XN-NF-79-59 (NP)

METHODOLOGY FOR CALCULATION OF PRESSURE DROP IN BWR FUEL ASSEMBLIES

AUGUST 1980

RICHLAND, WA 99352

EXXON NUCLEAR COMPANY, Inc.

XN-NF-79-59(NP)

Issue Date: 08/13/80

METHODOLOGY FOR CALCULATION OF PRESSURE DROP IN BWR FUEL ASSEMBLIES

By:

F. T. Adams
T. W. Patten

Approved: TL Krysinski 10/1/79
T. L. Krysinski, Manager — Date
Plant Transient Analysis

Approved: J F Patterson 10/1/79
J. F. Patterson, Manager — Date
Fuel Development Testing

Approved: J N Morgan 10/2/79
J. N. Morgan, Manager — Date
Licensing & Safety Engineering

Approved: J N Morgan for 10/2/79
G. A. Sofer, Manager — Date
Nuclear Fuels Engineering

Approved: G J Busselman 10/4/79
G. J. Busselman, Manager — Date
Neutronics & Fuel Management

/clc

EXXON NUCLEAR COMPANY, Inc.

NUCLEAR REGULATORY COMMISSION DISCLAIMER

IMPORTANT NOTICE REGARDING CONTENTS AND USE OF THIS DOCUMENT

PLEASE READ CAREFULLY

This technical report was derived through research and development programs sponsored by Exxon Nuclear Company, Inc. It is being submitted by Exxon Nuclear to the USNRC as part of a technical contribution to facilitate safety analyses by licensees of the USNRC which utilize Exxon Nuclear-fabricated reload fuel or other technical services provided by Exxon Nuclear for light water power reactors and it is true and correct to the best of Exxon Nuclear's knowledge, information, and belief. The information contained herein may be used by the USNRC in its review of this report, and by licensees or applicants before the USNRC which are customers of Exxon Nuclear in their demonstration of compliance with the USNRC's regulations.

Without derogating from the foregoing, neither Exxon Nuclear nor any person acting on its behalf:

A. Makes any warranty, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this document, or that the use of any information, apparatus, method, or process disclosed in this document will not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this document.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

METHODOLOGY FOR CALCULATION OF PRESSURE DROP IN BWR FUEL ASSEMBLIES

1.0 INTRODUCTION

The thermal-hydraulic analysis of boiling water reactor (BWR) fuel assemblies requires the determination of the distribution of reactor coolant flow throughout the core. The coolant flow in a BWR fuel assembly is constant along the axial length due to the presence of metal channels around each fuel assembly. Since all fuel assemblies freely communicate to the reactor plenums, the BWR core is hydraulically equivalent to a number of parallel flow paths. Because of this, the static pressure drop across each parallel flow path (fuel assembly) is equal. The assembly flows vary throughout the reactor core according to the assembly operating power levels (boiling two phase pressure drop) and the hydraulic characteristics of each assembly. This report details the methodology used to calculate the assembly pressure drop which determines the assembly coolant flow and varies according to the total recirculating flow and reactor power. The report also presents a comparison of that methodology to experimentally determined pressure drops in the bare rod and spacer regions.

The methodology presented for the calculation of pressure drop is composed of basic relations representing the various terms of the momentum equation and constitutive relationships (correlations) for void fraction and two-phase friction multiplier. Because the void fraction model is used to determine an average fluid density which in turn is used to determine gravitational and spacer pressure drop components, it is an implicit part of the methodology for calculating pressure drop.

The pressure drop in assemblies with both uniform and nonuniform axial heat flux profiles has been determined over a wide range of operating conditions as shown in Table 1.1. The prediction of this data provides an evaluation of the accuracy of the methodology and thereby provides a basis for estimating the accuracy of the determination of individual assembly flow rates.

The basis used for determining the accuracy of the methodology is the relative error defined as the difference between predicted and measured pressure drop divided by measured pressure drop, or

$$E = \frac{\Delta P_p - \Delta P_m}{\Delta P_m} \quad . \tag{1.1}$$

The average relative error and its standard deviation have been determined from the data comparison. The distribution of the relative errors has been examined to determine the nature of its frequency distribution, thereby characterizing the statistical performance of the methodology.

TABLE 1.1

RANGE OF OPERATING CONDITIONS

Pressure, psia	600-1500
Mass Velocity, 10^6 lbm/hr-ft^2	0.5-1.5
Inlet Subcooling, Btu/lbm	20-150
Assembly Averaged Exit Quality	0-0.8

2.0 SUMMARY

Pressure drop has been predicted with methodology described in this document. A total of 419 data points were predicted for five separate test assemblies employing two different spacer designs, three different axial power profiles, and operating in a wide range of mass velocity, pressure, inlet enthalpy, quality and assembly power. The basis of comparison of predicted and measured pressure drops was the relative error defined as the ratio of the predicted minus the measured pressure drop to the measured pressure drop (Equation 1.1). The overall mean relative error was determined to be -0.027 with a standard deviation of 0.033. No significant biases were observed in the data prediction. The data comparison is shown in Figure 2.1. The data comparison may be conservatively represented as a normal distribution.

Analytical procedures are also presented for calculating the single phase pressure drop across the orifices and lower tie plate and the two phase pressure drop across the upper tie plate. The methodology for calculating the two phase pressure drop associated with the upper tie plate and the flow expansion at the end of the assembly has not been experimentally verified, but is based on standard analytical procedures which have been verified by experimental data.[4, 10]

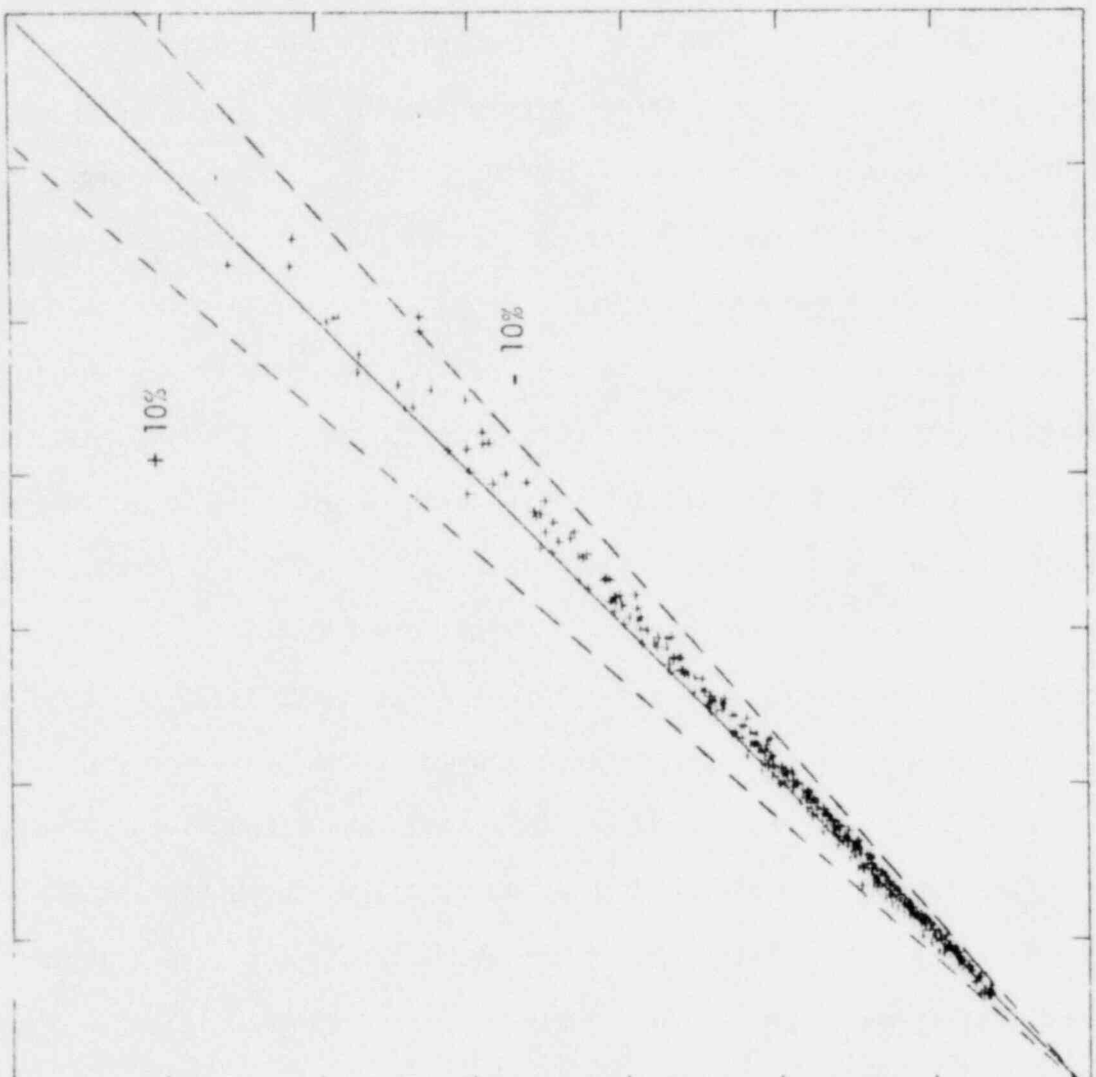

Figure 2.1 Comparison of Measured and Predicted Two-Phase Pressure Drop

3.0 THEORY AND CONSTITUTIVE RELATIONSHIPS

This section describes the theoretical basis of the pressure drop calculation and presents the constitutive relationships which are used for those quantities for which theoretical relations are either unavailable or inadequate. The pressure drop across an assembly is determined by summation of the various terms in the momentum equation and includes the contributions due to frictional, accelerational and gravitational forces. The basis of the pressure drop calculation is the momentum equation for separated flow: (4,11)

(3.1)

Constitutive relationships in the form of empirical correlations are employed for the void fraction, , and the bare rod two-phase friction multiplier

The single phase pressure drop across the lower orifice and tie plate is calculated as

$$\Delta P = \qquad (3.2)$$

or any other manner that is consistent with the procedure which has been used to reduce the experimental pressure drop data.[9] The losses in pressure due to the orifice and lower tie plate are modeled as planar or instantaneous losses in Equation 3.2 and are grouped together and represented as a single loss coefficient for simplicity. For the correct prediction of pressure drop in an operating assembly, the values of the orifice and lower tie plate loss coefficients must be augmented to reflect the fraction of assembly flow which passes through each component but bypasses the active region of the assembly by entering the bypass region through various bypass flow paths. Examples of such bypass flows are the flow through the gap between the lower tie plate and the assembly channel and the flow through the bypass holes in the lower tie plate. Proper modeling of the hydraulic characteristics of the fuel assemblies results in accurate predictions of component pressure drops under reactor operating conditions.

The two phase pressure drop at the upper tie plate is represented as the product of the single phase pressure loss and a two phase multiplier.

3.1 VOID FRACTION

The void fraction is used to calculate the average density of the two-phase mixture and is important in the calculation of the accelerational and gravitational components of the pressure drop. The void fraction correlation is therefore an implicit part of the methodology used to calculate two-phase pressure drop. The model incorporates the effects of thermal nonequilibrium by using a subcooled void model to determine the mass flow quality, X. This quantity is then used to calculate vapor and liquid volumetric fluxes, which in turn are used to calculate void fraction.

The subcooled void model employed is

Once the flow quality has been calculated, the void fraction may be determined. Void fraction is determined by a Zuber-Findlay model[4]

This model determines the void fraction from the superficial velocities of the vapor and liquid phases as:

$$\alpha = \frac{j_g}{C_o(j_g + j_f) + V_{gj}}$$

where

$$j_g = GX\nu_g$$

$$j_f = G(1-X)\nu_f$$

Constitutive relationships for C_o and V_{gj} are given in Appendix A.

3.2 TWO-PHASE FRICTION MULTIPLIER

The two-phase friction multiplier represents the augmentation of frictional losses in the bare rod region due to the interaction of the vapor and liquid phases. The model used augments the frictional forces as if all the flow present were liquid.

3.3 SAMPLE CALCULATION

A sample calculation is provided to illustrate the relative magnitude of the various terms in the pressure drop calculation. For the purposes of this example, a single BWR assembly is considered. The operating conditions and inlet and outlet flow conditions are shown in Table 3.1, and are typical of a relatively high powered BWR assembly in operation at full core power and flow. The results of the calculation are summarized in Table 3.2 and Figures 3.1 and 3.2. The fractional contribution of each component to the overall pressure gradient, as shown in Figure 3.2, is a function of the quality, with different components dominating in different quality ranges.

TABLE 3.1

OPERATING AND FLOW CONDITIONS

FOR SAMPLE CALCULATION OF PRESSURE DROP

Pressure	=	1000 psia
Mass Velocity	=	1×10^6 lbm/hr-ft^2 = 277.78 lbm/sec-ft^2
ΔZ	=	0.5 foot
f	=	0.0171
D	=	0.0452 feet
Flow Rate	=	30.758 lbm/sec
Inlet Enthalpy	=	522 Btu/lbm
Power	=	5.2 MW
Enthalpy Rise	=	160.27 Btu/lbm
Axial Profile	=	Uniform
	=	

Grid Spacers are not included in this calculation.

Fluid Properties

H_f	=	542.6 Btu/lbm
H_{fg}	=	650.5 Btu/lbm
ν_f	=	0.02159 ft^3/lbm
ν_g	=	0.4459 ft^3/lbm
σ	=	0.00123 lbf/ft

TABLE 3.2

RESULTS OF SAMPLE PRESSURE DROP CALCULATION

- dp/dZ (psi/ft)

Length (ft)

Figure 3.1 Contributions of ΔP Gradient

Fraction of Total -dp/dZ

Figure 3.2 Fractional Contributions of ΔP Gradient

4.0 COMPARISON OF CALCULATED AND MEASURED PRESSURE DROP

The pressure drop results cited in this report were acquired

testing conducted by ENC

The pressure drop results reflect the effects of pressure, mass velocity, inlet enthalpy, quality, power, assembly geometry and spacer design. This section describes the reduction of the single phase data to determine the applicable spacer loss coefficients and a comparison of measured and calculated pressure drop under two phase fluid flow. The test predictions have been characterized to determine the uncertainty in pressure drop associated with the calculational methods described in previous sections. Implicit in the calculational uncertainty is the measurement uncertainty inherent in the test facility as no attempt has been made to correct for the measurement uncertainties. Therefore the calculational uncertainty determined by this data comparison is larger than that attributable solely to the methodology employed.

4.1 REDUCTION OF SINGLE PHASE DATA

Single phase pressure drop data taken during critical heat flux testing was used to determine the combined pressure drop due to bare rod friction and spacer loss coefficients. The single phase friction factor used to determine the spacer loss coefficients is shown in Table 4.1, and is supported and experimentally by ENC single phase hydraulic testing on BWR fuel designs.[8,9] The grid spacers used in the nonuniform axial tests were different from those used for the uniform axial tests, and the two designs displayed similar, but different, spacer loss characteristics, as shown in Table 4.1 and Figure 4.1.

TABLE 4.1

EMPIRICAL LOSS COEFFICIENTS

	Nonuniform Axial Assemblies	Uniform Axial Assemblies
Bare Rod Friction Factor		
f =		
Spacer Loss Coefficient		
C_D =		

Figure 4.1 Spacer Loss Coefficients and Bare Rod Friction Factor as Functions of Reynolds Number

The pressure drop data was compiled from tests conducted on five different test assemblies. The cosine axial and upskew axial profile data (all nonuniform axial data) were acquired from two assemblies with the same hydraulic design while the uniform axial data were acquired with three assemblies of the same hydraulic design and differing only in the local peaking distribution within each assembly. The placement of the pressure taps and spacers is shown in Figures 4.2 and 4.3 for the nonuniform and uniform axial assemblies respectively while Figure 4.4 shows the axial power profiles produced by the test assemblies. Other pertinent hydraulic data is listed in Table 4.2.

The single phase pressure drop data acquired on test assemblies with a uniform axial power profile have been predicted to determine the uncertainty in the pressure drop calculations for single phase flow. The single phase calculational uncertainty is expected to represent a minimum value for the two phase pressure drop measurements because of the increased pressure fluctuations associated with two phase flow. The average relative error of the 41 single phase data points was determined to be -0.005 with a standard deviation of 0.006. The negligibly small one-half percent negative bias of the average prediction results from

The 0.6-percent standard deviation indicates the minimum level of the uncertainty associated with the measurement of the pressure drop. The predictions of the single phase pressure drops for each uniform axial test assembly are summarized in Table 4.3. There was no statistically significant variation between the predictions for each test group.

TABLE 4.2

HYDRAULIC DATA FOR TEST ASSEMBLIES

Assembly Type	Nonuniform Axial	Uniform Axial
Flow Area, in^2		
Wetted Perimeter, in		
Heated Perimeter, in		
Hydraulic Diameter, in		
Heated Length, in		

TABLE 4.3

STATISTICAL SUMMARY OF SINGLE PHASE DATA PREDICTIONS

Overall	41	-0.0047	0.0059

Figure 4.2 Pressure Tap and Spacer Locations for Nonuniform Axial Assemblies

Pressure Tap Location

Spacer Locations

Figure 4.3 Pressure Tap and Spacer Locations for Uniform Axial Assemblies

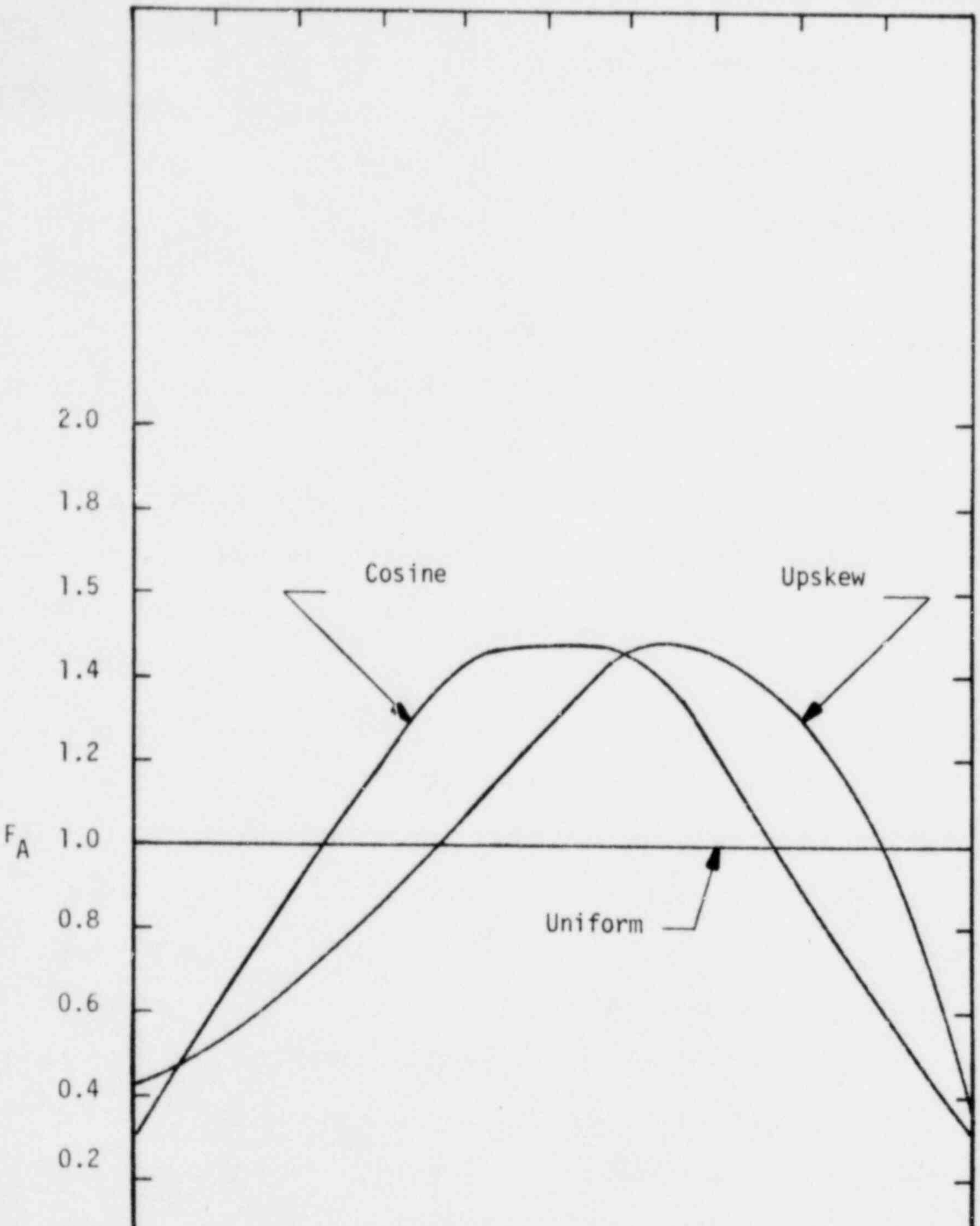

Figure 4.4 Axial Power Profiles

4.2 PREDICTION OF TWO PHASE DATA

The two phase pressure drop data acquired during critical heat flux testing were predicted for five separate test assemblies, three separate axial power profiles and a wide variety of operating conditions as indicated in Table 1.1. A statistical summary of the two phase data predictions is shown in Table 4.4. The overall mean relative error and standard deviation were determined by considering the between set as well as within set variations of the relative error.

The variation of the calculated and measured pressure drop as a function of inlet subcooling and mass velocity is shown in Figure 4.5 for the cosine data at 1000 psia. The methodology used represents the trends of the data well, indicating that all components of the two phase pressure drop,

are calculated with accuracy.

The trend of the relative error with absolute pressure is shown in Figure 4.6 for three test assemblies at a mass velocity of 1×10^6 lb/hr-ft^2. There is no significant trend in the error with pressure indicating that the calculational method used for void fraction and two phase friction multiplier correctly predicts the dependence of pressure drop on operating pressure.

The variation of the relative error with mass velocity at 1000 psia is shown in Figures 4.7 to 4.9 for the cosine, upskew and uniform-3 test assemblies. Although a slight trend with mass velocity is discernable, the magnitude of the variation is small, and is present only for relatively low mass velocities. Figures 4.6 through 4.9 indicate that the standard

TABLE 4.4

STATISTICAL SUMMARY OF TWO PHASE DATA PREDICTIONS

Overall	419	-0.0269	0.0329

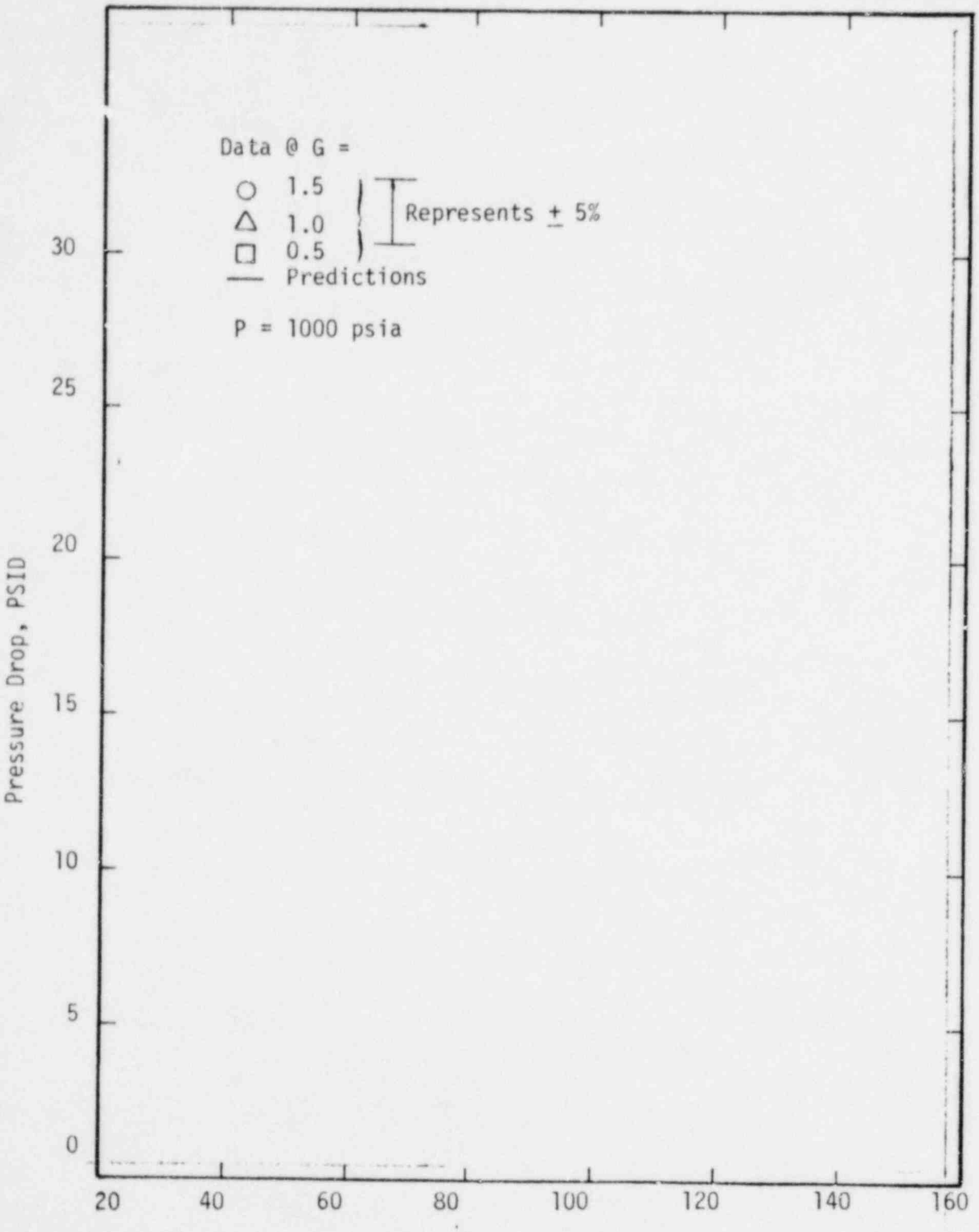

Figure 4.5 Variation of Pressure Drop with Inlet Subcooling for Cosine Axial Power Profile

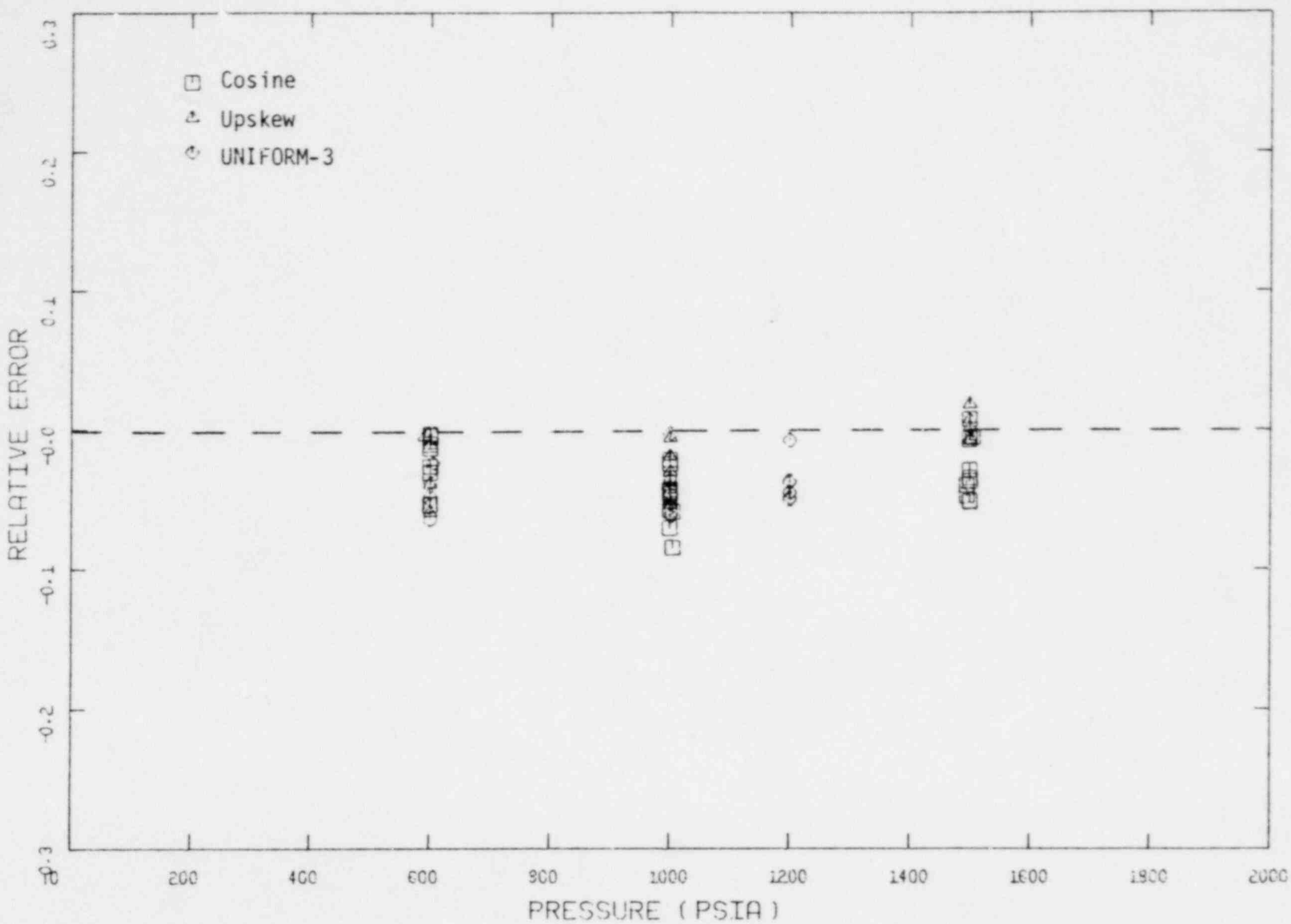

Figure 4.6 Variation of Relative Error with Pressure at a Mass Velocity of 1×10^6 lb/hr-ft^2.

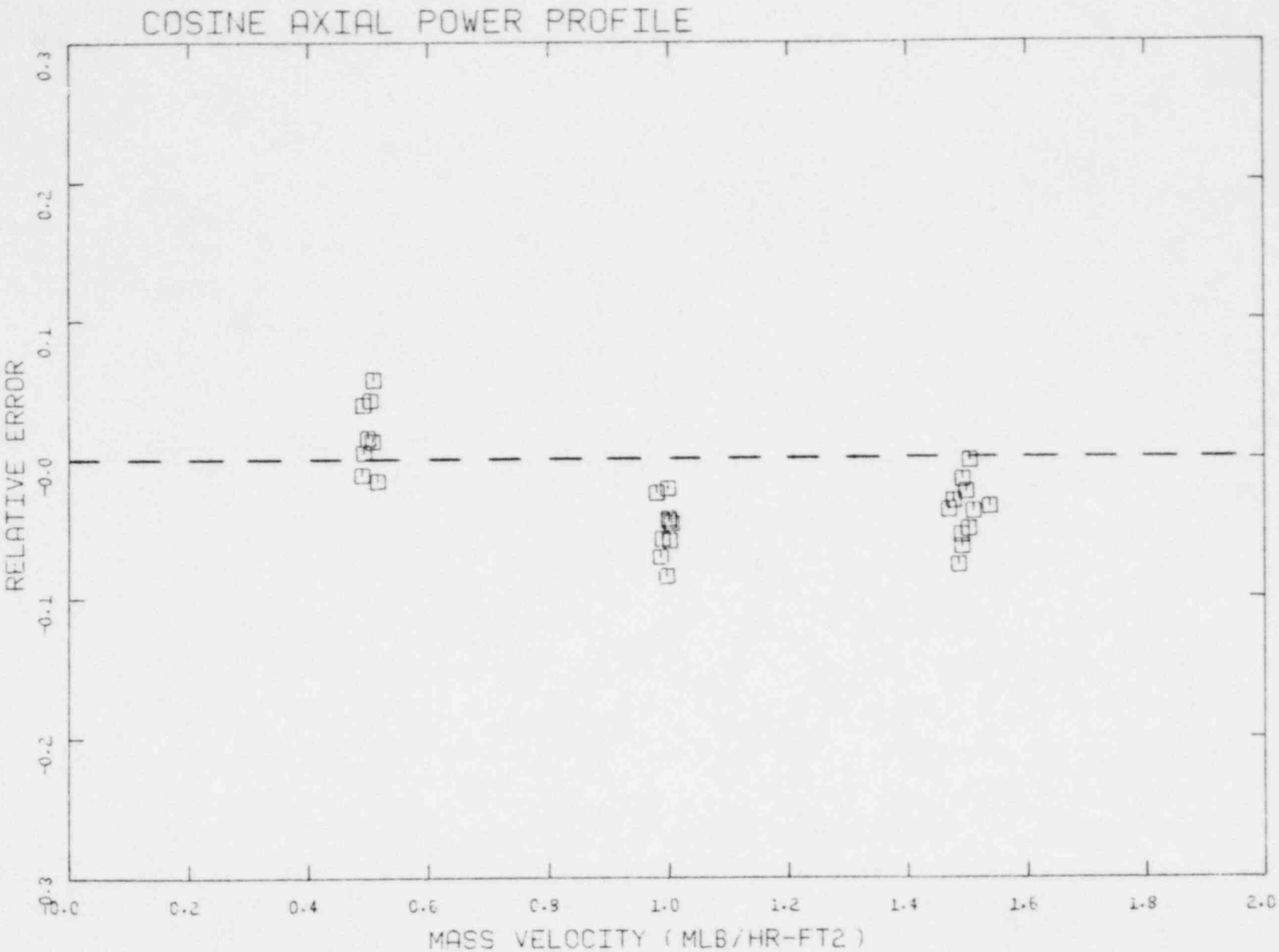

Figure 4.7 Variation of Relative Error with Mass Velocity for Cosine Assembly at 1000 psia.

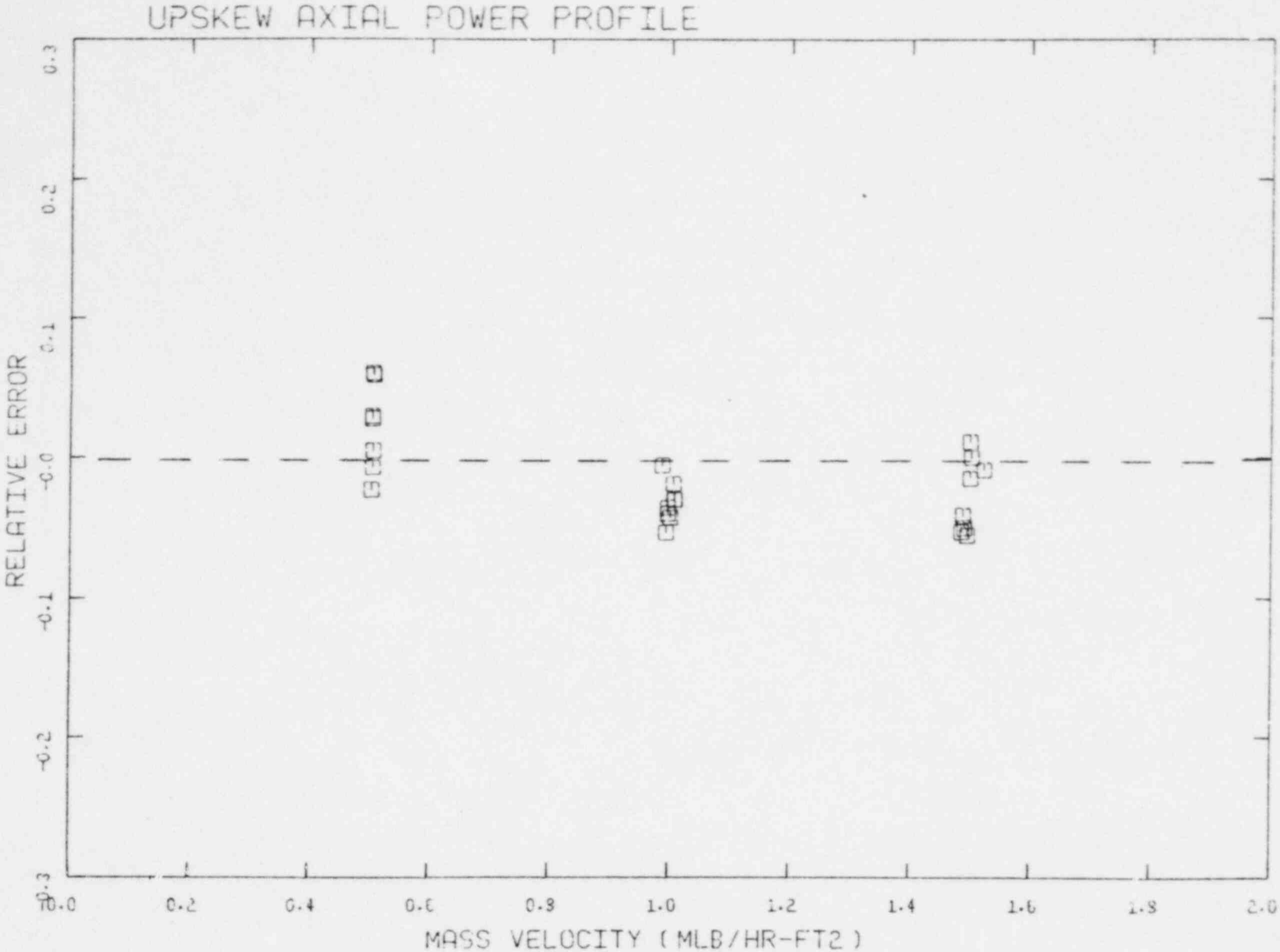

Figure 4.8 Variation of Relative Error with Mass Velocity for Upskew Assembly at Pressure of 1000 psia.

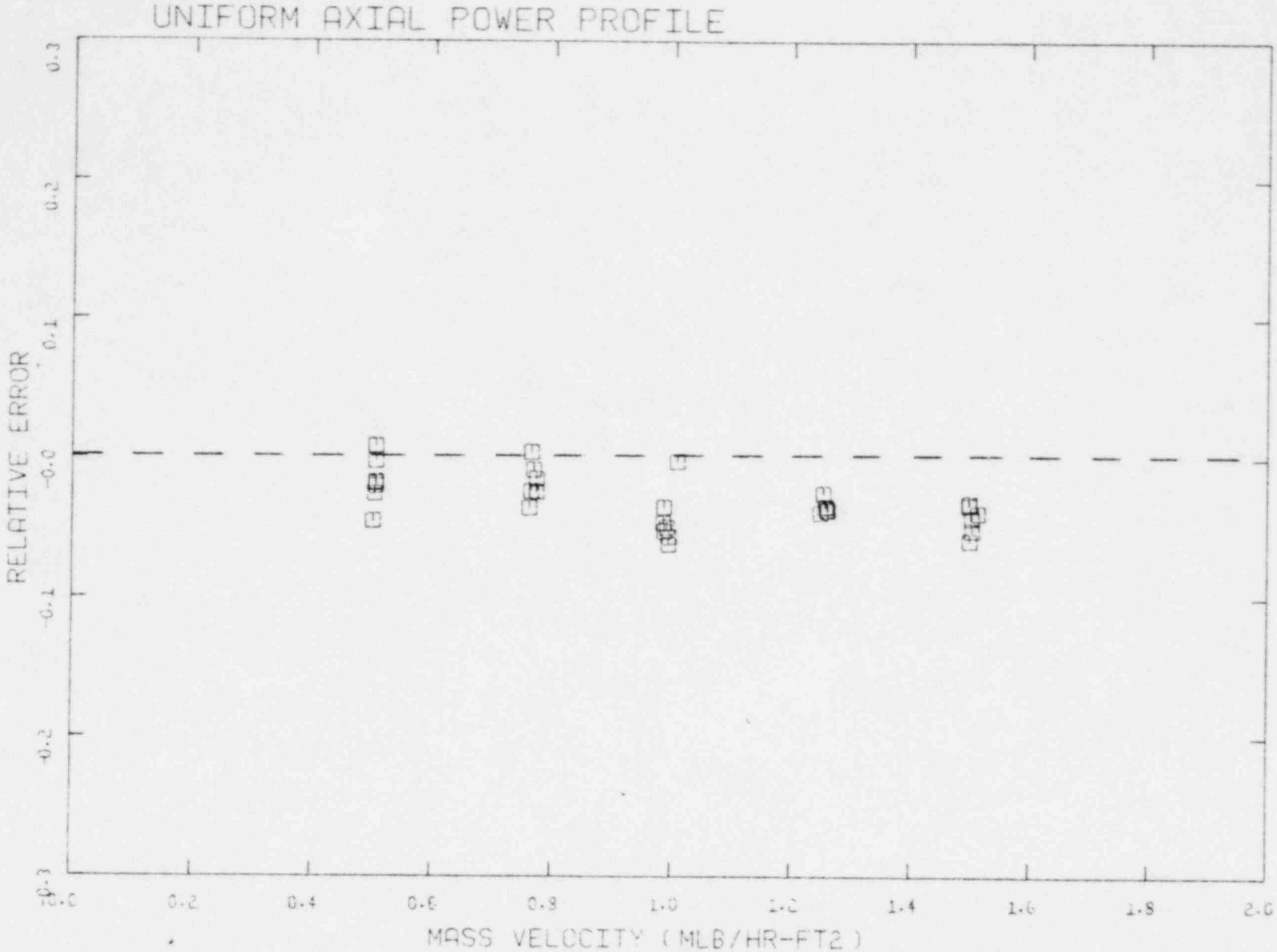

Figure 4.9 Variation of Relative Error with Mass Velocity for UNIFORM-3 Assembly at a Pressure of 1000 psia.

deviation of the relative errors at any single mass velocity and pressure is slightly less than two-percent.

Table 4.4 shows there is no variation in the mean relative error and standard deviation of the pressure drop predictions for the data taken on assemblies with nonuniform axial power distributions (cosine and upskew). The pressure drop predictions of the data taken on assemblies with uniform axial power profiles have mean relative errors as well as standard deviations different from those of the nonuniform axial data. Furthermore, the mean relative errors of the uniform axial data vary among each other. Because the standard deviations remain constant, the uniform axial data is likely to be from the same population but with shifted means. No physical explanation consistent with the bundle average modeling approach can be given for the observed shift in the mean relative errors, but the shift has been included in the statistical analysis of the data.

The difference between the mean relative errors of the uniform axial group and the nonuniform axial group as well as the difference between the mean relative errors of the single and two phase data is believed to be at least partially attributable to the numerical procedure

It is also possible that small but systematic errors in either the void fraction correlation or the two phase friction multiplier correlations could produce the differences in the mean relative errors. Other possible causes are the instrumentation and reduction of the single phase data to determine spacer loss coefficients. It is impossible to positively determine the cause of the shifts in mean relative error because the shifts are not statistically significant for a particular data set.

The two phase pressure drop data comparisons were statistically combined to determine an overall mean relative error and standard deviation as shown in Table 4.4. The variation in the mean relative error between data sets resulted in an augmentation of about 1.6-percent in the overall standard deviation. The normal distribution defined by the overall mean relative error and the overall standard deviation is shown in Figure 4.10 superimposed on a histogram of the data comparisons. The data comparisons are seen to be distributed non-normally, and fairly uniform over an error range from -5.5 percent to + 0.5 percent. Table 4.5 gives a comparison of the observed observations and expected observations assuming the normal distribution for various ranges about the overall mean. Because there are more observations close to the overall mean than are expected, it is conservative to represent the data comparison as a normal distribution.

Table 4.5

Comparison of Two Phase Pressure Drop Data
Comparison With A Normal Distribution

Range from Overall Mean in Standard Deviations	Observed Frequency	Expected Frequency From a Normal Distribution
± 1/4	151	83
± 1/2	224	160
± 1	336	286
± 1 1/2	383	363
± 2	402	400
± 2 1/2	410	414

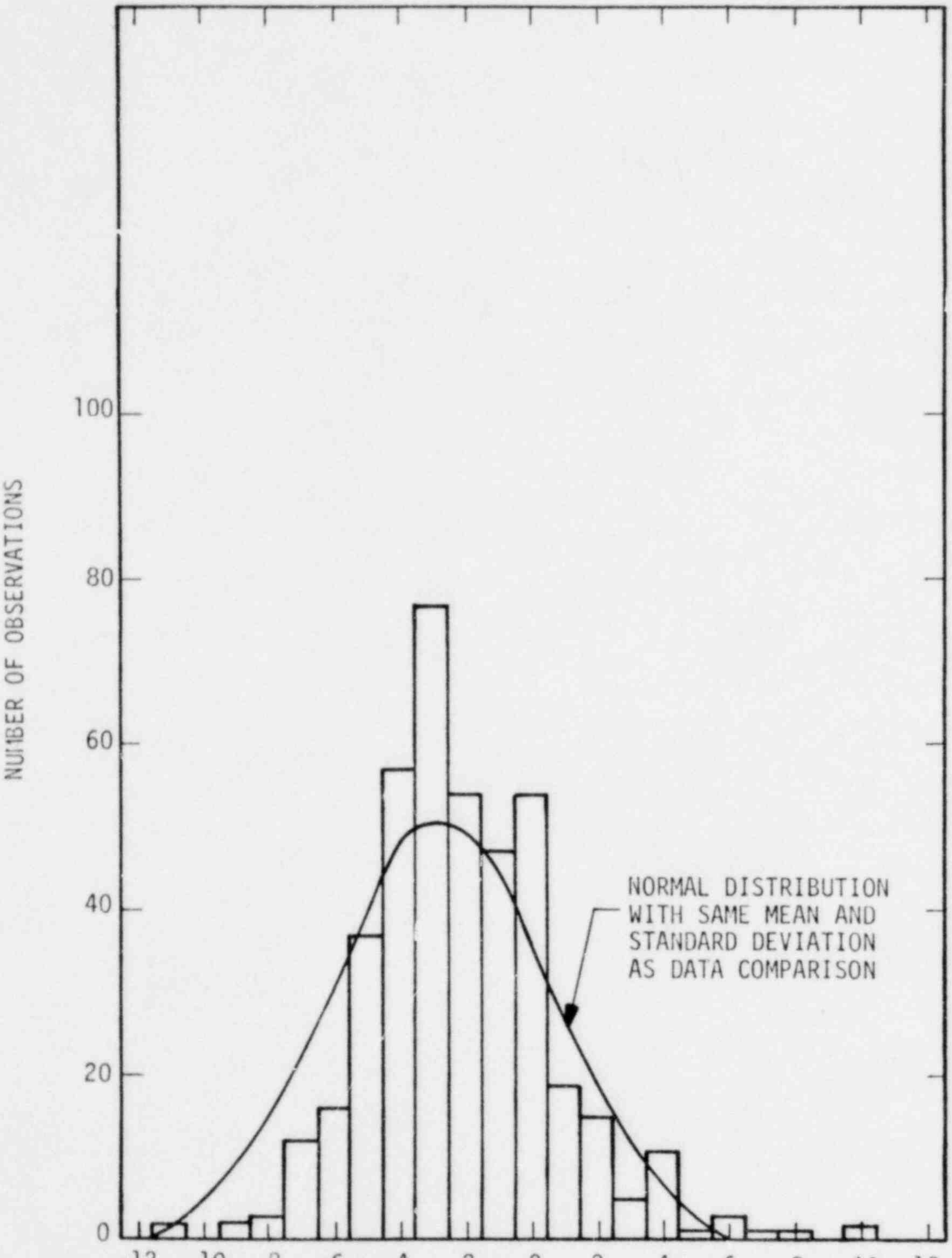

Figure 4.10 Histogram of two-phase pressure drop data comparison.

REFERENCES

1)

2)

3)

4) R. T. Lahey, Jr. and F. J. Moody, The Thermal-Hydraulics of a Boiling Water Nuclear Reactor, ANS Monogram, 1977.

5)

6)

7)

8) J. Yates, "Preliminary Report on KRB 7x7 Pressure Drop Test," XN-NF-77-63, December 1977.

9) K. P. Galbraith, "Evaluation of Single Phase Flow Hydraulic Loss Coefficients and Friction Factor for Oyster Creek 8x8 Fuel Design," April 1974.

10) C. J. Boroczy, "A Systematic Correlation for Two Phase Pressure Drop," NAA-SR-MEMO 11858, Atomics International, March 1966.

11) J. G. Collier, Convective Boiling and Condensation, McGraw-Hill, London, U.K. 1972.

NOTATION

C_D	Spacer Loss Coefficient
C_o	Parameter in Void Fraction Correlation
D	Hydraulic Diameter, ft
E	Relative Error
f	Bare Rod Friction Factor
g	Gravity Acceleration, 32.17 ft/sec^2
g_c	English Unit Conversion Factor, 32.17 $lbm\text{-}ft/lb_f\text{-}sec^2$
G	Mass Velocity, lbm/sec ft^2
j	Volumetric Flux or Superficial Velocity, ft^3/ft^2sec or ft/sec
P	Pressure, lb_f/ft^2 or psi
ΔP_m	Measured Pressure Drop, psi
ΔP_p	Calculated Pressure Drop, psi
V_{gj}	Parameter in Void Fraction Correlation, ft/sec
X	Mass Flow Quality
Z	Axial Length or Position, ft
α	Void Fraction
Δ	Change in Quantity
ν	Specific Volume, ft^3/lbm
ρ	Density, lbm/ft^3
σ	Surface Tension, lb_f/ft
ϕ^2	Two-Phase Friction Multiplier

NOTATION (contd)

Superscripts and Subscripts

e	Based upon assumption of thermodynamic equilibrium
f	Saturated Fluid
g	Saturated Vapor
l	Liquid, either subcooled or saturated
-	Average or Superficial

(A-1)

(A-2)

(A-3)

(A-4)

(A-5)

(B-1)

(B-2)

(B-3)

(B-4)

(B-5)

(B-6)

(B-7)

(B-8)

(B-9)

(B-10)

(B-11)

XN-NF-79-59(NP)

Issue Date: 08/13/80

METHODOLOGY FOR CALCULATION OF PRESSURE DROP IN BWR FUEL ASSEMBLIES

Distribution

GF Owsley

TW Patten

JF Patterson

USNRC/GF Owsley (20)

Document Control (5)