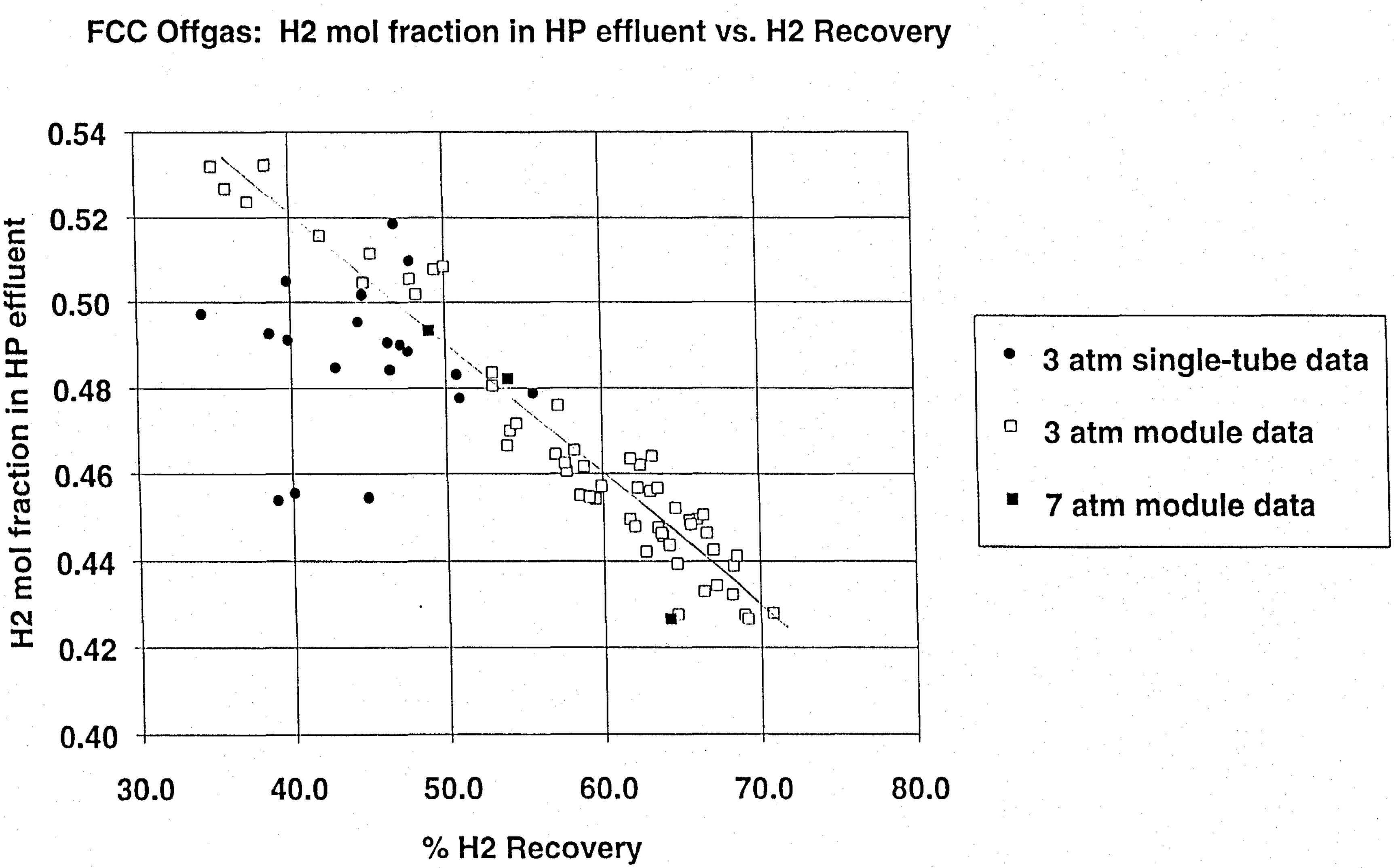

Figure 34. Performance of Multi-tube Module at 3 and 7 atm Feed Pressure H_2 Recovery vs H_2 Mole Fraction in High Pressure Effluent

MIXCHART.XLS Chart 32

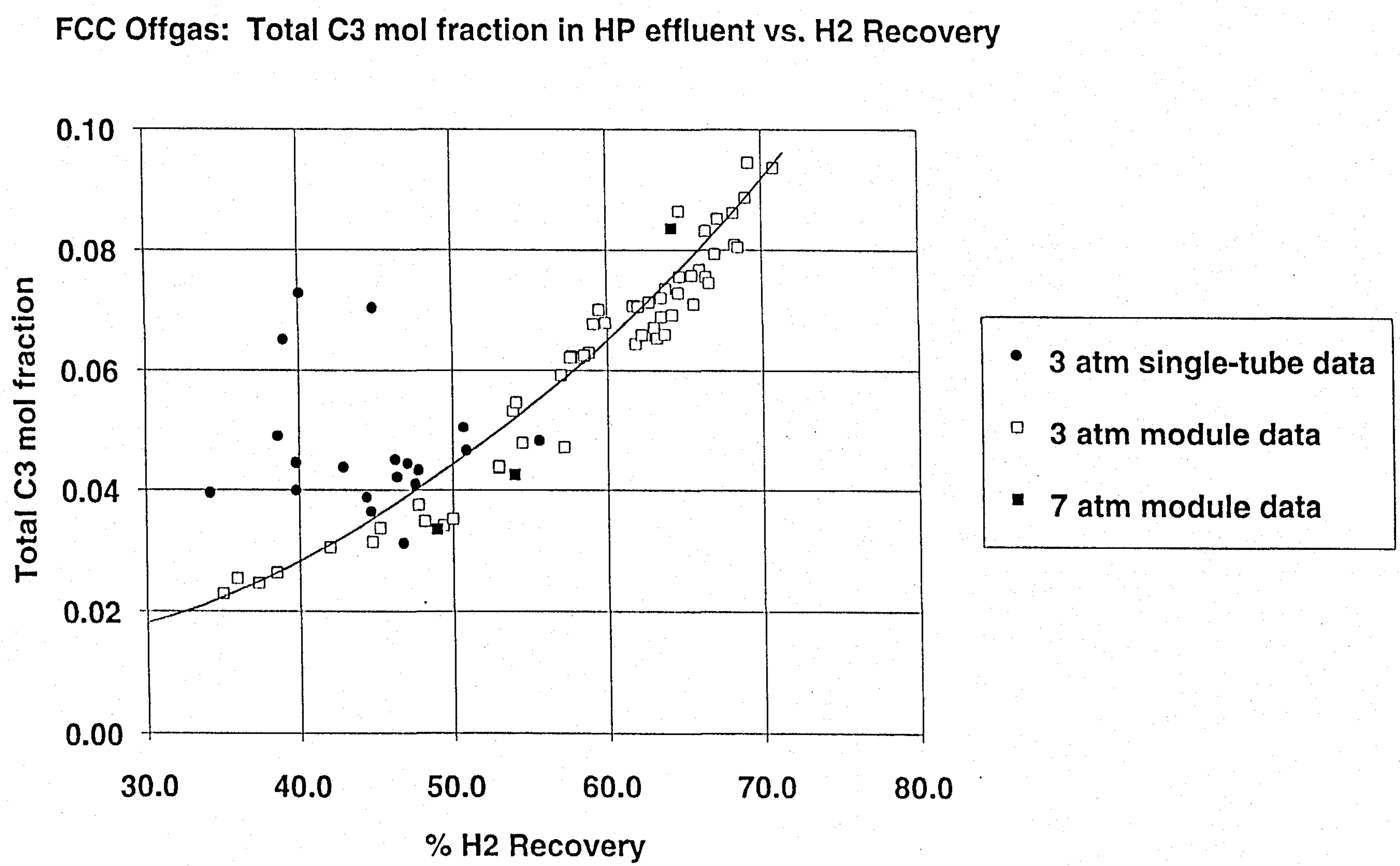

Figure 35. Performance of Multi-tube Module at 3 and 7 atm Feed Pressure H_2 Recovery vs Total C_3 Mole Fraction in High Pressure Effluent

3.9.3 Effects of Temperature, Feed Flow Rate and Feed Pressure

During the 2-month test period, the effects of variation in feed flow rate and membrane operating temperature were also investigated for the separation of hydrogen from hydrocarbons with the FCC mix. The results are shown in **Figure 36**. At a constant flow rate, a temperature change from 296 K to 306 K caused hydrogen recovery to decrease from 68% to 53% while concomitantly increasing the propylene rejection from 94% to 97%. Importantly, changes in temperature of this magnitude did not move the performance off the recovery-rejection curve but moved along the performance curve. The effect of temperature on moving from an operating point is not an unexpected result recognizing that the membrane separates by adsorption and surface diffusion through the pores of the carbon membrane. The effect of temperature on conventional pressure swing adsorption (PSA) used for separation of gases is of a similar nature and magnitude.

The effect of change of feed flow rate on the membrane operating point is also shown in **Figure 36.** Changing the feed flow rate has the same effect as the temperature i.e., it moves the membrane operating point along the same recovery-reject curve. A feed flow rate change (reduction) of 20% is required to decrease the hydrogen recovery from 68% to 53% while simultaneously increasing the propylene rejection from 94 to 97% with this FCC gas mix. The effect of feed pressure on membrane separation characteristics is shown in **Figures 28-35**. The data show that the membrane separation properties are only slightly affected at an elevated presssure (7 atm) with the FCC mixture, but the membrane area is decreased by 65-70% by increasing the pressure from 3 to 7 atm.

3.9.4 Effect of Feed and Sweep Directions on the Membrane Performance

The feed to the membrane module can be from the bottom or the top of the module. The sweep flow directions can be appropriately changed to be either co-current or counter-current. The effect of feed from the top or the bottom for the separation of the FCC mix was investigated. The data indicated that the preferred direction of feed is from the membrane bottom as it improves the membrane separation properties.

Sweep flow with the FCC mix was changed from counter-current to co-current. The data indicate that counter-current sweep is preferred. The observations are similar to those in the operation of heat exchangers where counter-current flow allows the maximum temperature driving force for heat exchange.

3.10 SSF Membrane Characteristics : Tubes vs Sheets

The benchmark performance data for the SSF membrane coated on carbon sheets was shown in **Figures 2-5** and that for tubes has been discussed in the previous sections of this report. The key differences between the two are :

MIXCHART.XLS Chart 94

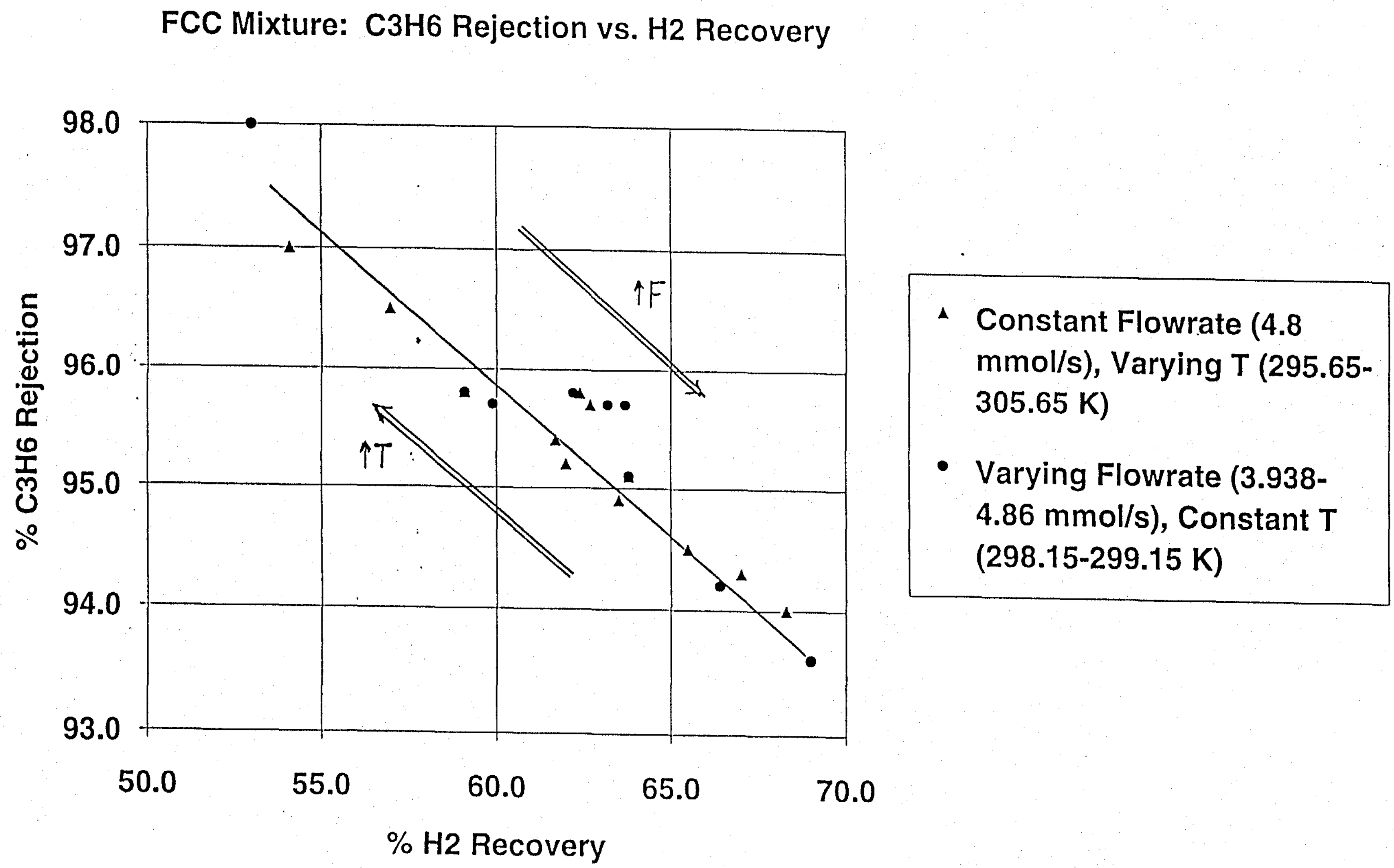

Figure 36. Effect of Temperature and Flow Rate on Membrane Performance