TABLE II (continued)

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March 26, 1964

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TO: J. P. MALONEY

FROM: R. H. TOWELL *R. H. Towell*
PILE ENGINEERING DIVISION

NEW BURNOUT CORRELATION FOR ANNULI

INTRODUCTION:

A number of burnout tests have been run subsequent to the publication of the burnout equations in DP-355 and DP-725. The range of variables was extended in these tests and the burnout heat flux was measured. This memorandum presents a modified empirical equation, which correlates the new data, for use in the design of fuel assemblies for the HWCTR. We expect to submit this material for a journal publication within the next quarter.

SUMMARY:

The results of 193 burnout tests of heated surfaces cooled by water in annuli were correlated with a standard deviation of 9.1% by the empirical equation:

$$\phi_{BO} = 257{,}000\ (1+0.040V)(1+0.030T_S).$$

The maximum deviation of the data from the equation is plus 26.1% and minus 22.8%. The range of variables correlated by the Equation is:

V, velocity of coolant: 5 to 42 ft/sec
T_S, subcooling: 10 to 95°C
ϕ_{BO}, heat flux at burnout: 1/2 to 2×10^6 pcu/(hr)(ft^2)
Pressure: 25 to 1200 psia
Length of heated surface: 19 to 40 inches
Annuli: ID, 1/2 inch to ∞ ; OD, 3/4 inch to ∞
Equivalent diameter: 1/4 to 1 inch
Vertically downward flow of water

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The annular burnout tests were obtained on the Strip Heater and Internally Heated Annulus at SRL and on an annulus formed by large tubes at Columbia University. The Strip Heater mocks up a portion of the annulus formed by two very large tubes and the Internally Heated Annulus used a 1/2-inch diameter heater tube housed in 3/4 to 1-1/2 inch ID glass tubes. The annulus tested at Columbia University was formed by two metal tubes 2.90-inches ID and 2.25-inches OD; only the inner tube was heated. All three units were resistance heated by direct current and cooled by vertically downward flowing water.

RECOMMENDATIONS:

The new burnout correlation is recommended for calculating the burnout safety factor; BOSF, in annular coolant channels of HWCTR fuel assemblies. The minimum BOSF to be used with the equation is 1.30, which is slightly larger than 3 standard deviations, 3σ. All of the 193 data points correlated by the equation were within the 3σ value.

DISCUSSION:

Background

In reactor operation a safe margin must be maintained between the operating heat flux and the burnout heat flux in order to prevent melting of the fuel and cladding. If the power density of the reactor is to be optimized, the burnout heat flux must be defined in order that the reactor may be operated at the minimum safe margin.

In DP-355, an empirical equation that correlated the results of 65 burnout tests on electrically-heated mockups was presented. A number of burnout tests have been run since DP-355 was published that extend the range of heater geometries and coolant variables. In particular, the pressure range has been extended to 1200 psi.

The DP-355 burnout equation,

$$\phi_{BO} = 266{,}000\ (1+0.0365V)(1+0.00914T_S)(1+0.0131P),$$

contains a linear pressure term that, as was stated in DP-355, "should not be extrapolated beyond the range of pressures listed (25 to 85 psia) without correcting for the decreased effect of pressure".

An equation that correlated the results of the initial high pressure tests was published in DP-725. Twenty-four burnout tests in the pressure range 60 to 1200 psia were correlated by the equation:

$\phi_{BO} = 490{,}000\ (1+0.040V)(1+0.010T_S)$. As shown by the equation, there was no appreciable pressure effect on burnout in the range 60 to 1200 psia. However, the equation was limited to the subcooling range 35 to 75°C.

In this memorandum, the burnout equations are modified to fit over the pressure range 25 to 1200 psia and the subcooling range 10 to 95°C for which data is now available.

Source of Data and Description of Equipment

SRL Strip Heater

A total of 64 burnout tests were made in the Strip Heater at SRL. The results are presented in Table I. Results of 55 tests were used in deriving the correlation; the other 9 were eliminated for the reasons indicated in Table I.

The Strip Heater, which represents a portion of an annulus formed by two very large tubes, consists of a 19-inch long by 2-inch wide metal strip that was resistance heated by direct current. Heat was transferred through one face of the strip into a rectangular coolant channel; the other face and the edges of the strip were "adiabatic". The coolant channel wall opposite the heated surface was transparent so that the tests could be observed. Water was pumped vertically downward, and the thickness of the coolant channel was varied from 1/8 to 1/4 inch.

SRL Internally Heated Annulus

A total of 71 burnout tests were made in the Internally Heated Annulus at SRL. The results are presented in Table II. Results of 69 tests were used in deriving the correlation; the other 2 were eliminated for the reasons indicated in Table II.

The Internally Heated Annulus tested at SRL consists of a 24-inch long by 0.500-inch OD tube that was resistance heated by direct current. Heat was transferred through the outer surface of the heated tube into an annular coolant channel formed by the heater and a glass outer-housing tube. Water was pumped vertically downward, and the equivalent diameter of the channel was varied from 0.25 to 1.00 inches (by varying the ID of the glass housing tube).

Columbia University Internally Heated Annulus

A total of 121 burnout tests were made in an Internally Heated Annulus at Columbia University; results were presented in Table VII of DP-805. Results of 33 tests were not used in deriving the correlation because of the anomalous conditions reported in DP-805. Results of the remaining 88 burnout tests are repeated in Table III for convenience. Sixty-nine of these tests were used in deriving the correlation; the other 19 were eliminated for the reasons indicated in Table III.

The Internally Heated Annulus tested at Columbia University was formed by two concentric tubes. The OD of the annulus was 2.90-inch and the ID was 2.25-inch. The inner tube was resistance heated by direct current and cooled only on the outer surface. The length of the heated surface was 24 and 40 inches.

Correlation of Burnout Results

The results of 193 burnout tests in annuli heated on one surface were correlated with a standard deviation of 9.1% by the equation:

$$\phi_{BO} = 257{,}000\ (1+0.040V)(1+0.030T_S),$$

where,

ϕ_{BO} = heat flux at burnout in Pcu/hr-ft^2,
V = mean velocity at the burnout site in ft/sec, and
T_S = mean subcooling at the burnout site in °C.

The burnout heat flux predicted by the equation is compared graphically with the measured value in Figure 1. The spread lines shown on Figure 1 correspond to twice the standard deviation or 18.2%. The maximum deviation from the equation is plus 26.1% and minus 22.8%.

Burnout heat fluxes measured at subcoolings less than 10°C at any velocity or with subcoolings up to 20°C and velocities less than 5 ft/sec are higher than predicted by the equation and were not used in determining the empirical constants and standard deviation. These points are identified in the drift plots in Figures 2 and 3 which show how the equation fits the data over the velocity and subcooling ranges. As shown in Figures 2 and 3, the equation predicts burnout heat fluxes that are as much as 45% below the measured burnout heat fluxes, for the following combinations of velocity and subcooling.

$V < 5$ ft/sec	$T_S < 20$°C
$V < 10$ ft/sec	$T_S < 15$°C
$V < 42$ ft/sec	$T_S < 10$°C

The correlation fits the data well at the extremes of the ranges tested as is shown in Table IV. The pressure, equivalent diameter, velocity and subcooling are divided into 3 levels (small, medium, and large) and the data grouped according to the level of each variable. The number of points in each of the 81 groups and the average and maximum deviations of the measured heat flux from the correlation are given.

The burnout results obtained on the 3 test sections are consistent with each other. The mean deviations of the data from the correlation when grouped according to the test section and the site are:

Site	Test Section	Number of Tests	Arithmatic Mean Deviation
SRL	Strip Heater	55	-2.1%
SRL	Internally Heated Annulus	69	+4.2%
Col. Univ.	Internally Heated Annulus	69	-2.4%

The burnout heat flux in these 193 tests was not affected by the pressure. The results are plotted against the pressure in Figure 4. Figure 4 shows that there is no consistent drift of the data from the correlation in the pressure range covered, and the standard deviation of the correlation cannot be decreased significantly by inclusion of a pressure term. It is therefore concluded that the pressure in the range 25 to 1200 psia does not affect subcooled, forced convection burnout appreciably.

The slope constants in the velocity and subcooling terms of the equation were selected, with aid of the IBM 704, to minimize the standard deviation of the correlation. The IBM 704 was coded to calculate the value of the intercept, D, in the equation $\phi = D(1+AV)(1+BT_S)$ for each burnout test, the average value, $\bar{D}$, for all the tests, and the standard deviation of D from $\bar{D}$. A number of values of the slope constants, A and B, were tested as shown in Table 5. The standard deviation of the correlation is minimized by the selected slope constants, but the standard deviation of the equation with the other slope constants shown in Table 5 is increased only a few percentage points from the minimum value. Thus, the burnout equation could be written with the values of the constants A, B, and D quite different from the selected values without significantly increasing the spread of the data. If the range of velocity and subcooling is extended by future tests, the constants may be altered to fit the new data at the extremes.

The departure of the measured burnout heat flux from the linear relationship of the correlation in the low subcooling and velocity ranges as shown in Figures 2 and 3 is probably due to an additional mechanism. An increase in the vibration of the test section and increase in the intensity of the sound originating in the test section were observed at SRL during burnout tests in the low subcooling and velocity regions. In some of these tests, the coolant flow in the test section was unstable (in short regions the flow appeared to stop or reverse itself even though the supply pressure to the test section remained constant). The departure of the burnout heat flux from the linear relationships with velocity and subcooling may be caused by the surging coolant flow or by the vibration of the heated surface induced by these surges, but the exact mechanism has not been identified.

Comparison of Correlations

The burnout correlation of DP-355,

$$\phi_{BO} = 2.66\text{x}10^5\ (1+0.0365V)(1+0.00914T_S)(1+0.0131P),$$

fits the data over small subcooling spans of about 30°C when the pressure term is evaluated between 25 and 85 psia. The DP-355 correlation and the new correlation are compared with each other and the data in Figure 5. The data points in Figure 5 are 3 to 6% below their proper position relative to the DP-355 correlation, because the slope constant in the velocity term on the ordinate of Figure 5 is larger than the slope constant in the DP-355 equation. When evaluated at 25 psia, the DP-355 correlation fits the data with subcoolings between 10 and 35°C; and when evaluated at 65 psia the DP-355 correlation fits the data with subcoolings between 55 and 85°C.

The data available to DP-355 are identified by solid symbols in Figure 5. The flagged symbols are the data points that were excluded from the new correlation for the reasons given in Tables 1 and 2. Three of the points used in DP-355 were excluded from the new correlation because the subcooling was less than 10°C. As discussed previously, burnout results in this region are as much as 90% above the new correlation probably due to flow surges. The shallow slope of the subcooling term of the DP-355 equation was determined largely by these three low subcooling points which are now known to be of a different family than the high subcooling points.

The correlation of DP-725 predicts burnout heat fluxes that are as much as 56% above the "best fit" of the burnout results with subcoolings between 10 and 50°C. The correlation of DP-725, the new correlation, and the burnout data are compared on Figure 6. The solid points represent the data correlated by the DP-725 equation. At 50°C subcooling, the DP-725 correlation predicts burnout heat fluxes 12% above the new correlation and at 10°C subcooling, the DP-725 equation is 56% high. The DP-725 equation correlated only 24 data points obtained in the SRL internally heated annulus with subcoolings in the range of 35 to 75°C. Further tests in the SRL annular test section with subcoolings between 25 and 35°C and between 75 and 95°C showed that the effect of subcooling is much stronger than predicted by the DP-725 equation.

Effect of Pressure on Burnout Heat Flux

The burnout correlation has no pressure term and as shown in Figure 4 the fit of the correlation would not be improved by the addition of a pressure term. This behavior, which indicates that burnout in forced convection, subcooled flow is not affected by pressure, is contrary to what one is led to expect by the relationship between pressure and the specific volume of steam. The specific volume of steam and the latent heat of vaporization of water for several pressures are given in the following table:

Pressure psia	V_g ft^3/lb	λ_v BTU/lb	V_g/λ_v ft^3/BTU
25	16.3	952	17.1×10^{-3}
100	4.41	889	4.96×10^{-3}
1200	0.340	622	0.545×10^{-3}

With two identical heaters operated at the same heat flux, velocity, and subcooling but one at 25 psia and the other at 1200 psia, approximately 1/30, $\left[\frac{V_g}{\lambda_v}_{1200} \div \frac{V_g}{\lambda_{v25}}\right]$, as much vapor volume will be generated at the surface of the heater operated at the higher pressure. If the heat flux on the heater operated at 25 psia produces sufficient vapor to cause burnout, one would expect that at the higher pressure the vapor generated by the same heat flux would be insufficient to produce burnout because the volume produced is decreased 30 times. In order to increase the volume produced at the higher pressure to the burnout level, one would increase the heat flux; i.e., one would expect the burnout heat flux to increase with increasing pressure.

However, the test results show that the burnout heat flux is not affected by the pressure and the above analysis cannot be correct. The absence of a pressure effect on burnout must mean that the instantaneous steam volume at the surface is not affected by the pressure even though the volume generated per unit of heat is strongly affected by the pressure. In the above analysis, the lifetime of the bubbles on the heated surface was assumed to be constant, but if the bubble lifetime varied with pressure equal and opposite to the change in steam volume, the instantaneous volume at the surface would be independent of the pressure. Although there is no lifetime equation describing the growth and decay of a bubble generated on a heated surface with subcooled forced convection, a qualitative description can be given.

When a bubble is formed at a heated surface, which is submerged in subcooled water, practically all the heat and vapor that go into the bubble come from the layer of superheated liquid adjacent to the surface. A bubble grows until it has discharged all the superheated liquid in its vicinity and then, since its top is in subcooled liquid, it will begin to collapse. Inrushing, subcooled water will reduce the bubble to a nucleus, and the cycle will be repeated as soon as the liquid is superheated.

The lifetime of a bubble is determined by its growth rate, i.e., how fast it discharges the local superheat and triggers its own collapse. A fast-growing bubble will have a short lifetime and a slower-growing bubble will have a longer lifetime. The lifetime of a bubble, L, may be expressed by the proportionality:

$$\frac{1}{L} \propto \frac{dV}{d\theta} \quad \text{where } \frac{dV}{d\theta} \text{ is the volumetric growth rate of a bubble.}$$

The rate of bubble growth in superheated water is given by the Zwick-Plesset equation(1), $\frac{dV}{d\theta} = \frac{V_g}{\lambda_v} \frac{k_L\, 4\pi R^2 (T_L - T_v)}{(\pi \alpha_L \theta/3)^{\frac{1}{2}}}$. This equation shows that the volumetric growth rate, $dV/d\theta$, is proportional to V_g/λ_v, the volume of vapor generated per unit of heat. The other terms in the equation are geometrical constants or physical properties that are not functions of the pressure.

The effect of pressure on the lifetime of a bubble is obtained as follows:

$$1/L \propto dV/d\theta \propto V_g/\lambda_v$$

$$\therefore \quad \frac{L_{25}}{L_{1200}} = \frac{(V_g/\lambda_v)_{1200}}{(V_g/\lambda_v)_{25}}$$

The right hand term can be evaluated from the preceding table.

$$\frac{L_{25}}{L_{1200}} = \frac{0.545 \times 10^{-3}}{17.1 \times 10^{-3}}$$

or

$$\frac{L_{25}}{L_{1200}} = \frac{1}{30}$$

The last equation shows that the bubble lifetime at 25 psia is 1/30 the bubble lifetime at 1200 psia.

The volume of steam, S, on a surface cooled by boiling must be directly proportional to heat flux, Ø; the volume of vapor generated per unit of heat, V_g/λ_v; and the lifetime of the bubbles, L; or $S \propto Ø\,(V_g/\lambda_v)L$. Again comparing two identical heaters operated at the

(1) Advances in Chemical Engineering Vol. I, 1956, page 69, Edited by T. B. Drew and J. W. Hoopes, Jr.

same heat flux, velocity and subcooling but one at 25 psia and the other at 1200 psia, the effect of pressure on the volume of steam at the two surfaces may be obtained from the last proportionality:

$$\frac{(S)_{25}}{(S)_{1200}} = \left[\frac{(Vg/\lambda v)_{25}}{(Vg/\lambda v)_{1200}}\right] \left[\frac{(L)_{25}}{(L)_{1200}}\right]$$

or

$$\frac{(S)_{25}}{(S)_{1200}} = \left[\frac{30}{1}\right] \left[\frac{1}{30}\right]$$

At 25 psia the volume of vapor formed is 30 times larger than at 1200 psia, but the lifetime of the bubbles at 25 psia is only 1/30 the lifetime at 1200 psia. The vapor volume on the surface and the burnout heat flux of the two heaters are not affected by the pressure because any change in the generated volume caused by changing the pressure is compensated by an equal and opposite change in the lifetime of the bubbles.

RHT/jj

TABLE I

EXPERIMENTAL RESULTS - BURNOUT WITH SUBCOOLED WATER IN SRL STRIP HEATER

Run No.	Equivalent Diameter Inches	Coolant Velocity ft/sec	Pressure psia	Sub-cooling °C	Measured Heat Flux at Burnout, 10^6 pcu/hr-ft^2	Predicted Heat Flux at Burnout, 10^6 pcu/hr-ft^2	Deviation Meas. from Predicted %
R001	0.250	19.0	38.	46.0	0.88	1.08	-18.3 (a)
R002	0.250	19.0	38.	39.0	0.85	0.98	-13.2 (a)
R003	0.250	18.0	37.	74.0	1.02	1.42	-28.4 (a)
R004	0.250	19.0	36.	44.0	0.88	1.05	-16.0 (a)
R005	0.250	19.0	38.	42.0	0.81	1.02	-20.7 (a)
R006	0.250	19.0	40.	29.0	0.82	0.85	-3.2 (a)
R007	0.250	19.0	42.	40.0	0.83	1.00	-16.8 (a)
R008	0.250	18.0	42.	16.0	0.70	0.65	7.0
R009	0.250	18.0	44.	10.0	0.74	0.57	28.8 (b)
R010	0.250	19.0	40.	6.0	0.74	0.53	38.5 (b)
R011	0.250	20.0	43.	30.0	0.94	0.88	7.0
R012	0.250	19.0	39.	29.0	0.98	0.85	16.0
R013	0.250	19.0	39.	28.0	0.92	0.83	10.5
R014	0.250	17.0	38.	41.0	0.99	0.96	2.7
R015	0.250	19.0	40.	23.0	0.82	0.96	7.4
R016	0.250	20.0	39.	49.0	1.13	1.14	-1.2
R017	0.250	19.0	39.	57.0	1.15	1.23	-6.3
R018	0.250	19.0	39.	29.0	0.99	0.84	17.1
R019	0.460	19.0	50.	45.0	0.94	1.06	-11.7
R020	0.470	19.0	50.	45.0	1.00	1.06	-5.9
R021	0.460	19.0	50.	45.0	1.00	1.06	-5.9
R022	0.460	19.0	51.	55.0	1.21	1.20	0.7
R023	0.460	19.0	51.	63.0	1.21	1.31	-7.4
R024	0.450	19.0	51.	71.0	1.40	1.41	-1.2
R025	0.470	19.0	51.	72.0	1.35	1.43	-5.5
R026	0.240	33.0	50.	45.0	1.41	1.40	0.7
R027	0.240	34.0	60.	55.0	1.64	1.61	1.9
R028	0.250	34.0	49.	33.0	1.20	1.20	-0.4
R029	0.250	34.0	49.	43.0	1.33	1.38	-4.3
R030	0.260	33.0	50.	51.0	1.53	1.50	1.5
R031	0.260	33.0	49.	56.0	1.56	1.59	-2.4
R032	0.240	33.0	60.	41.0	1.28	1.33	-3.9
R033	0.260	33.0	49.	26.0	1.34	1.06	26.1
R034	0.250	34.0	49.	59.0	1.52	1.67	-9.4
R035	0.250	34.0	50.	61.0	1.49	1.71	-13.3
R036	0.250	34.0	52.	65.0	1.63	1.79	-9.0

(a) Poor heat balance.

(b) $T_S < 10°C$.

TABLE I (continued)

R037	0.340	16.0	41.	23.0	0.69	0.71	-3.2
R038	0.340	17.0	40.	42.0	0.86	0.97	-11.7
R039	0.340	18.0	39.	59.0	0.95	1.23	-22.7
R040	0.340	18.0	40.	56.0	1.07	1.19	-9.8
R041	0.340	18.0	39.	45.0	0.90	1.04	-13.3
R042	0.240	33.0	25.	50.0	1.19	1.49	-20.2
R043	0.250	33.0	25.	44.0	1.21	1.38	-12.5
R044	0.250	5.0	39.	36.0	0.57	0.64	-11.3
R045	0.240	42.0	55.	35.0	1.31	1.42	-7.4
R046	0.240	42.0	55.	39.0	1.39	1.50	-7.1
R047	0.240	42.0	55.	57.0	1.64	1.87	-12.1
R048	0.250	39.0	55.	54.0	1.77	1.72	2.7
R049	0.260	38.0	55.	53.0	1.76	1.67	5.1
R050	0.260	38.0	55.	54.0	1.62	1.70	-4.7
R051	0.260	33.0	86.	61.0	1.72	1.69	1.9
R066	0.260	35.0	51.	42.0	1.57	1.40	12.4
R067	0.270	31.0	52.	38.0	1.34	1.23	8.9
R068	0.250	31.0	54.	49.0	1.39	1.42	-2.4
R069	0.390	34.0	86.	49.0	1.54	1.49	2.7
R070	0.220	40.0	51.	38.0	1.44	1.43	0.7
R071	0.270	32.0	51.	37.0	1.32	1.24	6.6
R072	0.270	33.0	50.	43.0	1.36	1.36	-0.4
R073	0.230	31.0	50.	54.0	1.60	1.51	6.2
R074	0.240	32.0	50.	40.0	1.21	1.30	-6.3
R075	0.390	17.0	50.	36.0	0.95	0.89	5.8
R204T	0.240	33.3	50.	61.0	1.40	1.69	-17.6
R205T	0.240	33.3	85.	35.0	1.16	1.23	-5.5
R206T	0.240	32.7	30.	39.0	1.14	1.29	-11.3

TABLE II

EXPERIMENTAL RESULTS - BURNOUT WITH SUBCOOLED WATER IN SRL INTERNALLY HEATED ANNULUS

Run No.	Equivalent Diameter Inches	Coolant Velocity ft/sec	Pressure psia	Sub-cooling °C	Measured Heat Flux at Burnout, 10^6 pcu/hr-ft^2	Predicted Heat Flux at Burnout, 10^6 pcu/hr-ft^2	Deviation Meas. from Predicted %
A052	0.250	10.0	43.	38.9	0.81	0.78	3.9
A053	0.250	20.2	42.	42.0	0.96	1.05	-8.6
A054	0.250	20.2	42.	43.0	1.01	1.06	-5.1
A055	0.250	20.0	41.	34.7	1.03	0.95	8.9
A056	0.250	20.2	37.	6.5	0.81	0.56	45.9 (a)
A057	0.250	20.0	53.	60.5	1.16	1.30	-10.9
A058	0.250	20.0	62.	72.0	1.24	1.46	-15.2 (b)
A059	0.250	20.0	63.	35.0	1.16	0.95	22.1
A060	0.250	19.9	65.	71.5	1.31	1.45	-9.8
A061	0.250	20.3	42.	28.6	0.97	0.86	12.1
A062	0.250	33.5	49.	39.0	1.43	1.30	9.7
A063	0.250	33.5	49.	32.5	1.37	1.19	15.2
A064	0.250	33.5	50.	26.5	1.29	1.08	19.3
A076	0.250	5.4	40.	33.8	0.65	0.63	3.1
A083	0.250	34.3	50.	51.6	1.51	1.56	2.8
A086	0.250	15.0	53.	42.3	1.10	0.94	17.0
A170	0.250	15.3	152.	87.0	1.46	1.49	-2.4
A171	0.250	15.3	30.	44.0	0.99	0.97	3.1
A172	0.250	15.0	93.	40.5	1.04	1.00	14.0
A173	0.250	15.0	95.	50.0	1.04	1.03	1.2
A174	0.250	20.0	100.	47.0	1.09	1.11	-2.4
A077	0.375	31.6	89.	64.6	1.82	1.71	6.6
A084	0.375	24.9	49.	49.1	1.25	1.28	-1.6
A085	0.375	19.8	50.	41.1	1.12	1.03	8.9
A087	0.375	15.0	51.	51.0	1.10	1.03	5.8
A100	0.375	12.0	65.	65.5	1.21	1.13	7.4
A101	0.375	12.0	110.	70.[illegible]	1.26	1.18	6.6
A102	0.375	12.0	25.	42.4	0.98	0.86	13.2
A103	0.375	12.0	100.	57.3	1.25	1.04	21.0
A104	0.375	12.0	40.	52.8	1.04	0.98	5.8
A078	0.500	24.2	88.	54.1	1.66	1.33	25.2
A079	0.500	34.1	63.	48.1	1.66	1.49	11.7
A080	0.500	13.0	65.	64.7	1.24	1.15	7.9
A081	0.500	34.6	65.	60.5	1.85	1.72	7.4
A088	0.500	15.0	53.	49.0	1.08	1.02	6.2
A163	0.500	23.0	524.	44.0	1.31	1.14	14.4

(a) $T_S < 10°C$.

(b) Suspected hot spot.

TABLE II (continued)

A164	0.500	24.5	521.	65.5	1.65	1.50	9.3
A165	0.500	10.4	525.	76.4	1.14	1.20	-4.7
A166	0.500	10.9	521.	34.6	0.89	0.76	18.3
A167	0.500	26.4	1221.	66.6	1.71	1.59	7.8
A175	0.500	20.1	100.	45.0	1.12	1.09	2.7
A176	0.500	19.9	100.	28.0	0.74	0.85	-12.9
A177	0.500	19.8	50.	54.0	1.06	1.20	-12.1
A326D	0.500	15.3	100.	43.0	0.96	0.95	1.2
A327D	0.500	15.0	100.	39.0	0.82	0.89	-8.2
A328D	0.500	15.0	100.	37.0	0.84	0.87	-3.2
A329D	0.500	14.5	100.	28.0	0.73	0.75	-2.4
A330D	0.500	20.0	100.	32.0	0.84	0.91	-7.4
A331D	0.500	20.4	100.	85.0	1.83	1.65	10.5
A332D	0.500	5.0	100.	77.0	0.97	1.02	-5.1
A333D	0.500	5.0	100.	74.0	0.97	0.99	-2.4
A334D	0.500	10.0	100.	36.0	0.81	0.81	8.2
A335D	0.500	10.0	100.	35.0	0.81	0.74	9.7
A336D	0.500	15.0	100.	95.0	1.62	1.59	2.3
A337D	0.500	24.2	100.	42.0	1.11	1.14	-2.8
A338D	0.500	10.0	100.	94.0	1.25	1.38	-9.0
A339D	0.500	10.0	100.	36.0	0.73	0.75	-2.4
A340D	0.500	27.9	100.	91.0	2.08	2.02	2.7
A082	0.750	21.3	63.	59.3	1.35	1.32	1.9
A094	0.750	22.6	90.	73.6	1.72	1.57	9.7
A095	0.750	12.0	65.	64.1	1.17	1.11	5.1
A096	0.750	11.9	27.	45.9	0.87	0.90	-3.6
A097	0.750	11.8	110.	73.8	1.27	1.22	4.3
A098	0.750	11.8	28.	47.3	0.86	0.91	-5.9
A099	0.750	11.8	101.	71.8	1.24	1.19	3.9
A168	0.750	13.2	521.	55.4	1.14	1.05	8.9
A169	0.750	8.5	1141.	74.0	1.10	1.10	-0.8
A323D	0.750	15.0	100.	63.0	1.28	1.19	7.8
A089	1.000	13.5	52.	57.4	1.09	1.08	1.2
A090	1.000	16.4	60.	65.1	1.34	1.26	6.6
A091	1.000	19.2	75.	67.8	1.55	1.40	12.4

TABLE III

EXPERIMENTAL RESULTS - BURNOUT WITH SUBCOOLED WATER IN COLUMBIA UNIVERSITY INTERNALLY HEATED ANNULUS

Data Abstracted From DP-805 - Table VII

Run No.	Equivalent Diameter Inches	Coolant Velocity ft/sec	Pressure psia	Sub-cooling °C	Measured Heat Flux at Burnout, 10^6 pcu/hr-ft^2	Predicted Heat Flux at Burnout, 10^6 pcu/hr-ft^2	Deviation Meas. from Predicted %
C007	0.650	20.0	1000.	15.0	0.64	0.67	-4.7
C008	0.650	20.0	1000.	27.0	0.83	0.84	-0.8
C009	0.650	20.0	1000.	37.0	1.01	0.98	3.5
C010	0.650	20.0	1000.	44.0	1.16	1.07	8.2
C011	0.650	20.0	1000.	33.0	0.93	0.92	1.2
C012	0.650	20.0	1000.	21.0	0.73	0.75	-3.2
C013	0.650	20.0	1000.	5.0	0.52	0.53	-2.4 (a)
C014	0.650	10.0	1000.	39.0	0.73	0.78	-6.7
C015	0.650	10.0	1000.	50.0	0.81	0.90	-10.2
C016	0.650	10.0	1000.	61.0	0.89	1.01	-12.5
C017	0.650	10.0	1000.	70.0	0.95	1.11	-14.8
C018	0.650	10.0	1000.	58.0	0.84	0.98	-14.8
C019	0.650	10.0	1000.	31.0	0.65	0.69	-6.3
C020	0.650	10.0	1000.	23.0	0.61	0.61	0.4
C021	0.650	10.0	1000.	16.0	0.57	0.53	7.0
C022	0.650	10.0	1000.	6.7	0.54	0.43	24.9 (a)
C023	0.650	10.0	1000.	2.8	0.52	0.39	33.5 (a)
C024	0.650	20.0	1000.	21.0	0.68	0.75	-9.7
C025	0.650	20.0	1000.	32.0	0.82	0.91	-9.7
C026	0.650	10.0	1000.	43.0	0.74	0.82	-10.2
C027	0.650	20.0	1000.	33.0	0.86	0.92	-6.7
C028	0.650	20.0	1000.	10.0	0.54	0.60	-10.2
C029	0.650	20.0	1000.	10.0	0.55	0.60	-8.6
C030	0.650	15.0	1000.	3.3	0.49	0.45	8.6 (a)
C031	0.650	15.0	1000.	8.3	0.52	0.51	1.2 (a)
C032	0.650	15.0	1000.	14.0	0.56	0.58	-4.3
C033	0.650	15.0	1000.	23.0	0.64	0.69	-7.8
C034	0.650	20.0	1000.	23.0	0.73	0.78	-6.7
C035	0.650	15.0	1000.	31.0	0.73	0.80	-8.2
C036	0.650	15.0	1000.	39.0	0.82	0.89	-8.2
C037	0.650	15.0	1000.	49.0	0.91	1.02	-10.5
C038	0.650	15.0	1000.	58.0	1.01	1.13	-10.5
C039	0.650	10.0	1000.	54.0	0.82	0.94	-12.9
C040	0.650	20.0	1000.	25.0	0.75	0.81	-7.4
C046	0.650	20.0	500.	9.4	0.65	0.59	9.7 (a)
C047	0.650	20.0	500.	23.0	0.72	0.78	-7.8

TABLE III (continued)

C048	0.650	20.0	500.	30.0	0.78	0.88	-11.3	
C049	0.650	15.0	500.	31.0	0.79	0.79	-0.4	
C050	0.650	15.0	500.	17.0	0.63	0.62	1.6	
C051	0.650	20.0	500.	32.0	0.82	0.91	-9.7	
C052	0.650	20.0	500.	24.0	0.70	0.80	-12.1	
C053	0.650	10.0	1000.	33.0	0.68	0.71	-5.1	
C054	0.650	15.0	1000.	32.0	0.68	0.80	-15.6	
C055	0.650	15.0	1000.	34.0	0.86	0.83	3.5	
C056	0.650	20.0	1000.	24.0	0.86	0.79	8.2	
C057	0.650	20.0	1000.	2.8	0.51	0.50	1.6	(a)
C058	0.650	15.0	1000.	2.8	0.48	0.45	7.8	(a)
C059	0.650	10.0	1000.	3.3	0.50	0.40	26.5	(a)
C060	0.650	10.0	1000.	17.0	0.59	0.54	8.6	
C061	0.650	15.0	1000.	17.0	0.63	0.62	1.6	
C062	0.650	20.0	1000.	17.0	0.71	0.70	1.6	
C063	0.650	10.0	1000.	33.0	0.74	0.72	3.5	
C064	0.650	20.0	1000.	33.0	1.01	0.92	9.7	
C065	0.650	15.0	1000.	32.0	0.84	0.81	4.3	
C066	0.650	10.0	500.	2.8	0.74	0.39	89.9	(a)
C067	0.650	15.0	500.	3.3	0.67	0.45	48.2	(a)
C068	0.650	20.0	500.	3.3	0.61	0.51	19.8	(a)
C071	0.650	10.0	500.	17.0	0.56	0.54	3.1	
C073	0.650	10.0	1000.	8.3	0.55	0.45	22.6	(a)
C074	0.650	15.0	1000.	8.3	0.54	0.51	5.1	(a)
C075	0.650	20.0	1000.	8.9	0.57	0.59	-2.7	(a)
C076	0.650	20.0	1000.	17.0	0.71	0.70	1.6	
C077	0.650	24.0	1000.	17.0	0.75	0.77	-1.6	
C078	0.650	20.0	1000.	17.0	0.70	0.70	0.4	
C079	0.650	20.0	1000.	17.0	0.69	0.70	-4.7	
C080	0.650	5.0	1000.	17.0	0.74	0.47	58.8	(b)
C081	0.650	10.0	1000.	26.0	0.66	0.64	3.1	
C082	0.650	15.0	1000.	25.0	0.72	0.72	0.	
C083	0.650	20.0	1000.	17.0	0.71	0.70	1.6	
C084	0.650	5.0	1000.	34.0	0.72	0.63	15.6	
C085	0.650	15.0	500.	33.0	0.82	0.82	0.4	
C086	0.650	15.0	500.	32.0	0.82	0.80	1.6	

TABLE III (continued)

C087	0.650	10.0	500.	33.0	0.67	0.72	-6.7
C093	0.650	20.0	1000.	23.0	0.72	0.78	-7.8
C094	0.650	20.0	750.	16.0	0.69	0.68	0.8
C095	0.650	10.0	750.	14.0	0.68	0.51	33.1 (c)
C096	0.650	10.0	750.	33.0	0.78	0.72	8.9
C097	0.650	10.0	500.	2.2	0.74	0.38	93.0 (a)
C098	0.650	10.0	500.	7.8	0.74	0.44	66.5 (a)
C102	0.650	20.0	500.	23.0	0.84	0.78	7.4
C105	0.650	15.0	500.	33.0	0.82	0.82	0.4
C107	0.650	20.0	1000.	24.0	0.77	0.79	-3.2
C108	0.650	20.0	1000.	25.0	0.78	0.81	-3.6
C117	0.650	20.0	500.	34.0	0.95	0.93	1.6
C118	0.650	20.0	500.	62.0	1.06	1.33	-19.8
C119	0.650	20.0	1000.	50.0	1.29	1.16	11.7
C120	0.650	20.0	1000.	58.0	1.43	1.27	12.8
C121	0.650	20.0	1000.	66.0	1.56	1.37	13.2

(a) $T_S < 10°C$.

(b) $T_S < 20°C$, $V < 5$ ft/sec.

(c) $T_S < 15°C$, $V < 10$ ft/sec.

TABLE IV

NUMBER OF EXPERIMENTS AND DEVIATIONS FOR COMBINATIONS OF VARIABLES

	P_S, D_S			P_S, D_M			P_S, D_L		
	V_S	V_M	V_L	V_S	V_M	V_L	V_S	V_M	V_L
T_S	0	8 +12.1% +19.3%	1 +26.1%	0	1 -3.2%	0	0	0	0
T_M	4 +3.4% +17.9%	11 +3.9% +22.1%	25 -2.3% -20.2%	4 +7.8% +13.2%	12 -8.9% -22.7%	2 +9.5% +11.7%	3 -2.8% -5.9%	1 +1.9%	0
T_L	0	2 -10.4% -10.9%	3 -13.3% -17.6%	2 +7.6% +7.6%	3 -4.7% -7.4%	0	1 +5.1%	2 +9.5% +12.4%	0

	P_M, D_S			P_M, D_M			P_M, D_L		
	V_S	V_M	V_L	V_S	V_M	V_L	V_S	V_M	V_L
T_S	0	0	0	1 -2.4%	1 -12.9%	0	2 +2.4% +3.1%	4 -3.5 -12.1	0
T_M	2 7.6% 14.0%	1 -2.4%	1 -5.5%	7 +6.1% +21.0%	6 +5.6% +25.2%	1 2.7%	6 +0.7% +8.9%	2 -4.1% -9.7%	0
T_L	0	1 -2.4%	1 1.9%	6 -2.1% -9.0%	3 +7.5% +10.5%	1 6.6%	3 +5.3% +7.8%	2 -5.1% -19.8%	0

	P_L, D_S			P_L, D_M			P_L, D_L		
	V_S	V_M	V_L	V_S	V_M	V_L	V_S	V_M	V_L
T_S	0	0	0	0	0	0	11 +0.9% +8.3%	16 -4.3% -10.2%	0
T_M	0	0	0	0	0	0	17 -4.9% +15.7%	8 +3.8% +12.8%	0
T_L	0	0	0	0	1 +7.8%	0	3 -9.3% -14.8%	1 +13.2%	0

Numbers in blocks are total tests in group, average and maximum deviations from correlation. Subscripts indicate levels of variables.

Range	Small	Medium	Large
P, Pressure	20-80	80-700	700-1200
Equivalent Dia.	0.2-0.3	0.3-0.6	0.6-1.0
V, Velocity	0-15	15-30	30-45
T, Subcooling	10-30	30-60	60-95

TABLE V

STANDARD DEVIATION OF ANNULAR BURNOUT DATA

Percent Standard Deviation (2σ) of Data from the Equation $\phi = D(1+AV)(1+BT_s)$ for Several Values of A and B

B \ A	0.030	0.035	0.040 (Selected Value of A)	0.045	
0.020	20.7%	20.1%	19.9%	20.0%	
0.025	19.5%	18.7%	18.5%	18.7%	
0.030	19.1%	18.4%	18.2%	18.3%	← Selected Value of B
0.035	19.4%	18.7%	18.5%	18.7%	
0.040	20.1%	19.5%	19.3%	19.4%	

FIGURE 1

BURNOUT CORRELATION FOR ANNULAR CHANNELS

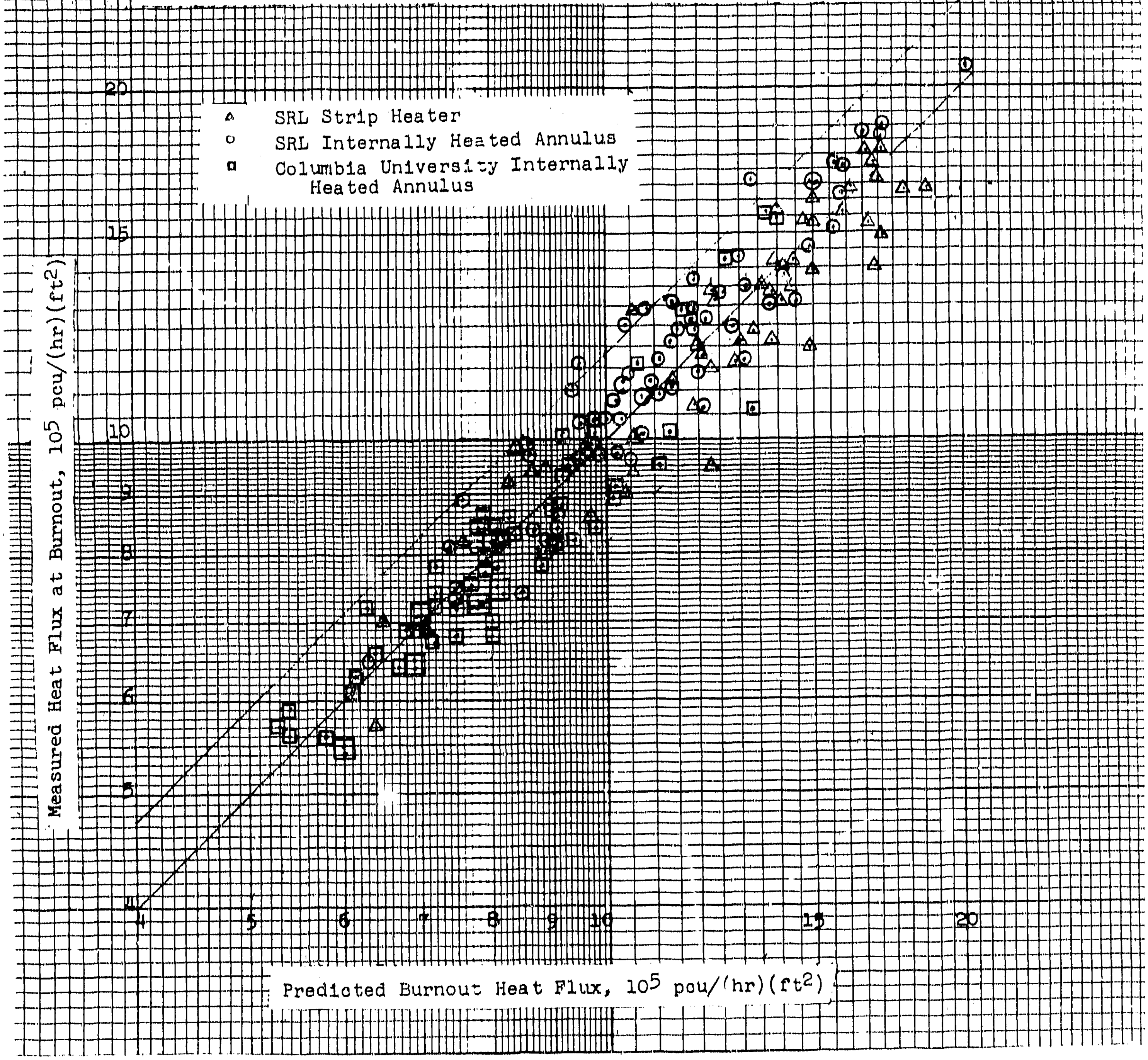


FIGURE 2

DRIFT OF ANNULAR DATA WITH VELOCITY

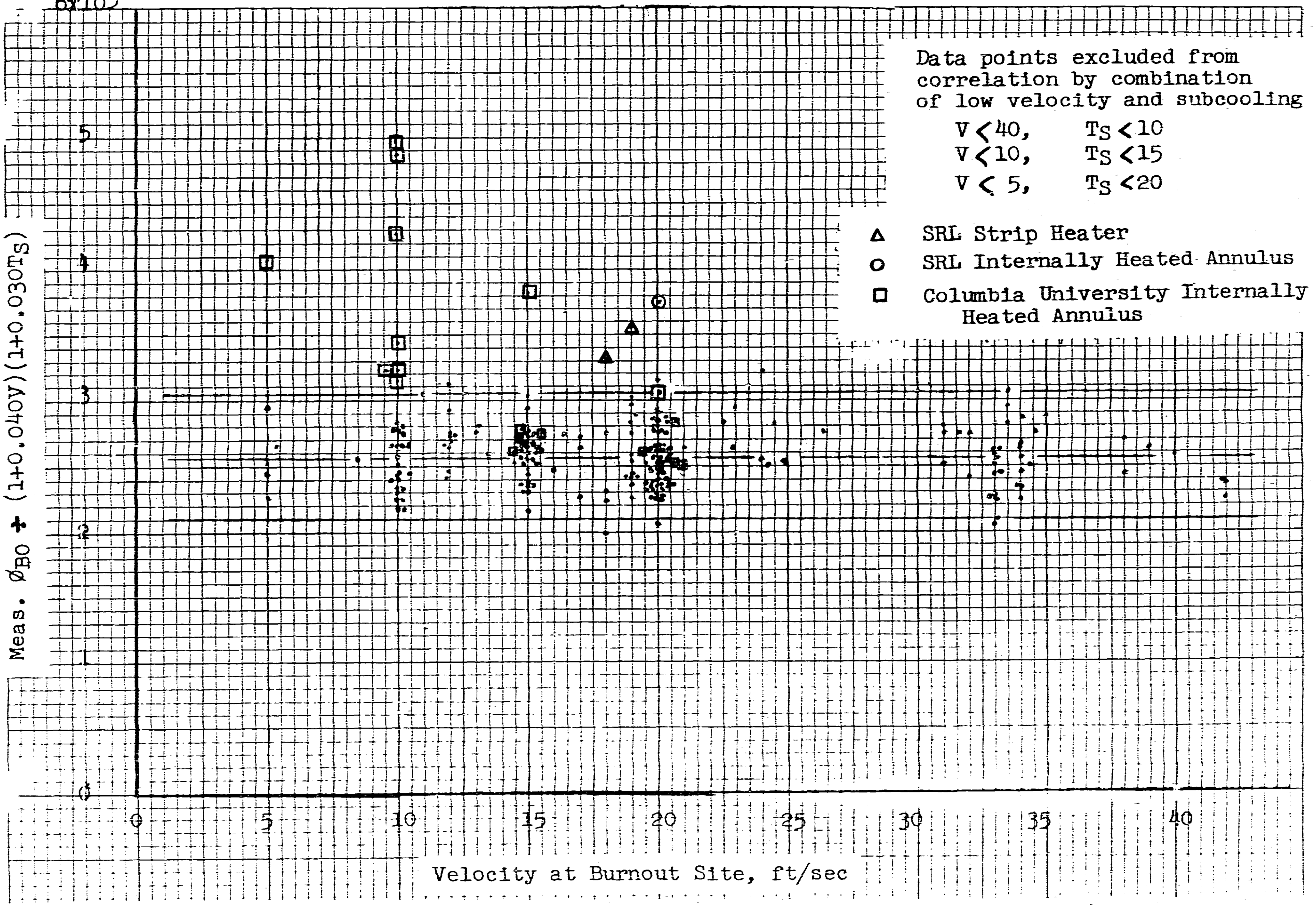


FIGURE 3

DRIFT OF ANNULAR DATA WITH SUBCOOLING

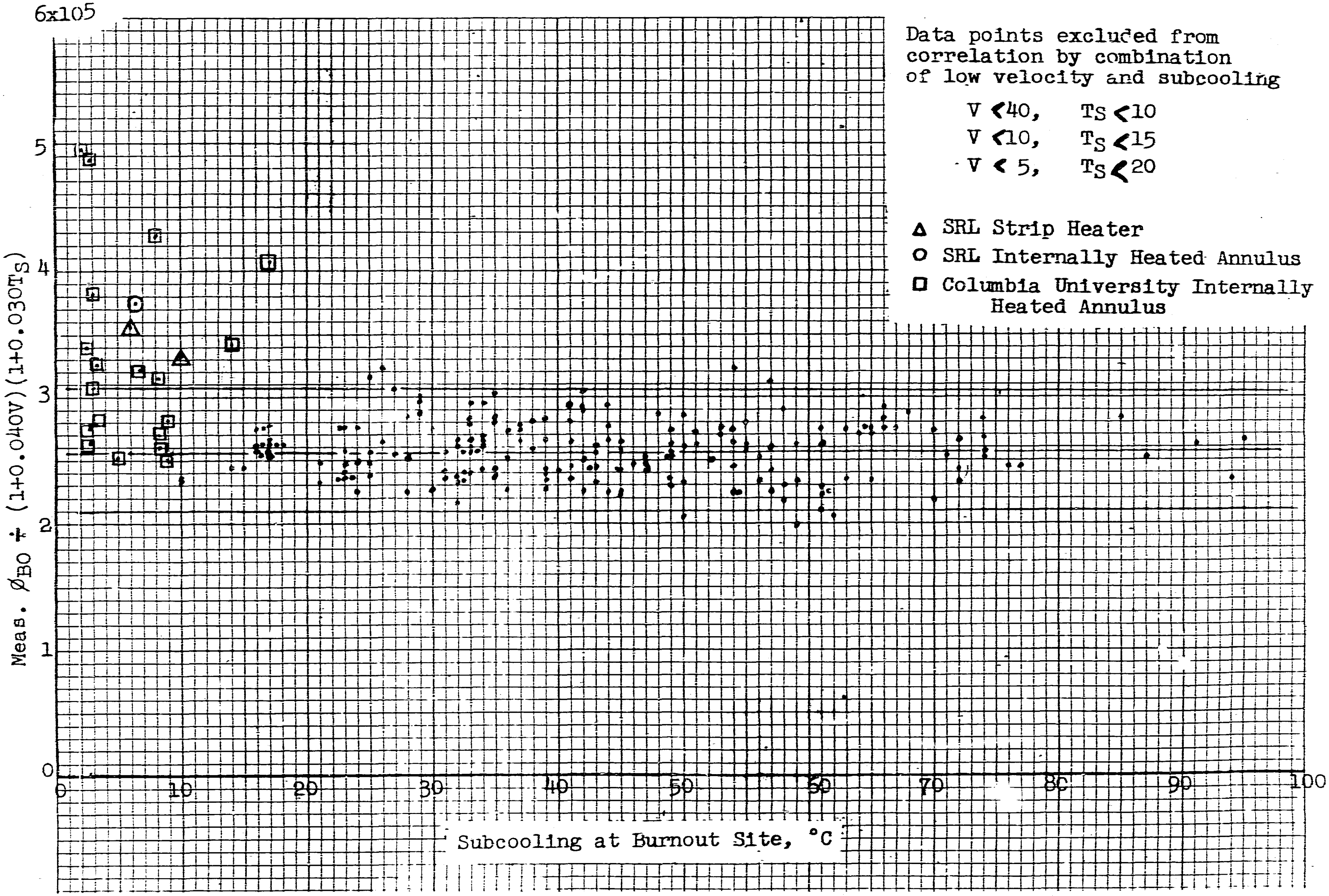


FIGURE 4

DRIFT OF ANNULAR DATA WITH PRESSURE

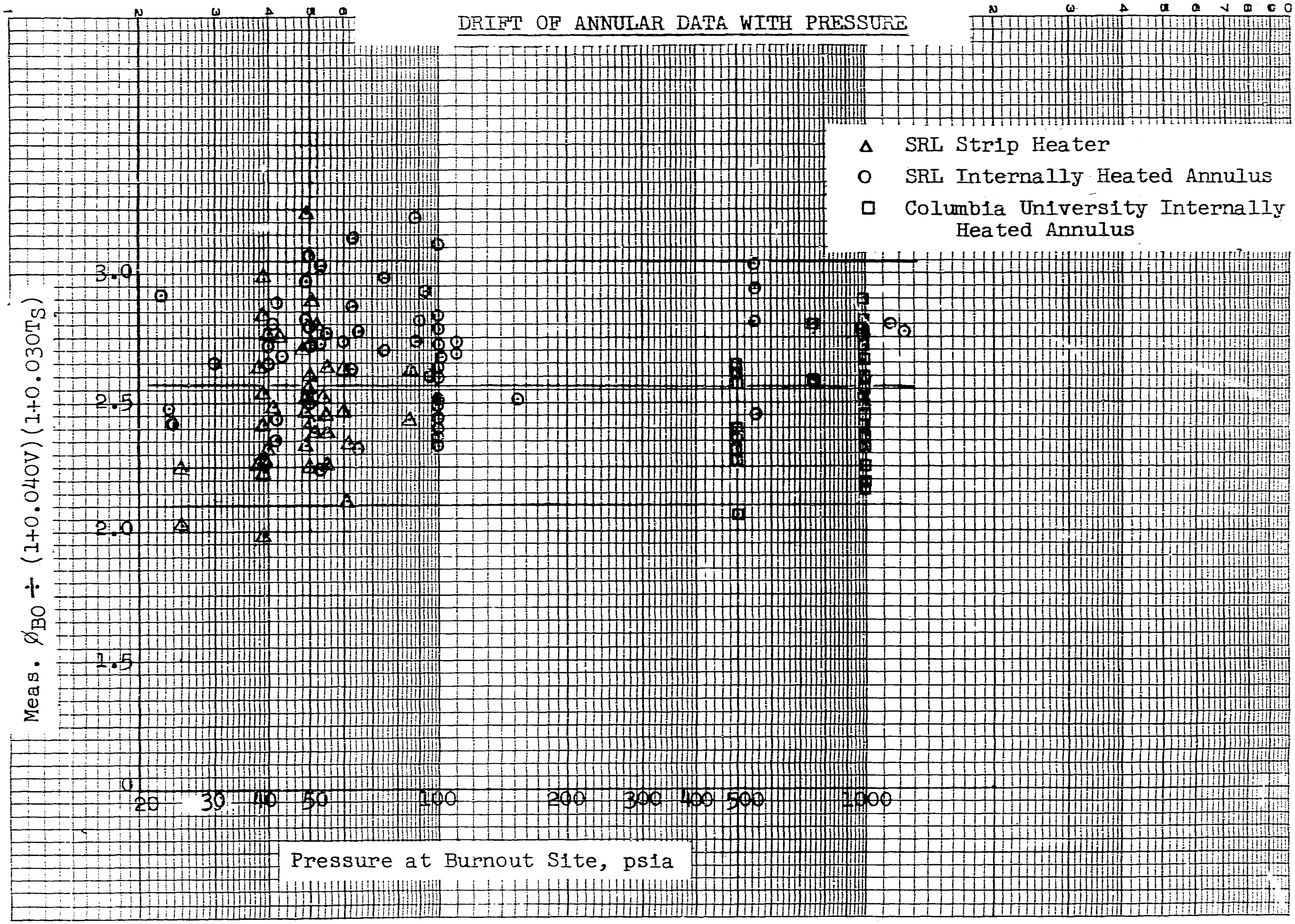


FIGURE 5

COMPARISON WITH CORRELATION OF DP-355

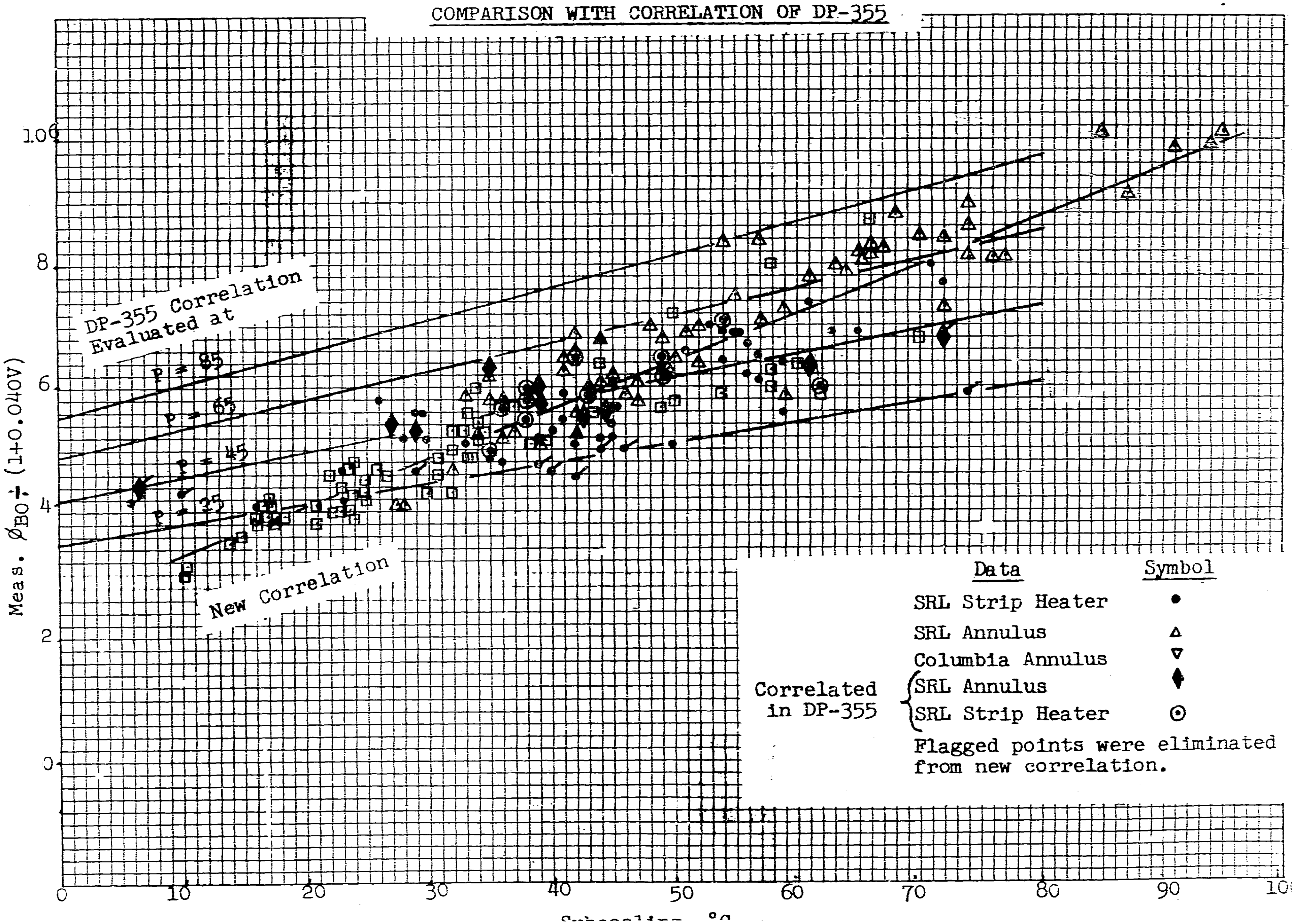
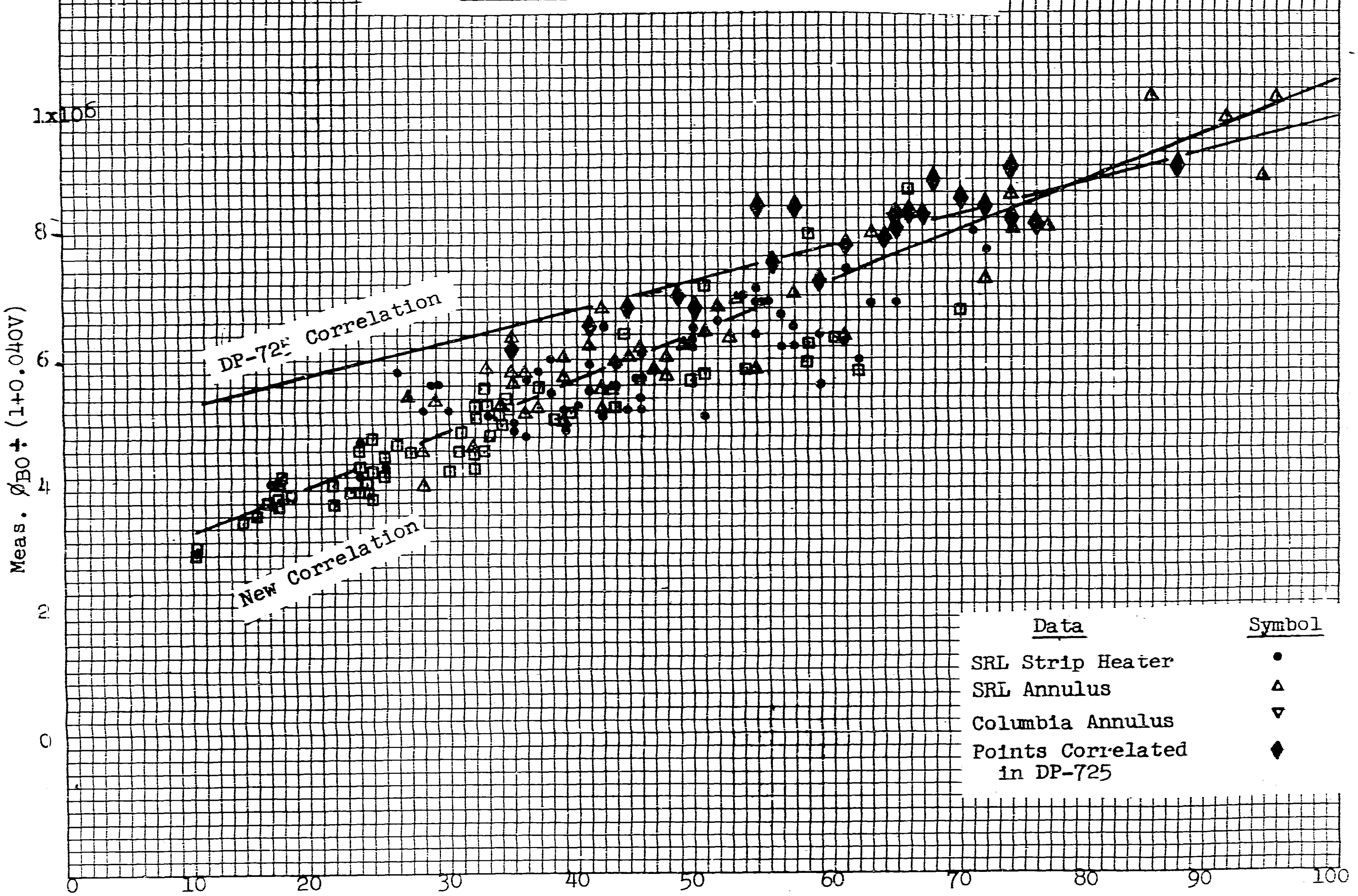


FIGURE 6

COMPARISON WITH CORRELATION OF DP-725



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