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DPST-65-486

PROBABILITY OF FILM BOILING BURNOUT (U)

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DPST-65-486

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June 15, 1966

M E M O R A N D U M

TO: E. C. NELSON

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

PROBABILITY OF FILM BOILING BURNOUT

INTRODUCTION

The power of some SRP fuel assemblies is limited by the burnout safety factor (BOSF) in some applications. This power limitation is unnecessarily restrictive, because the current conservatism in predicting film boiling burnout is unusually large compared to that in predicting unstable flow in fuel assemblies. In the past, most SRP fuel assemblies operated at the flow instability limit and were far enough removed from burnout that a convenient and very conservative burnout limit system could be used. If the same degree of safety was used for both burnout and flow instability, the power of BOSF-limited assemblies could be increased. This memorandum, which is part of the program(1) to improve the system for protection against burnout, evaluates the probability and consequences of burnout at various BOSF levels. This information was incorporated in DPSTM-110(2).

SUMMARY

The Normal or Gaussian distribution curve is shown to predict unrealistically large burnout probabilities at BOSF's greater than 1.29. Preliminary tests indicate that burnout is an invarient phenomena; the scatter of the experimental burnout results about the correlation is caused by finite random uncertainties in the measurements

and inadequacies in the correlation. Analyses of statistical procedures and results of the burnout tests show that a chopped Gaussian distribution is the best representation of the experimental data. The probability of burnout at BOSF's larger than 1.29 (the maximum deviation from the correlation) is negligibly small, and the continued use of 1.30 as the Technical Limit on BOSF is recommended after applicable hot spot factors are included. The consequences of burnout; i.e., the amount of fuel melted and fission product release, are estimated from reactor tests and incidents.

DISCUSSION

Background

The power of some SRP fuel assemblies is limited by the burnout safety factor (BOSF) in some applications. This power limitation is unnecessarily restrictive, because the current conservatism in predicting film boiling burnout is unusually large compared to that in predicting unstable flow in fuel assemblies. Actually, the conservatism in predicting burnout does not need to be as large as that for flow instability, because fuel damage as a result of film boiling burnout is expected to be much less severe than damage as a result of flow instability. In the past, most SRP assemblies operated at temperature limits that protected against flow instability and were far enough removed from film boiling burnout that a convenient and very conservative burnout limit system could be used. If the same degree of safety for protection against flow instability and film boiling burnout were used, the power of BOSF limited assemblies could be increased.

As discussed in DPSTM-110[2], a Technical Limit on BOSF of 1.30 is specified at which the probability of significant damage is negligibly small for normal continuous operation at the limit. Film boiling burnout in SRP assemblies is predicted from results obtained on electrically heated mockups of nested tube assemblies. The burnout heat flux is given by an emperical correlation[3] of 193 tests which has a standard deviation of 9.1%. The maximum deviations of burnout heat flux in the tests, +26.1% and -22.7%, correspond to BOSF's of 0.793 and 1.29.

Gaussian or Normal Distribution

One approach to estimating the probability of burnout is to assume that the burnout test results are a random sample from the universe* of burnout data and that this universe has a normal or Gaussian distribution. In this approach (which is the common statistical method) the probability of burnout at a given BOSF is equated to the area under the portion of the Gaussian distribution curve up to that BOSF divided by the total area under the curve (Figure 1). Because the areas under the Gaussian curve are known very precisely (area tables with 6 significant digits are available), the area ratio can be calculated with great precision. However, this precision is deceiving and unwarranted unless the original assumption (the universe of burnout data has a Gaussian distribution) is valid.

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* In this memorandum, universe of burnout data includes all possible burnout data with independent variables in the ranges samples by the 193 tests of the burnout correlation.

The assumption that the universe of burnout data has a Gaussian distribution can be tested by comparing the distribution of test results with the Gaussian curve. The distribution of the test results about the burnout correlation is compared qualitatively with the Gaussian curve in Figures 2 and 3, and quantitatively the the Chi-Square test[(4)]. The Chi-Square test shows that the distribution of 193 random samples from a Gaussian universe has the same distribution 1 out of 10 times as the 193 burnout results. The difference between the Gaussian distribution and the distribution of burnout results is not large enough to reject the hypothesis that the universe of burnout data has a Gaussian distribution. However the hypothesis is not proven, because the Chi-Square test is a necessary but not sufficient condition for proof of the hypothesis. In Figure 3, the distribution of the test results is shown as a function of the BOSF. Because the BOSF is inversely related to the normal standard deviate (abscissa of Figure 2 divided by σ) both the test results and the Gaussian distribution are skewed in this figure.

Inapplicability of Gaussian Distribution

The assumption that the universe of burnout data has a Gaussian distribution is rejected on a theoretical basis. In the derivation of the Gaussian distribution equation, it is assumed that the deviations may have values ranging from $+\infty$ to $-\infty$. This assumption is a mathematical artifice that produces an analytical equation which can be integrated and otherwise manipulated; the assumption is not met by most real phenomena, because most phenomena have a finite range of possible values. Film boiling burnout, for instance, is a threshold phenomena. Burnout occurs when the mode of cooling changes from nucleate boiling to film boiling, and there is no other known mechanism that could cause film boiling burnout at BOSF levels where the heat flux is not large enough to even initiate nucleate boiling.

Use of a Gaussian distribution leads to the unreasonable conclusion that there is a significant probability of burnout on some assemblies at heat fluxes insufficient to initiate nucleate boiling. Such is the case for the High Flux and Curium-II assemblies where nucleate boiling is not expected to commence on the nominal surface until the BOSF reaches 1.38 and 1.44, respectively. The Gaussian probability of burnout at a BOSF of 1.40 is about 1 in 1000 (corresponding to a confidence level of 99.9%). Because burnout cannot occur at heat fluxes that are insufficient to initiate nucleate boiling or that are just barely large enough to start boiling, the actual probability of these two assemblies burning out at a BOSF of 1.40 is negligible. In the discussions below, it will be shown that a chopped Gaussian distribution is the best representation of the experimental burnout data.

Burnout - An Invariant Phenomenon

Repeated observations of the burnout heat flux in forced flow of subcooled water obtained recently in the SRL Heat Transfer Facility show that the universe of burnout data does not have a Gaussian Distribution. In these tests, all the independent variables were held constant, and the reproducibility of the burnout heat flux was determined. In one set of 24 repeated burnout observations, the largest value of the burnout heat flux was 11.8% above the lowest value. Similar reproducibility was obtained in an independent set of 10 burnout observations where the maximum burnout heat flux was 9.6% above the minimum value. In 59 burnout tests (discussed later) where only the subcooling was varied, the maximum deviation was about ±12%. These burnout observations show that film boiling burnout in forced flow of subcooled water is a reproducible phenomenon that is not subject to the large random deviations described by the Gaussian distribution.

Repeated observations of invariant phenomena scatter about the true value due to the imperfect resolution of the measuring technique. If the maximum deviations of a large set of observations are equal to or less than the product of the resolution uncertainties, it may be assumed that the deviations are due to the measurement uncertainties and that the phenomenon is invariant. Such is the case with the repeated burnout observations. The measurement uncertainties in these observations are as follows:

- o Heat flux; 0.5% on voltage and 2.5% on current for a combined uncertainty of 3.0%.
- o Velocity; 0.8% on flow measurement (0.5% on transducer and 0.25% on Brown recorder) which affects the scatter on the burnout heat flux by 0.4%.
- o Subcooling; 0.2°C on thermocouple, 0.7°C on pressure, 0.3°C on Brown recorder, and 0.5°C on local variations from mean bulk temperature for a combined uncertainty of 3.3% on subcooling which affects the scatter on the burnout heat flux by 2.0%.

The maximum product of the measurement uncertainties comprising each burnout observation is ±5.5%, or the maximum observed value is expected to be 11.7% larger than the minimum. In the set of 24 repeated burnout observations, the maximum observation was 11.8% greater than the minimum observation which is excellent agreement with the expected value of 11.7%. In the independent set of 10 repeated observations, the maximum observation was 9.6% above the minimum value. These tests show that film boiling burnout in forced flow of subcooled water does not vary randomly more than a few percent (if at all) and can be treated as an invariant phenomenon for practical applications. Therefore, the Gaussian distribution curve does not describe the universe of burnout data.

Distributions with Finite Boundaries

The random deviations in a set of repeated observations, which are caused by measurement uncertainties, tend to have a Gaussian distribution just as do the burnout results in Figures 1 and 2. However, the Gaussian distribution is approached as a limiting case. According to the Central Limit Theorem[5], the sum of N uncertainties, in whatever form they may be distributed, tends to be distributed as the Gaussian distribution when N approaches infinity. Because N (the number of uncertainties) is the same as the number of individual measurements comprising each observation, the distribution of the observations would approach a Gaussian distribution only for an infinite number of individual measurements per observation. Repeated observations that require a finite number of individual measurements per observation will tend to be scattered about the mean value as per the Central Limit Theorem, but the observations will have finite boundaries and not the infinite boundaries of the Gaussian curve.

The type of distribution curve that would be observed with a finite number of measurements per observation can be illustrated by the casting of dice. N dice are cast simultaneously. The sum of each cast corresponds to the observation; the frequency with which each sum is obtained corresponds to the distribution of the observations; the number of casts corresponds to the number of times the observation is repeated; the number of dice corresponds to the number of measurements comprising the observation; and the face values of each die corresponds to the unresolved portion of each measurement.

If one die is cast, a very large number of times, the frequency with which each sum appears has a flat distribution, and no sum less than 1 or greater than 6 is obtained as shown in Figure 4. If 2 dice are cast simultaneously, the frequency distribution of the sums is triangular about the most frequent value, 7 (Figure 4), and no sum less than 2 or greater than 12 is obtained. When 3 dice are cast simultaneously, the frequency distribution of the sums begins to appear like a Gaussian distribution about the most frequent values, 10 and 11. However, no sums less than 3 or greater than 18 are observed (Figure 4). When 4 dice are cast simultaneously, the frequency distribution of the sums closely resembles the Gaussian distribution about the most frequent value, 14, as predicted by the Central Limit Theorem, with the exception that the distribution has finite boundaries at 4 and 24.

The dice casting illustration can be extended to the limiting case provided the dice are changed slightly. The special dice would have 7 faces instead of 6 (as ordinary dice) and the faces would be numbered 3, 2, 1, 0, -1, -2, and -3. When an infinite number of these special dice are simultaneously cast an infinite number of times, the sums obtained would range from $+\infty$ to $-\infty$, and the frequency with which each sum occurs would fit the Gaussian distribution curve about the most probable value which is zero.

If a sufficient number of repeated observations have been made, just as in the casting of a finite number of dice, all the uncertainties in the individual measurements will occur by chance in the same direction and at their maximum value. Therefore, the maximum and minimum observed values in a sufficiently large set will mark the finite boundaries of the actual distribution curve of the observations. If there is no systematic error in the observations, the true value of the phenomenon being measured will lie half-way between the maximum and minimum observations; the true value does not correspond necessarily to the average value of all the repeated observations. Just how many burnout observations are required to mark the finite boundaries of the distribution curve is unknown. The number of observations required depends on the number of measurements comprising the observation, the distribution within the resolution band, and the coupling between the uncertainties.

Deviations about the Burnout Correlation

The tests correlated by the burnout equation are affected by more uncertainties than those included in the two sets of 24 and 10 repeated observations. A single test section was used in each set of the repeated observations so that only uncertainties in current, voltage, flow, pressure, and coolant temperature (as shown on page 4) affected the scatter. Several test sections were used for the tests previously correlated so that the correlation is affected by additional uncertainties in the measurement of surface area, local heat generation, and coolant flow area. Although control tests were made, minor differences in the test facilities, operating techniques, and unrecognized non-idealities may have contributed also to the uncertainties in the tests correlated by the equation. The measurement uncertainties in the tests previously correlated are as follows:

- Heat flux; 0.5% on voltage, 2.5% on current, 0.5% on surface area and 2.0% local heat generation for a combined effect of 5.6%.
- Velocity; 3.0% on flow measurement (orifice meter) and 0.5% on flow area which affect the scatter about the correlation by 1.6%.
- Subcooling; 3.3% on subcooling measurement and 3% for wide channel which affect the scatter about the correlation by 3.8%.

From these measurement uncertainties, the finite boundaries of the distribution curve of the correlated burnout results are predicted to be +11.4% and -10.3% from the true value.

The maximum deviations of the correlated test results about the burnout equation (+26.1% and -22.7%) are outside the distribution boundaries predicted from the measurement uncertainties. Because burnout is an invariant phenomena, these large deviations show that the current equation does not predict the burnout conditions as well as might be done. The inadequacy of the burnout correlation may result from 1) inappropriateness of the algebraic form of the equation and 2) minor variables not used as correlating variables as well as from the inaccuracies in the data discussed above.

As part of a program to improve the fit of the burnout correlation, 152 burnout tests were recently completed. The results[6] of 59 of these tests, which were at a velocity of ~ 30 ft/sec, are compared with the burnout correlation in Figure 5. All 59 tests fall within the stated accuracy of the burnout correlation[2] even though the results are not corrected for a 2 ft/sec variation in coolant velocity. However, these 59 tests (as well as the rest of the 152 tests) show that significant improvements can be made in the method of predicting burnout. The maximum deviation of these 59 tests from their "best fit line" is about ±12% without any velocity correction. Similar deviations were observed in the rest of the 152 tests which were at velocities of 15 and 45 ft/sec. The measurement resolution in these 152 tests was improved significantly over the tests previously correlated. Further tests to improve the burnout correlation are underway.

Burnout Probability at the Technical Limit on BOSF

Provided certain conditions are met, the inadequacies of the current burnout correlation do not preclude using it to predict the BOSF and probability of burnout of SRP fuel assemblies. These conditions are 1) all variables encountered in the fuel assemblies must be in the ranges covered by the correlation and 2) a sufficiently large number of tests with variables in the range of the fuel assembly are correlated so that the maximum deviations are present in the test results.

In Figure 6, the tested ranges of the two major variables, velocity and subcooling, are divided into 4 levels each. The number of tests in each level, the mean deviation of the tests in each level from the correlation, and the maximum negative and positive deviations in each level are shown. How well a particular fuel assembly meets these two conditions may be judged from this figure.

In the levels where the maximum negative deviations from the correlation are encountered the number of tests is thought to be sufficiently large so that these deviations mark the finite boundaries of the distribution curve. The maximum negative deviation in any level corresponds to a BOSF of 1.29. The continued use of 1.30 as the Technical Limit on BOSF is recommended, and the probability of burnout at this BOSF level is negligible. A lower Technical Limit on BOSF is expected with an improved burnout correlation.

The probability of burnout at BOSF's less than 1.30 is estimated from the Gaussian distribution curve with the tails chopped off so that the burnout probability beyond a BOSF of 1.30 is negligible. The chopped Gaussian distribution is preferred over the actual distribution of the test results, because the Central Limit Theorem predicts that the results approach the Gaussian distribution. Because of the inadequacies of the correlation and data, these probabilities are too large for BOSF's greater than 1.10, but they are conservative and are a considerable improvement over the infinite Gaussian distribution for BOSF's $>$1.29. The probabilities of burnout based on the Gaussian distribution, the chopped Gaussian distribution, the actual distribution of the tests about the current correlation, and an estimated distribution with an improved correlation are compared in the following table.

Probability of Burnout, %

BOSF	Gaussian* Distribution	Chopped Gaussian* Distribution	Distribution About Current Correlation	Estimated Dist. About Improved Correlation
1.5	0.04	Negligible	Negligible	Negligible
1.4	0.09	Negligible	Negligible	Negligible
1.3	0.58	Negligible	Negligible	Negligible
1.25	1.46	1.46	0.98	Negligible
1.20	3.29	3.29	1.97	Negligible
1.15	7.93	7.93	3.5	Negligible
1.10	16.3	16.3	16.7	1.0
1.00	50.0	50.0	50.0	50.0

* These probabilities are for a sample of 193 burnout points; the correction for sample size does not affect the probabilities significantly and has been neglected.

Consequence of Burnout

Under steady-state conditions, reactor fuel assemblies are operated at BOSF's above the Technical Limit of 1.30. Burnout is highly unlikely at BOSF's $\geq$ 1.30, and the probability of significant damage is considered to be negligible during steady-state operation at this limit. However, certain infrequent incidents may produce excursions below the steady-state BOSF. Excursions to BOSF's less than the Technical Limit on BOSF may be allowed provided that the consequence of fuel failure, i.e., the fission product release, is acceptably low. This approach is fully developed in DPSTM-110.

One of the quantities that must be evaluated in order to predict the consequence of burnout failure is the potential fission product release from the melted fuel. In the SPERT tests[7], six fuel assemblies (each 2 foot long) were melted during deliberate power ramps. The amount of melting in the two tests where failure was by burnout was 0 and about 7%; with worst flow instability test, 20 to 25% of the fuel was melted.

These tests showed that the melted fuel in a local burnout incident did not precipitate complete melting of an assembly by blocking off the coolant channels or a steam explosion through chemical reactions. The melted fuel flowed out of the core into the coolant stream; some froze on the cladding downstream of the burnout site; some froze in large agglomerates that settled near the bottom of the test assembly; and some formed smaller particles (< 20 microns in diameter) that circulated with the coolant.

Results of the SPERT flow instability tests are supported by flow instability incidents[8,9] in the Materials Testing Reactor (MTR) and Engineering Test Reactor (ETR). Fuel elements in both reactors melted due to flow instability when the influent was partially blocked by foreign bodies. Only the fuel in the blocked assemblies was melted and the melted fuel did not cause a steam explosion. In the MTR incident, 10% of the fuel in the affected assembly was melted.

On the basis of the SPERT tests and the SRL burnout tests of mockups with nominal and local hot spots, the amount of fission products released from a nominal hot spot on a fuel tube during a burnout incident is estimated conservatively as 10%. In addition, some of the melted fuel froze on the downstream cladding in the SPERT tests; hence, the amount of nonvolatile fission products released to the coolant would be less than the amount melted. In the burnout test with 7% melting, photographs and local metal temperatures during the power ramp show that only fuel in the minimum BOSF zone was affected, and most of the fuel in this zone was melted. Because most of the fuel in the minimum BOSF zone was melted, the percentage of fuel melted in production assemblies during possible incidents would not be increased significantly by differences between conditions in the SPERT tests and those in SRP fuel assemblies.

The photographs of the two tubes that failed by burnout also show that the amount of melting should be typical of assemblies influenced by nonidealities or hot spots that occur frequently on every fuel assembly. These hot spots are 1) neutron flux gradient, 2) hot subchannels, and 3) rib upset. When burnout occurs in a small region where a fuel segregation defect accumulates geometrically with the other hot spots, far less melting would occur than in the SPERT burnout test with 7% damage. It is estimated that about ½% of the fuel would be melted in such a region.

PROGRAM

In DPST-65-246[1] a heat transfer program to enable operation of BOSF limited charges at smaller margins between the operating and burnout heat fluxes than in the past was presented. This program included:

- o Measure effects of nonidealities and develop statistical method of applying such factors to BOSF limits.
- o Measure effects of aluminum surfaces, cosine heat generation, and heating from both surfaces on heat transfer burnout.
- o Evaluate methods of reducing non-idealities in production fuel assemblies.
- o Re-evaluate Technical and Operating Limits on BOSF.

The program has been expanded to:

- o Develop an improved burnout correlation based on available tests and additional tests with improved measurements of the minor variables.

The Technical Limit on BOSF with the current correlation is 1.30. With an improved correlation, it may be possible to reduce the Technical Limit on BOSF to $<$ 1.15 and still maintain the same degree of safety as applied to the temperature limits on fuel effluent coolant. Operation with a Technical Limit as low as 1.15 would yield power gains of about 8% in BOSF limited assemblies.

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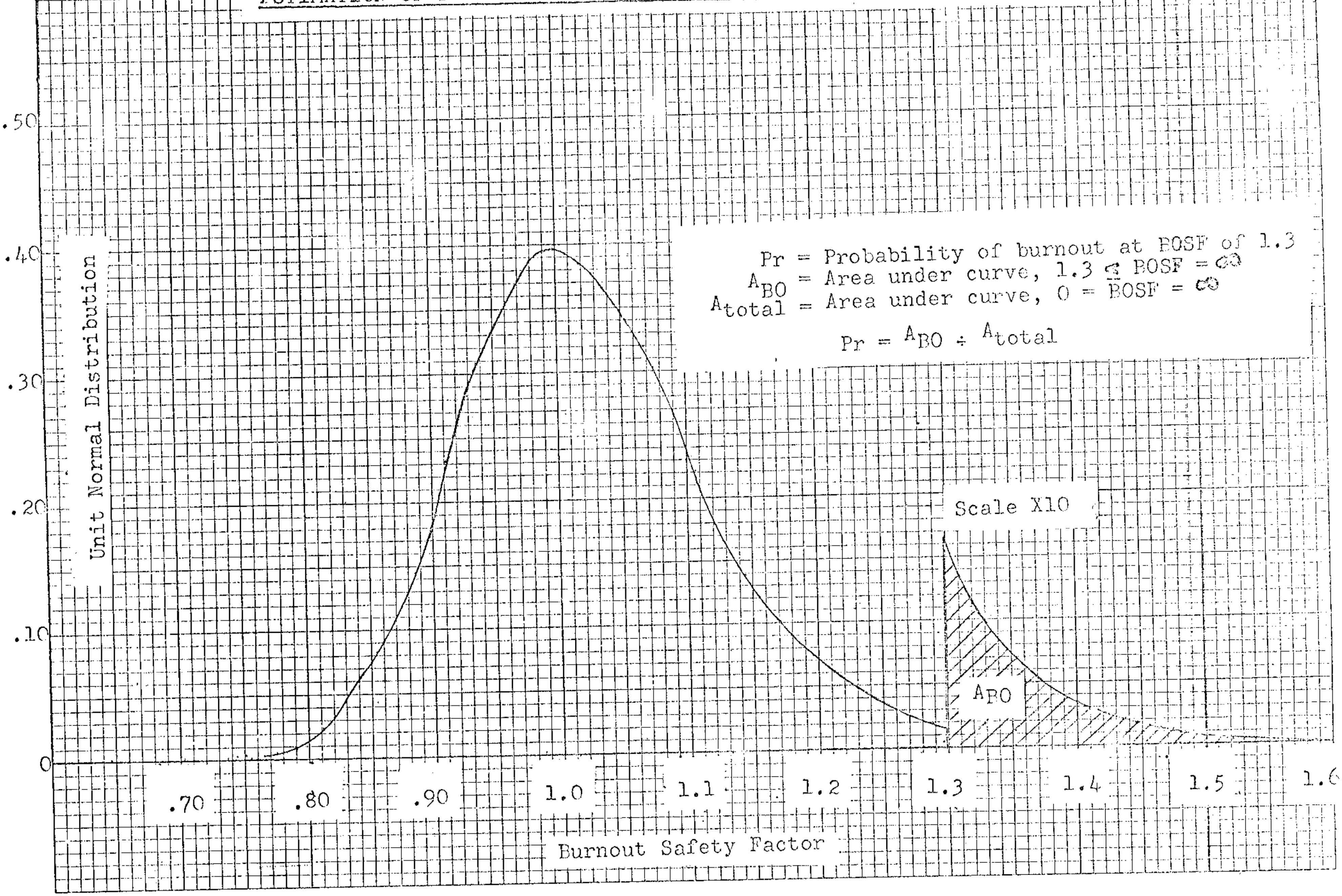
FIGURE 1

ESTIMATION OF BURNOUT PROBABILITY ASSUMING GAUSSIAN DISTRIBUTION



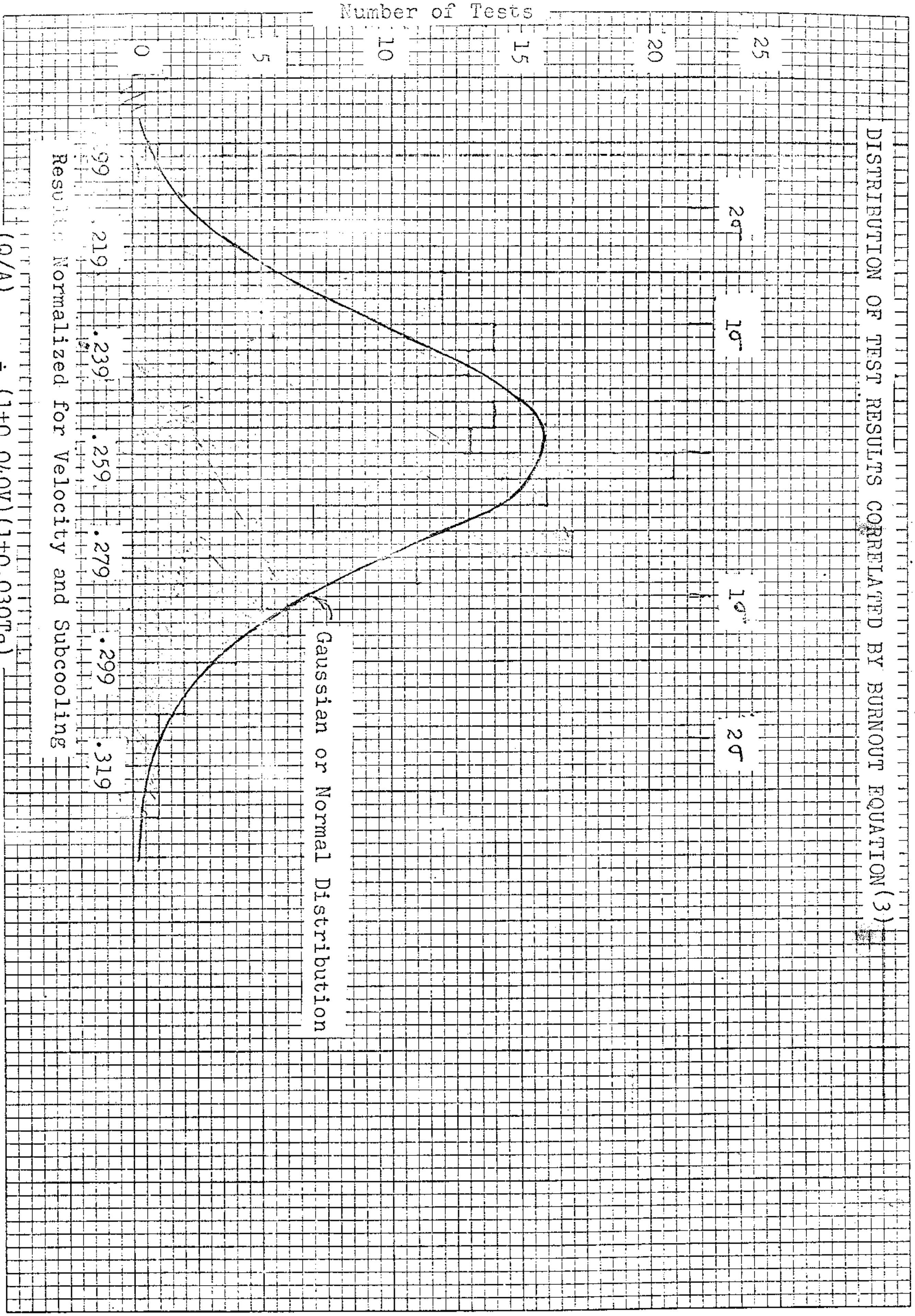
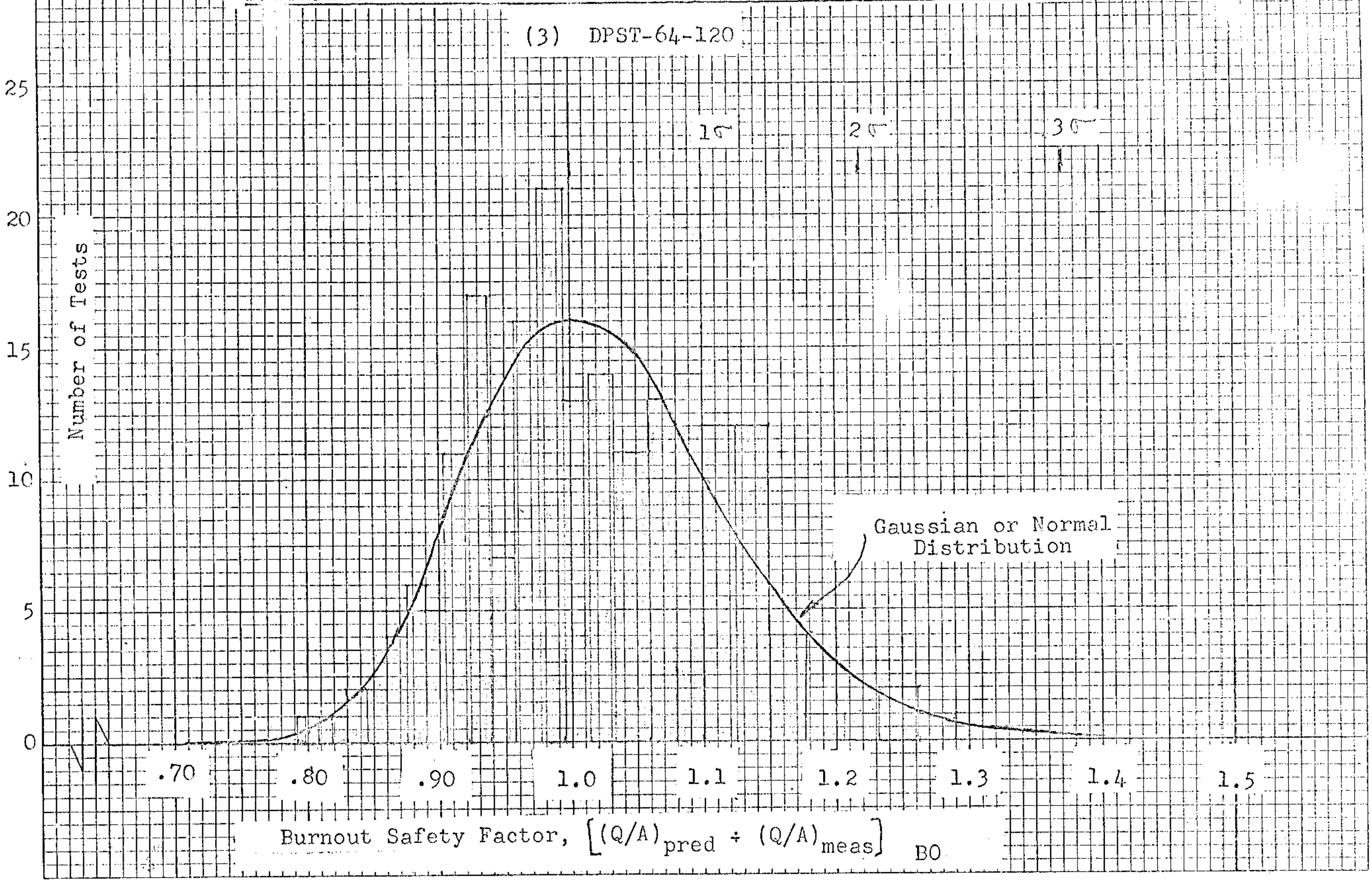

DISTRIBUTION OF TEST RESULTS CORRELATED BY BURNOUT EQUATION (3)
Number of Tests
0
5
10
15
20
25
2σ
1σ
1σ
2σ
Gaussian or Normal Distribution
.199
.219
.239
.259
.279
.299
.319
Results Normalized for Velocity and Subcooling
(Q/A)meas ÷ (1+0.040V)(1+0.030Ts)

FIGURE-2

FIGURE 3

DISTRIBUTION OF TEST RESULTS CORRELATED BY BURNOUT EQUATION(3)



(3) DPST-64-120

FIGURE 4

DISTRIBUTION OF SUMS OF SIMULTANEOUSLY CAST DICE

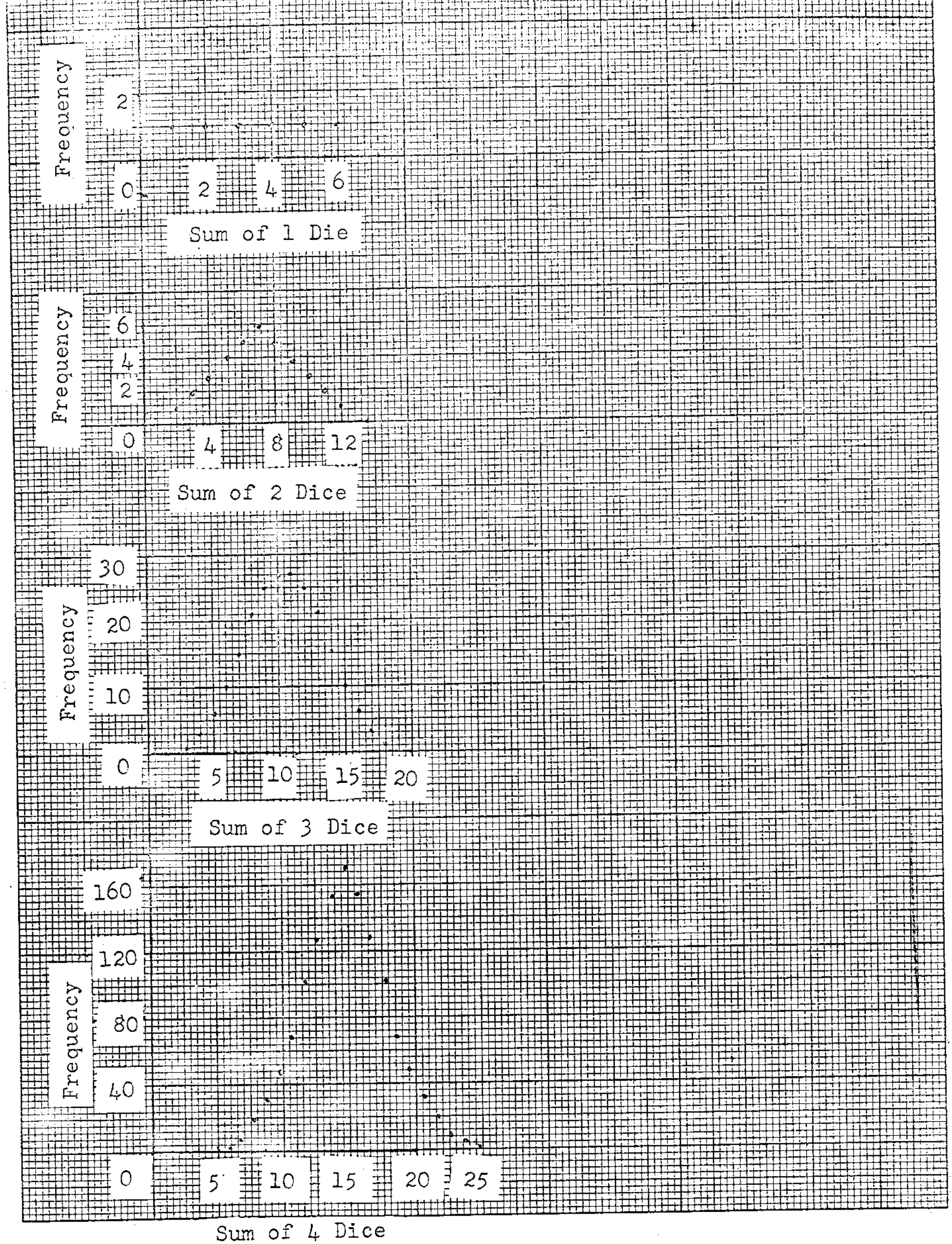


FIGURE 5

FILM BOILING BURNOUT AT 30 FT/SEC

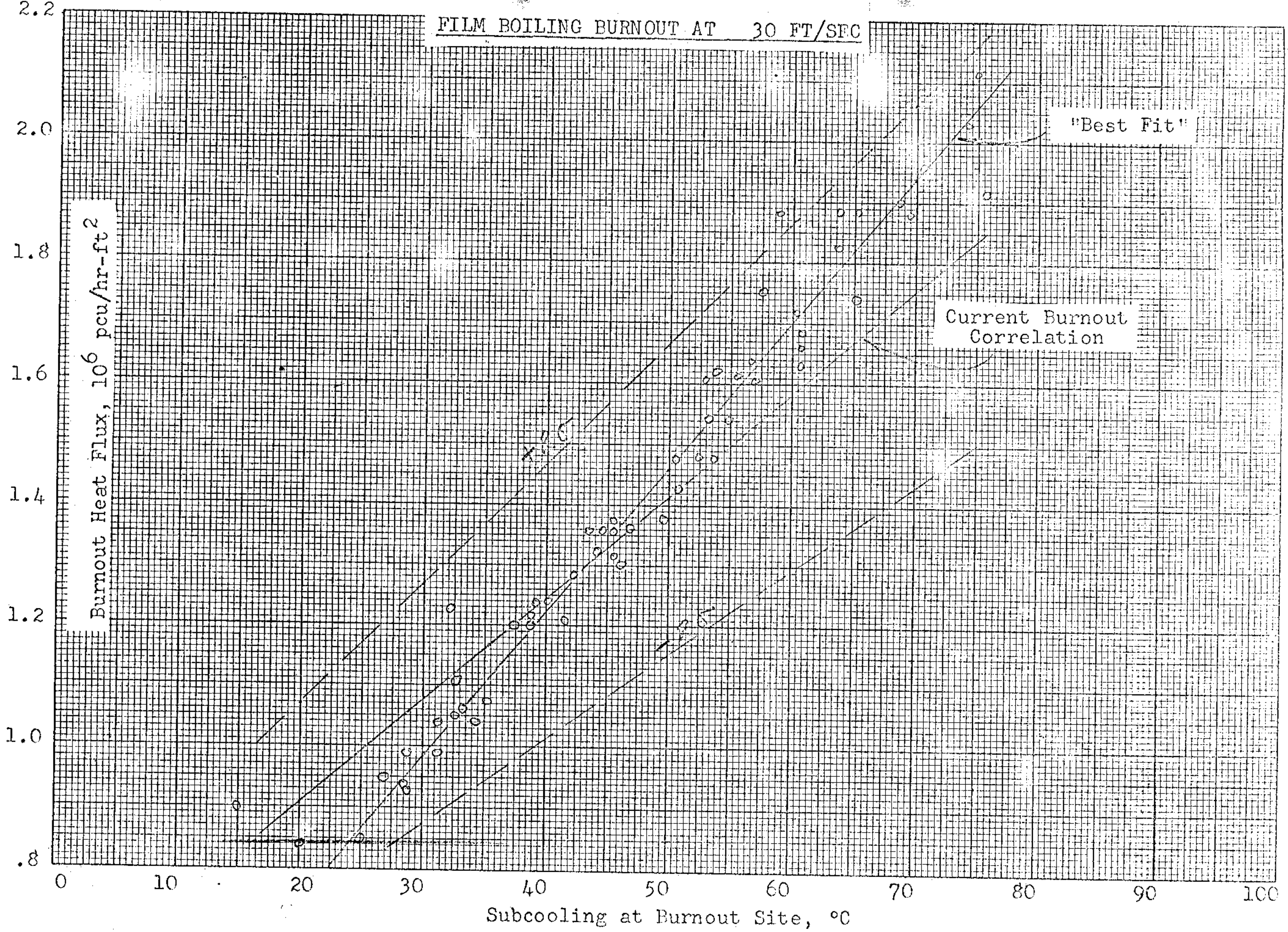


FIGURE 6

DISTRIBUTION OF TEST RESULTS ABOUT CORRELATION BY SUBRANGES

Velocity ft/sec \ Subcooling, °C	10-29.9	30.0 to 49.9	50.0 to 69.9	70.0 to 95
5.0 to 14.9	6 + 3.3% -2.4%, +8.6%	18 + 1.5% -11.3%, +18.3%	11 + 0.6% -14.8%, +21.0%	9 - 0.1% -14.8%, +7.8%
15.0 to 24.9	35 - 3.8% -12.9%,+17.1%	46 - 0.4% -15.6%,+22.1%	20 - 0.1% -22.7%,+25.2%	7 + 0.5% -9.8%, +10.5%
25.0 to 34.9	2 + 22.7% , +26.3%	16 0.5% -12.5%, +15.2%	14 - 2.6% -20.2%, +7.8%	1 , +2.7%
35.0 to 50.0	0	4 - 0.5% -7.4%, 12.4%	4 -2.3% -12.1%, +5.1%	0

Figures in each block are 1) number of tests in block, 2) mean deviation of tests in block from correlation, 3) maximum negative and positive deviations in block.