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M. GUYETTE and N. HOPPE
(BelgoNucléaire)

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EURATOM/US Agreement for Cooperation
EURAEC Report No. 1915 prepared by
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Contract Euratom/BelgoNucléaire/CEN No. 001-64-1 TRUB
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Printed by Vanmelle
Brussels, November 1967

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Brussels, November 1967 — 48 Pages — 15 Figures — FB 60

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Various methods of predicting DNB in non-uniformly heated channels are examined.

A comparison between experimental values and theoretical predictions shows that the use of the F factor developed by Westinghouse, always improves the validity of the predictions for all the considered correlations.

In the case of marked non-uniformities like hot patches and low qualities the discrepancies between experimental values and theoretical predictions are generally too large as to allow the use of the selected method of calculation for detailed design and performance studies.

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SUMMARY

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KEYWORDS

NUCLEATE BOILING
BIBLIOGRAPHY
TUBES
COOLANT LOOPS

HEATING
VARIATIONS
NUMERICALS

Departure nucleate boiling

BIBLIOGRAPHICAL REVIEW OF DNB DATA IN NON-UNIFORMLY HEATED CHANNELS AND COMPARISON WITH THEORETICAL PREDICTIONS BY WAPD - 188, W - 2 AND W - 3 CORRELATIONS (+)

INTRODUCTION

The heat flux distributions to be considered in core design and performance studies are generally non-uniform ones.

In the cases where these distributions have large non-uniformities such as hot patches most of the predictions by existing correlations differ appreciably from the measured values. In order to achieve a higher core performance in these cases it is desired to have an improved method of DNB calculations in non-uniform channels.

A bibliographical review of DNB correlations and methods of calculation has therefore been carried out with a view to select the most appropriate means of calculation of DNB heat fluxes in the case of marked non-uniformities.

(+) Manuscript received on September 29, 1967.

1. EXPERIMENTAL DATA FOR AXIALLY NON-UNIFORM HEAT FLUX PROFILES.

A search for DNB experimental data for non-uniformly heated channels has been carried out in the literature. All the data collected are summarized in the tables of Appendix I and Appendix II. Appendix I is relative to axial non-uniformities, while Appendix II is relative to radial non-uniformities. One has distributed these data in three main groups according to the type of axial profiles :

(i) hot patch profiles

(ii) cosine or chopped cosine profiles

(iii) and miscellaneous profiles including skewed cosine.

The data examined are generally too scanty and too lacking in precision to draw precise conclusions on the effects of heat flux non-uniformity on DNB. However some general trends can be found :

1. 1. Hot patches

These profiles are generally characterized by a hot spot factor ε which is the ratio of the heat flux at a point in the hot patch to the one that would exist at that point if the section was not patched. The experimental values are often expressed in terms of the peak effectiveness E_p. This parameter is given by :

$$E_p = \frac{q''_{\text{DNB uniform}} - q''_{\text{DNB avg}}}{q''_{\text{DNB peak}} - q''_{\text{DNB avg}}}$$

where :

$q''_{\text{DNB uniform}}$: DNB heat flux of a uniform heated section with the same fluid conditions (at the inlet or at the DNB location depending on the authors) and the same channel geometry.

$q''_{\text{DNB peak}}$: local value of the hot patch flux when DNB occurs

$q''_{DNB\ avg}$: average value of the heat flux in the patched section when DNB occurs.

Data of Weiss (10)(11), Styrikowitch (14), Tong (17), Todreas (18) and Stevens (19) (21) were examined. Qualitatively all these data show that the peak effectiveness E_p decreases when the quality at the DNB point increases. In other words at a given pressure the influence of a hot patch in DNB will be stronger for smaller values of the local enthalpy. A decrease of the length of the hot spot decreases the peak effectiveness while an increase of the hot spot factor increases the peak effectiveness.

Consistent trends in the effects of the other parameters as pressure, mass velocity, channel geometry, on the peak effectiveness could not be deduced from the analysis of the considered results.

1.2. Cosine or chopped cosine profiles.

More confusing is the examination of the data obtained with cosine or chopped cosine profiles. (1), (7), (9), (13), (22), (23), (24), (8), (25), (26), (27), (28), (29), (30), (18), (31), (16), (20), (43), (44).

Indeed the difference between the data for uniform and corresponding cosine profile having the same inlet conditions is often smaller than the experimental error.

One can only conclude that the DNB power of a cosine or chopped cosine profile is generally comprised between ± 20 % of the power for a uniformly heated section having the same geometry and the same inlet conditions.

1.3. Miscellaneous distributions.

These distributions comprise primarily dissymmetrical cosine as upskewed or downskewed chopped cosines or ramps (44), (18), (30), (26), (22), (15), (42), (3), (4), (5), (12), (37), (38). The downskewed cosine profile (peak near the outlet) shows generally a smaller DNB power than the uniform one having the same geometry and the same inlet conditions. The upskewed cosine profile (peak near the inlet) is from the DNB point of view very near the same as the symmetric cosine profile.

A consistent trend for all these distributions is that a profile having a peak near the outlet is less favourable than a uniform profile. The influence of the peak is generally more pronounced when the local quality at the level of the peak is smaller.

2. METHODS OF APPLICATION OF EXISTING CORRELATIONS FOR AXIALLY NON-UNIFORM DISTRIBUTIONS.

One has examined in the literature the main methods used for predicting the DNB heat fluxes in non-uniformly heated channels. These methods are summarized hereunder.

2. 1. System parameter and local parameter correlations (2), (39), (6).

DNB correlations are generally expressed in terms of either system parameters or local parameters. In the first type correlations the independent variables are generally the inlet enthalpy, the mass velocity, the equivalent diameter, the length of the channel and the system pressure. The dependent parameter is in this case either the DNB heat flux or the DNB enthalpy.

The second type correlations involve as independent variables : local enthalpy or quality, mass velocity, equivalent diameter, length of the channel and the pressure, the dependent variable being generally the DNB heat flux.

For uniformly heated channels, these two types of correlations can be deduced from one another with the help of the heat balance equation :

$$H_{DNB} - H_{in} = P_h L \; q''_{DNB}/G$$

In this equation :

H_{DNB} : enthalpy at the DNB point

H_{in} : inlet enthalpy

P_h : heated perimeter of the channel

L : total heated length

G : mass velocity

q''_{DNB} : DNB heat flux

This is no more true when the axial heat flux distribution is non-uniform.

However some authors state that the average DNB heat flux of a non-uniformly heated channel is approximately equal to that of a uniformly heated one having the same inlet enthalpy, mass velocity and geometry. However experimental evidence shows that this is not always true. For instance a channel with sub-cooled exit conditions having a distribution with a peak near the exit will have an average DNB heat flux smaller than in the case of an uniform distribution. The simple application of a system parameters correlation for a non-uniformly heated profile is thus only valid for limited applications.

2.2. Reference channel.

Generally the calculation of the DNB heat flux for a non uniformly heated channel is carried out for a number of points along the channel. For each point of calculation it is customary to define a "reference" uniformly heated channel. The parameters selected for describing this "reference" channel differ from one author to the other. The most common ones are given hereunder.

2.2.1. Length of the reference channel.

(i) Local length.

The length of the reference channel is equal to the length of the non-uniformly heated channel from its inlet up to the point of calculation.

(ii) Total length.

The length of the reference channel is equal to the total length of the non-uniformly heated section.

(iii) Equivalent length.

The length of the reference channel is equal to the length of an hypotetical uniformly heated channel having :

- a total power output equal to that of the non-uniformly heated channel between the inlet and the considered point.
- an uniform heat flux equal to the local flux at the considered point of the non-uniformly heated channel.

2.2.2. Diameter of the reference channel

(i) Wetted equivalent diameter.

The reference channel is assumed to be a round tube having a diameter equal to the wetted equivalent diameter of the non-uniformly heated channel D_e defined by :

$$D_e = \frac{4\,A}{P_w}$$

where :

D_e	equivalent wetted diameter
A	cross section of the channel
P_w	wetted perimeter of the channel

(ii) Heated equivalent diameter.

The reference channel is considered as a round tube of the same diameter as the heated diameter of the non-uniformly heated channel defined by :

$$D_h = \frac{4\,A}{P_h}$$

where :

P_h	heated perimeter of the channel.

(iii) The reference channel has a diameter which is a function of the values D_e and D_h defined hereabove.

2.2.3. Reference fluid conditions.

The mass velocity and the enthalpy of the fluid in the reference channel are taken the same as in the non-uniformly heated one either at the inlet or at the considered point according as use is made of a system parameter or a local parameter concept.

2.2.4. Values of the heat flux compared with the DNB flux.

The value of the DNB heat flux predicted by the correlation can be compared with either the local heat flux or the average heat flux up to the point of calculation.

2.3. Current methods of calculation.

It results from the hereabove paragraphs that a variety of values can be used in principle for each of the parameters intervening in the DNB correlation, leading to a number of different values of the predicted DNB fluxes. However, only three methods of calculation are currently used :

2.3.1. Overall power or average flux.

In this method using a system parameter correlation, one assumes that for the same inlet conditions and the same geometry, the non-uniformly heated channel and the reference channel have the same total heating power i.e. the same average heat flux or the same enthalpy increase when DNB occurs. This method is also called overall length concept because the comparison is made on DNB power over the whole channel length in each case regardless of the position of DNB.

2.3.2. Equivalent length method or integrated power method.

This method uses a system parameter correlation.
At any point of calculation reference is made to the equivalent length defined as hereabove. Comparison of the DNB heat flux is made with the local heat flux.

2.3.3. Local length method.

Calculations are made using the local length concept defined hereabove.
Comparison of the DNB heat flux is made on the local heat flux when using a local parameter correlation and on the average heat flux for a system parameter correlation.

3. SELECTION OF A PREFERRED METHOD OF CALCULATION OF THE DNB HEAT FLUXES FOR AXIALLY NON-UNIFORM DISTRIBUTIONS

From the previous paragraph it appears that there exists three main possibilities of choosing the "reference" channel for the calculation of DNB heat fluxes in non-uniformly heated channels.

The first possibility is based on the overall power method. Predictions of the DNB power by this method do not depend upon the shape of the heat flux distribution and their successful application is therefore limited. This method appears to give fair predictions of the DNB power in some cases as cosine profiles but does not provide any indication on the location of DNB. Moreover, this method fails completely to predict DNB occurence for hot patched profiles. For this reason, this method has not been selected as the preferred one.

On another hand the equivalent length method and the local length method allow to predict the location of DNB occurence.

The local length method can be easily applied and is currently referred to in the literature. For this reason this method has been selected here. However the use of this method does not lead to a fair prediction of the known experimental data. An improved mean of calculation based on the local length method has therefore been worked out. This makes use of the F factor developed by Westinghouse (40). This method takes into account the memory effect on DNB. It is based on the fact that the DNB occurence depends as well upon the bulk fluid conditions as upon the conditions of the boundary layer along the heating surface. A method of determination of these boundary layer conditions has been worked out based on the fact that a superheated liquid layer is insulated from the bulk coolant flow by a bubble layer.

Using a simplified model for the representation of the liquid layer and making a heat balance of this layer, leads to an expression giving the non-uniform DNB heat flux as a function of the heat flux in the equivalent uniformly heated channel.

In this expression the value of a constant C is given by an empirical correlation. This relation is general and can be used with any correlation predicting the DNB heat flux in uniformly heated channels.
Hereafter use will be made of this factor in conjunction with three correlations, in order to determine the improvement brought by the use of the F factor.
The expression of the F factor is as follows :

$$F = \frac{C}{q''_{loc}\left(1 - e^{-C\, l_{DNB}}\right)} \int_{o}^{l_{DNB}} q''(z)\, e^{-C(l_{DNB}-z)}\, dz$$

with

$$q''_{DNB,N} = \frac{q''_{DNB,EU}}{F}$$

where

$q''_{DNB,N}$: non-uniform DNB heat flux

$q''_{DNB,EU}$: equivalent uniform DNB heat flux

C : empirical constant

z : axial distance from inception of local boiling

l_{DNB} : distance from inception of local boiling to point of DNB

The value of the constant C in the report of Tong (40) is given by :

$$C = 0.44 \frac{(1 - \chi_{DNB})^{7.9}}{(G/10^6)^{1.72}} \quad \text{in.}^{-1}$$

where

χ_{DNB} : quality at DNB point

G : mass velocity

Studies have also been performed by Fiat and Sorin (1), (30) in order to improve the value of the constant C in the equation of F.

These studies have led to the following equations :

for $-0.25 < \chi < 0.15$

$$C = 6.86\ 10^{2}\ \frac{(1-\chi)^{a}}{G\ f\,(T_{sat})}\quad \text{in.}^{-1}$$

with $a = 6.105 + 0.44\ 10^{-3}\ (p - 1000)$

$$f(T_{sat}) = 39.74836\ 10^{-15}\ T_{sat}^{4} - 64.83156\ 10^{-12}\ T_{sat}^{3}$$

$$- 38.6336\ 10^{-9}\ T_{sat}^{2} + 47.189\ 10^{-6}\ T_{sat}$$

$$- 1.9452\ 10^{-3}$$

for $0.15 < \chi < 0.65$

$$C = 8.09\ 10^{-5}\ \frac{1}{\chi\ v_{g}\ (G/_{10}6)^{1.5}\ De}\quad \text{in.}^{-1}$$

4. COMPARISON OF THE PREDICTIONS BY THREE SELECTED CORRELATIONS WITH EXPERIMENTAL VALUES

4. 1. Correlations used

The three following correlations WAPD-188, Westinghouse W-1 or W-2 and Westinghouse W-3 have been used for comparing available experimental data on non-uniformly heated channels with theoretical predictions.

4. 1. 1. WAPD-188 correlation

Use has been done of the best fit correlation for round tubes given in the Appendix III.

4. 1. 2. W-1 and W-2 correlations (29)

The W-2 correlations differ from the W-1 ones by a factor taking into account the influence of non heated walls in the channel. For channels without unheated walls the expressions of the W-1 and W-2 correlations are identical. As in this paper one has only considered experimental results for channels without unheated walls no distinction is made between these two correlations. The equations are also given in Appendix III. The first equation has been used for qualities smaller than zero. The second one is used for quality values larger than zero. The DNB margin predicted by the two correlations hereabove is not necessarily the same for a quality equal to zero. As it will be shown later this is the reason for some observed discrepancies.

4. 1. 3. W-3 correlation

The expression of this correlation is given in the Appendix III. This equation is valid in the range of outlet qualities between - 0. 15 and + 0. 15. When attempt is made to use it for qualities larger than + 0. 15 the correlation gives very small values of DNB heat fluxes and even negative values. Care must thus be taken when using this correlation out of its validity range.

4. 2. Comparison of theoretical predictions with experimental data

The difference between the experimental values and the predicted ones when the F factor is not used are generally more important for distributions with hot patches. For this reason the available experimental data on hot patches were chosen preferentially to show the effect of the use of the F factor with the three considered correlations. Almost all the known experimental data with hot patches are relative to round tubes. This allows to eliminate the uncertainties involved in the choice of the equivalent diameter (either wetted or heated).

4. 2. 1. Data from AEEW-R 426 (19)

These data were extracted from (19) and were adapted to a water system using the scaling factors determined by Eastwood and Stevens (45) (21). Comparison has been made for three values of the channel length and one value of the mass velocity. The experimental values are plotted versus the corresponding predicted ones for the same inlet enthalpy in Figures 1 , 2 and 3. Figure 1 is relative to the WAPD-188 correlation. Agreement is much better when the F factor is used although calculations still largely underpredict the DNB fluxes. The agreement becomes however similar to that obtained for the data on uniform heated channels, reported in (19).

The W-2 correlation predicts very well in this particular case altough the F factor is not used for qualities larger than zero. For the points between brackets a DNB margin of 1 was calculated in the subcooled region before this margin reaches 1 in the quality region. This is due to the overprediction of the ΔH equations for the very short lengths. The prediction of the W-2 correlations for these points should therefore not be regarded as valid.

All the points for L = 38. 80 in.and 73. 50 in.in these data have outlet qualities far out of the validity range of the W-3 correlation. For this reason the W-3 correlation could not be used. When applying the F factor it can be seen from Figures 1 to 3 that there is little difference between the results obtained with respectively the Tong and the Fiat expressions.

4.2.2. Data from WAPD-TH-338 (10)

These data are relative to rectangular channels.

The experimental values and the theoretical predictions are given for each correlation on Figures 4, 5 and 6.

These Figures show that the agreement between experimental and predicted values is better when using the F factor for all the correlations. The difference between predictions using respectively the Tong and the Fiat expressions of F is rather small.

4. 2. 3. Data from Doklady vol. 7 N° 7 (14)

In this report data obtained in the absence or in the presence of a compressible volume between the inlet throttle and the heating section are given in form of curves for various total lengths, hot spot lengths and mass velocities. Only those with no compressible volume have been examined. One has used the data in the - 0. 2, + 0. 2 outlet quality range for the short tubes (16 cm) and in the whole outlet quality range for the longer tubes (50 and 94. 5 cm). Comparing the experimental and predicted values one must bear in mind that the pressure (1422 psia) lies out of the validity range (1850 - 2150 psia) of the WAPD-188 correlation. Again the $\frac{L}{D}$ ratio for the smallest length (ratio of 20) lies out of the $\frac{L}{D}$ validity range of the WAPD-188 and W-2 correlations (between 21 and 365) and the smallest section length (6. 3 in) lies out of the validity range of the W-3 correlation (10-79 in). These correlations have nevertheless been applied to the considered data but such a comparison is given only to examine the behaviour of these correlations out of their validity range.

For the smallest length notable discrepancies are obtained. However it can be seen from Figures 7 to 12 that the F factor utilization reduces it and in this case errors are generally less than 20 % in the - 0. 2, + 0. outlet quality range.

In the average length case (50cm) the utilization of the F factor is most favourable for the WAPD-188 correlation. Discrepancies decrease from about 40 % below 20 % for the highest mass velocity except for an outlet quality higher than 0. 35 and from 50 % below 30 % for the lowest mass velocity. In the same way utilization of the F factor reduces discrepancy for the W-2 correlation but large errors arise in certain cases (in brackets) when along the test section the subcooled equation and the quality equation are used successively, leading to an erroneous DNB prediction upstream the hot spot associated with the q'' DNB correlation.

The W-3 correlation predicts generally well except for outlet qualities far from its validity range (- 0. 15 to + 0. 15) in outlet quality. Utilization of the Fiat F factor generally yields better agreement than the utilization of the Tong F factor.

In the largest considered length, the agreement when F factors are applied to WAPD-188 correlation is much better; the errors decrease from 50 % to 25 % even at high outlet quality (0 . 6), the F Fiat utilization giving errors below 20 %. WAPD-188 predicts rather well the uniform case.

Except at outlet qualities larger than 0. 55, the Δ H DNB-W-2 correlation gives good results ($<$ 20 %), the agreement being better than that for the uniform case prediction (25 %).

The W-3 correlation has not been examined for this length, the DNB qualities lying much out of its validity range.

With the shortcomings mentioned hereabove, it appears that utilization of the F factor yields an improved agreement (± 20 %) within the correlation validity range, the Fiat F factor being generally better than the Tong F factor especially at low DNB qualities. The best agreement is generally obtained with the W-3 correlation.

4.2.4. Data from Eur 2490 e (30)

These experimental data, obtained with downskewed cosine profiles having a form factor of 1.4, have been compared with correlations (Fig. 13 to 15). Application of F_{Tong} and F_{Fiat} factors has practically no influence on the predicted values. This is due to the fact that the values of the F factors are close to unity in the DNB region. Correlations give overpredicted values, particularly for the WAPD-188 and W-2 correlations at a mass velocity of 0.142 kg/cm^2 sec when the exit quality is positive (overprediction larger than 20 % for $x_{out} > 3$ % or $x_{in} > -30$ %). Except for this case predictions by the three considered correlations show a good agreement with experimental values, the W-3 correlation appearing to be the best one.

5. CONCLUSIONS

From the analysis of available experimental data on DNB heat flux in non-uniformly heated channels one could deduce some general trends. The most significant one is that the influence of the non-uniformities on the DNB decreases when the inlet quality increases, all the other parameters (geometry, pressure, mass velocity) being kept unchanged.

A survey of various methods of application of DNB correlations has also been performed. Out of these the local length method appears to give better predictions than the overall power method and is more easily applied than the equivalent length method. The local length method was applied with the WAPD - 188, W-2 and W-3 correlations. The use of the F factor developed by Westinghouse always improves the predictions particularly for profiles with hot patches.

The values of the F factor calculated by the Tong correlation do not differ appreciably from those calculated by the FIAT correlation.

Of the three considered correlations, the W-3 appears to be the best one when used in its range of validity for what concerns the quality (outlet quality between - 0.15 and + 0.15).

However in the case of marked non-uniformities like hot patches and low qualities the discrepancies between experimental values and theoretical predictions are generally too large as to allow the use of the selected method of calculations for detailed design and performance studies.

Further experimental and theoretical work in this field appears therefore to be desirable.

6. ACKNOWLEDGEMENTS

The authors wish to acknowledge the useful discussions they had with M. de Waegh in the course of the preparation and the accomplishment of this work.

BIBLIOGRAPHY

(1) Previti et al. An investigation on some parameters influencing non-uniform heat flux DNB prediction
EUR 3114 e (1966)

(2) Previti et al. Forced convection burnout and hydrodynamic instability experiments for water at high pressure. Part III - Comparison between experimental burnout data and theoretical prediction for uniform and non-uniform heat flux distribution
EUR 3113 e (1966)

(3) Alessandrini et al. Critical heat flux for fully developed flow steam - water mixtures in round vertical tubes with an intermediate non heated section
CISE R-69 (1963)

(4) Styrikovitch et al. Teploenergetika n° 5 (1960) p. 81

(5) Becker A correlation for burnout prediction in vertical rod bundle
S 349 (1966)

(6) Barnett The prediction of burnout in non-uniformly heated rod clusters from burnout data for uniformly heated round tubes
AEEW-R 362 (1964)

(7) Lee Burnout data for high pressure water in a tube with uniform and cosine axial heat flux distributions
VDMC/PWP/P 134 (1964)

(8) Lee and Obertelli An experimental investigation of forced convection burnout in high pressure water. Part II - Preliminary results for round tubes with non-uniform axial heat flux distribution
AEEW - R 309 (1963)

(9) Lee An experimental investigation of forced convection burnout in high pressure water. Part III - Long tubes with uniform and non-uniform axial heating
AEEW - R 355 (1965)

(10) Weiss Hot patch burnout tests in a 0.097 in x 1 in x 27 in long rectangular channel at 2000 psia
WAPD - TH - 338 (1957)

(11) Weiss 1.3 : 1 hot patch burnout tests at 800, 1200 and 2000 psia in a 0.093 in x 1 in x 27 in long rectangular channel
WAPD - TH - 412 (1958)

(12) Iudd et al. Burnout in tubular flow with non-uniform heat flux
BAW - 3238 - 9 (1965)

(13) De Bortolli et al. Forced convection heat transfer burnout studies for water in rectangular channels and round tubes at pressures above 500 psia
WAPD - 188 (1958)

(14) Styrikovitch et al. The influence of local raised heat fluxes along the length of a channel on the boiling crisis
Sov. Phys. Doklady vol. 7 n° 7 pp. 597-599 (1963)

(15) Styrikovitch at al. The effect of uneven heating along a tube on the critical thermal streams
Sov. Phys. Doklady vol. 6 n° 8 pp. 691-693 (1962)

(16) Casterline Second experimental study of dryout in a long vertical tube with a cosine heat flux
Columbia University Topical Report n° 5 of Task XVI of Contract (AT/30-3)-187

(17) Tong DNB (burnout) studies in an open lattice core
Vol. 1 - WCAP 3736 (1964)

(18) Todreas and Roshenow The effect of axial heat flow distribution on burnout in annular two phases flow
AIChE p. 78 (1966)

(19) Stevens et al. An experimental comparison between forced convection burnout in Freon-12 flowing vertically upwards through uniformly and non-uniformly heated round tubes
AEEW - R 426 (1965)

(20) Lee An experimental investigation of forced convection burnout in high pressure water. Part IV - Large diameter tubes at about 1600 psia
AEEW - R - 479 (1966)

(21) Stevens et al. An experimental investigation into forced convection burnout in Freon, with reference to burnout in water uniformly heated round tubes with vertical upflow
AEEW - R 321 (1964)

(22) Bertoletti et al. Critical heat flux data for fully developed of steam water mixture in round tubes with a non-uniform axial power distribution
CISE R - 74 (1963)

(23) De Bortolli et al. Additional burnout data for a rectangular channel having a cosine axial heat flux
WAPD - TH - 227 (1956)

(24)	Cook	A boiling water reactor research and development program - First quarterly report (1960) GEAP - 3558
(25)	Iudd et al.	Non-uniform heat generation experimental program BAW - 3238 - 8 (1965)
(26)	Janssen and Kervinen	Burnout conditions for non-uniformly heated rod in annular geometry GEAP - 3755 (1963)
(27)	Bell	Correlation of burnout heat flux data at 2000 psia Nucl. Sci. & Eng. 7, pp. 245 - 251 (1960)
(28)	Longo	A statistical study of subcooled burnout including the effect of local hot spots KAPL - 1744 (1957)
(29)	Tong et al.	New correlations predict DNB conditions Nucleonics (May 1963)
(30)	Biancone et al.	Forced convection burnout and hydrodynamic instability experiments for water at high pressure. Part I : Presentation of data for round tubes with uniform and non-uniform power distribution EUR. 2490 e (1965)
(31)	Smith	Non-uniform heat flux burnout with upward water flow WCAP - 2795 (1965)
(32)	Styrikovitch et al.	Influence of non-uniform heating of the perimeter of a tube on the critical heat flux Soviet Physics - Doklady vol.4, n° 4 p.794 (1960)
(33)	Miropolskii et al.	Critical heat flux in uniform and non-uniform heating of the circumference of steam generating tubes Teploenergetika vol. 11, p. 64 (1958)
(34)	Alekseev et al.	Burnout heat flux under forced water flow 3rd United Nation International Conference on the Peaceful Uses of Atomic Energy Paper A/CONF. 28/P/327 a (May 1964)
(35)	Lee	Burnout in a channel with non-uniform circumferential heat flux AEEW - R 477 (1966)
(36)	De Bortoli	Departure from nucleate boiling tests at 2000 psia on rectangular channels with a flux peak in the corners WAPD - AD - TH 519 (1959)

(37) Iudd et al. Non-uniform heat generation experimental programs BAW - 3238 - 7 (1965)

(38) Wilson Burnout data correlation from uniformly and non-uniformly heated channels CONF - 64507 p. 45 - 65 2nd Eur. AEC two phases flow meeting Germantown (1964) and CONF - 651110 - 5 (1965)

(39) Tong DNB prediction for an axially non-uniform heat flux distribution WCAP 2815 Rev. 1 (1965)

(40) Tong et al. Influence of axially non-uniform heat flux on DNB AIChE - Preprint 17, 8th Nat. heat transfer Los Angeles (1965) and WCAP - 2767

(41) Bennet et al. Studies of burnout in boiling heat transfer to water in round tubes with non-uniform heating AERE - R 5076 (1966)

(42) Galson and Polomik Burnout data available to boiling water reactors ANS Pitts. Meeting - June 6 (1957)

(43) Iudd et al. Effects of non-uniform heat generation rates on burnout in annular and tubular flow BAW - 3238 - 12 (1966)

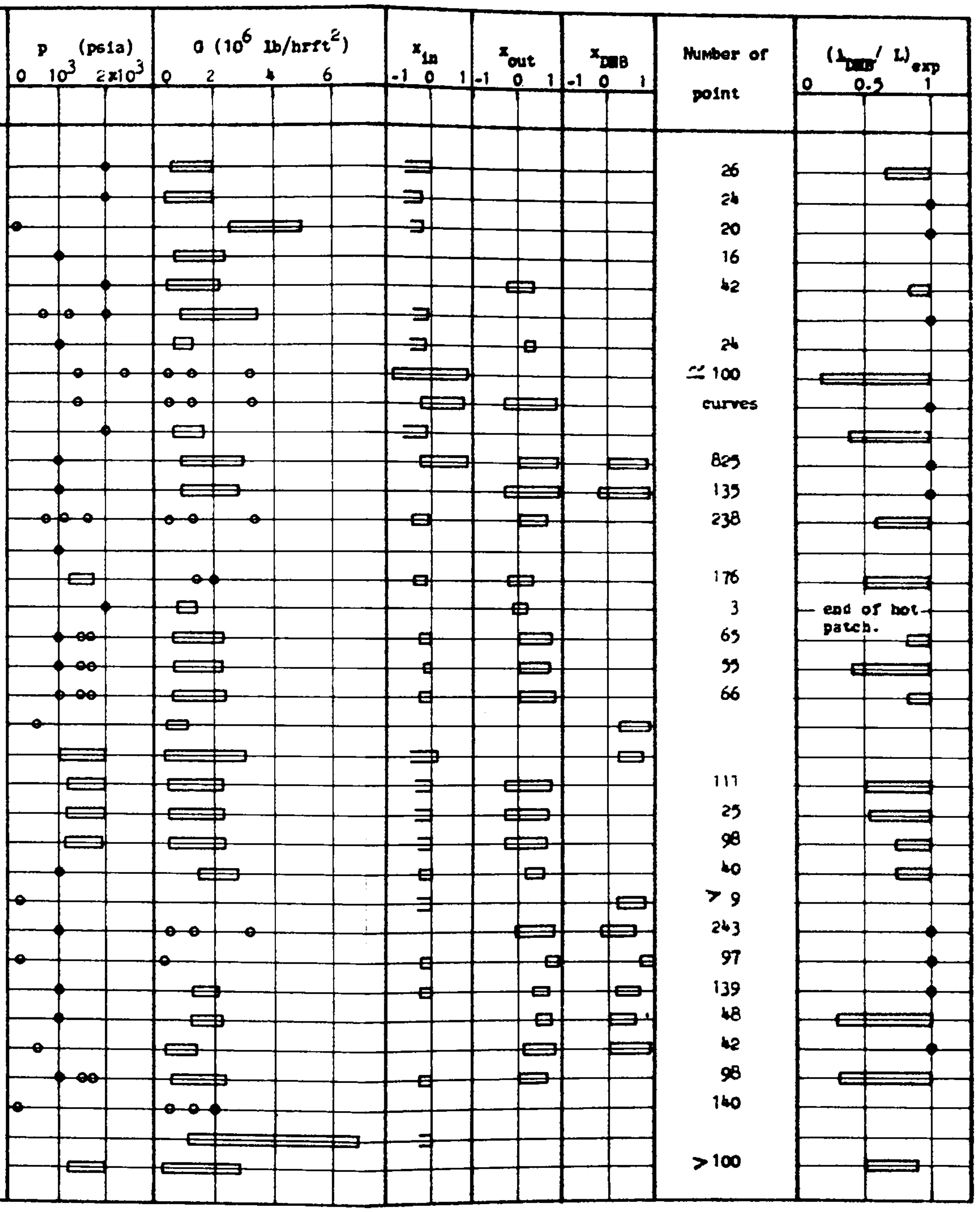
(44) Swenson et al. The influence of axial heat flux distribution on the departure from nucleate boiling in a water cooled tube ASME paper n° 62 - WA - 297 (1962)

(45) Eastwood The scaling of two phase flow using Freon A progress report. Paper presented at the 2nd European meeting on two phase flow Ispra (1966)

- APPENDIX 1 -

MAIN SOURCES OF EXPERIMENTAL RESULTS WITH NOW UNIFORM AXIAL HEAT FLUX DISTRIBUTIONS.

Ref.	Source	Date	Axial power** distribution	M q''_M/q''_m	N q''_M/q''_{avg}	*** Channel shape	L (inch)	De (inch)	$\frac{L}{De}$	Number of point
23	WAPD-TH-227	56	C			R	27	0.12	225	26
10	WAPD-TH-338	57	H l_1 = 1.375 in.	1.98		R	27	0.170	159	24
28	KAPL-1744	57	H l_1 = 0.065 to 0.875in.	1 to 4		T	8	0.25	32	20
42	Galson-Polomik	57	non-uniform			A	108	0.298	322	16
13	WAPD-188	58	C		1.38	R	27	0.11	245	42
11	WAPD-TH-412	58	H l_1 = 1.5 in.	1.3		R	27	0.176	153	
24	GEAP-3558	60	C	2.92	1.30	A	108	0.336	322	24
15	Dokl.Vol.6 N°8	61	UR-DR	4.9	2.3	T	6.3	0.238	27	≃ 100
14	Dokl.Vol.7 N°7	62	H l_1 = 0 to 0.25 in.	1 ; 1.35 ; 2		T	6.3 to 37	0.31	20 to 118	curves
44	ASME 62-WA-297	62	C-UC-DC-HUC		1.2 to 1.9	T	72	0.422	171	
3	CISE R-69	63	CP			T	15 and 29	0.19	80 and 150	825
22	CISE R-74	63	UC-DR-C	2.36	1.31	T	25.4	0.314	81	135
8	AEEW R-309	63	C-UC	2.4 and 9.70	1.27 and 1.42	T	72	0.383	188	238
26	GEAP-3755	63	C-DC			A				
7	VDMC-PWP/P 134	64	C		1.27 and 1.17	T	39.4	0.625	63	176
17	WCAP-3736	64	HUC		3.14	bundle	108	0.457	236	3
25	BAW-3238-8	64	C		1.4	T	72	0.417	173	65
	BAW-3238-6		UC	5	1.4	T	72	0.417	173	55
37	BAW-3238-7	65	DC	5	1.4	T	72	0.417	173	66
38	Conf.651110-5	65	non-uniform							
40	WCAP-2767	65	CP-H-UR-DR-C			T	25 to 72	0.177 to 0.446		
30	Eur. 2490 e	65	C		1.4	T	51.5	0.67	77	111
	Eur. 2490 e		UC		1.4	T	46.5	0.455	102	25
	Eur. 2490 e		DC		1.4	T	46.5	0.455	102	98
9	AEEW-R-355	65	C		1.37	T	144	0.373	286	40
31	WCAP-2795	65	H-CP $l_1/L \simeq 0.5$			A				> 9
19	AEEW-R-426 *	65	H l_1 = 3 in.	2.05		T (Freon)	9.5 to 74 in	0.24	31.5 to 268	243
41	AERE-R-5076	66	CP l_1 = 6 to 24 in.			T	72 to 96	0.366	197 to 266	97
	AERE-R-5076		CP l_1 = 24 in.			T	168	0.497	338	139
	AERE-R-5076		UR		2 ; 3 ; 3.7	T	156	0.495	315	48
5	3-349	66	UR-DR	2.5	1.25	T	39.4	0.394	100	42
43	BAW-3238-12	66	C		1.4	A	72	(0.417)	(173)	98
18	MIT 9843-37	66	C-UC-DC-UR-DR-HUC-H			T	30 to 48	0.214	140 to 224	140
12	Columbia University	66	C		1.54	T	192	0.4	450	
20	AEEW-R-479	66	C		1.16 to 1.63	T	39.4 and 47	0.625 ; 1.11	42 ; 63	> 100



* Range values have been translated in water system.

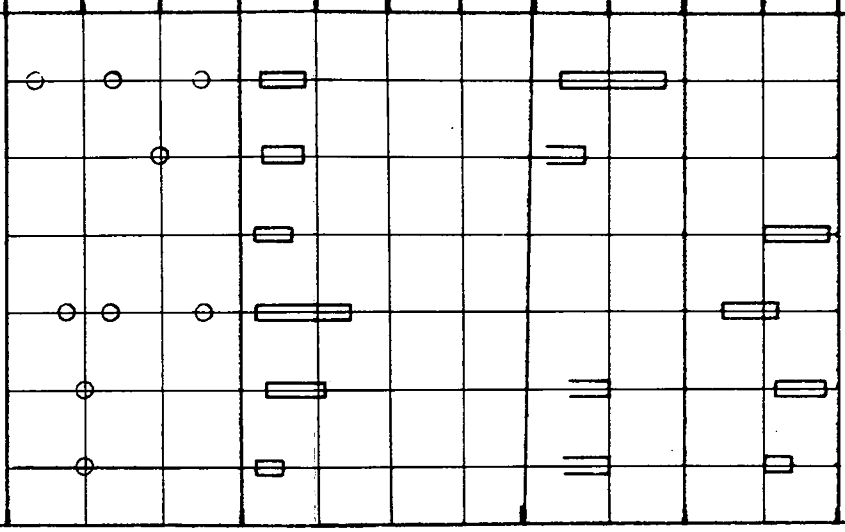
** C : symetrical chopped cosine
UC : upskewed chopped cosine
DC : downskewed chopped cosine
H : hotpatch at the end of the section
UR : inlet peaked ramp
DR : outlet peaked ramp
CP : cold patch
HUC : hot patch on upskewed cosine

*** T : round tube
R : rectangular channel
A : annular channel.

- APPENDIX 2 -

MAIN SOURCES OF EXPERIMENTAL RESULTS FOR NON UNIFORM RADIAL HEAT FLUX DISTRIBUTIONS.

Ref.	Source	Date	Circumferential power distribution	M q''_M/q''_m	N q''_M/q''_{avg}	✱ channel shape	L inch	De inch	$\frac{L}{De}$	p psia 0 10^3 2.10^3	G (10^6 lb/hrft^2) 0 2 4 6	x_{in} -1 0 1	x_{out} -1 0 1	Number of points
33	Teploenerg 11	58	Flux tilt	3.8	1.8	T	5.9	0.222	26.5					
36	WAPD-AD-TH-519	59	peak in corners		1.38 ; 1.83	R	12	0.05	240					32
32	Dokl-Vol.4 n°4	60	Flux tilt	3 to 18	1.5 to 3.7	T	5.9 ; 18.4	0.24 ; 0.74	25					> 200
34	P/327 a Geneva	64	Flux tilt		1.12 to 1.5	T	39.4	0.394	100					> 100
35	AEE W-R.477	66	Flux tilt		1.21	T	68	0.376	180					30
	AEE W-R.477		Flux tilt		1.29	A	31.5	0.216	145					12



✱ T : round tube
R : rectangular channel
A : annular channel.

APPENDIX III

EXPRESSIONS OF THE CORRELATIONS USED

WAPD-188 Correlation (13)

$$q''_{DNB} = 0.28 \times 10^{6} \left(\frac{H_{DNB}}{10^{3}} \right)^{-2.5} \left(1 + \frac{G}{10^{7}} \right)^{2} e^{-0.0012\ L/De}$$

where

q''_{DNB}	DNB heat flux	Btu/hr ft^2
H_{DNB}	local enthalpy at DNB	Btu/lb
G	mass velocity	lb/hr ft^2
L	length	ft
De	equivalent diameter	ft

W-1 and W-2 Correlations (29)

for $x_{out} < 0$

$$q''_{DNB} = (0.23 \times 10^{6} + 0.094\ G)\ (3.00 + 0.01\ \Delta T_{sc})$$

$$(0.435 + 1.23\ e^{-0.0093\ L/De})\ (1.7 - 1.4\ e^{-a})$$

where

$$a = 0.532 \left[\frac{H_f - H_{in}}{H_{fg}} \right]^{3/4} (\rho_g / \rho_f)^{-1/3}$$

for $x_{out} > 0$

$$\Delta H_{DNB} = 0.529\ (H_f - H_{in}) + (0.825 + 2.36\ e^{-204\ De})\ H_{fg}\ e^{-1.5\ G/10^{6}}$$

$$- 0.41\ H_{fg}\ e^{-0.0048\ L/De} - 1.12\ H_{fg}\ \rho_g / \rho_f + 0.548\ H_{fg}$$

In these equations :

ΔT_{sc} : local subcooling $= T_{sat} - T_{loc}$ °F

L : distance from inlet to point of DNB ft

H_f : saturated liquid enthalpy Btu/lb

H_{fg} : latent heat of evaporation Btu/lb

ρ_g : density of saturated stream lb/ft^3

ρ_f : density of saturated liquid lb/ft^3

W-3 Correlation (39)

$$\begin{aligned}\frac{q''_{DNB,EU}}{10^6} = & \Big[(2.022 - 0.0004302\ p) \\ & + (0.1722 - 0.0000984\ p)\ e^{(18.177 - 0.004129\ p)\chi}\Big] \\ & \times \Big[(0.1484 - 1.596\ \chi + 0.1729\ \chi\ |\chi|\ )\ G/10^6 + 1.037\Big] \\ & \times \Big[\ 1.157 - 0.869\ \chi\ \Big] \times \Big[\ 0.2664 + 0.8357\ e^{-3.151\ De}\Big] \\ & \times \Big[\ 0.8258 + 0.000794\ (H_{sat} - H_{in})\Big]\end{aligned}$$

where

p : pressure psia

χ : local quality -

G : mass velocity $lb/hr\ ft^2$

De : equivalent diameter in.

H_{sat} : saturation enthalpy Btu /lb

H_{in} : inlet enthalpy Btu/ lb

COMPARISON OF RESULTS FROM AEEW-R426 WITH THE WAPD-188 CORRELATION

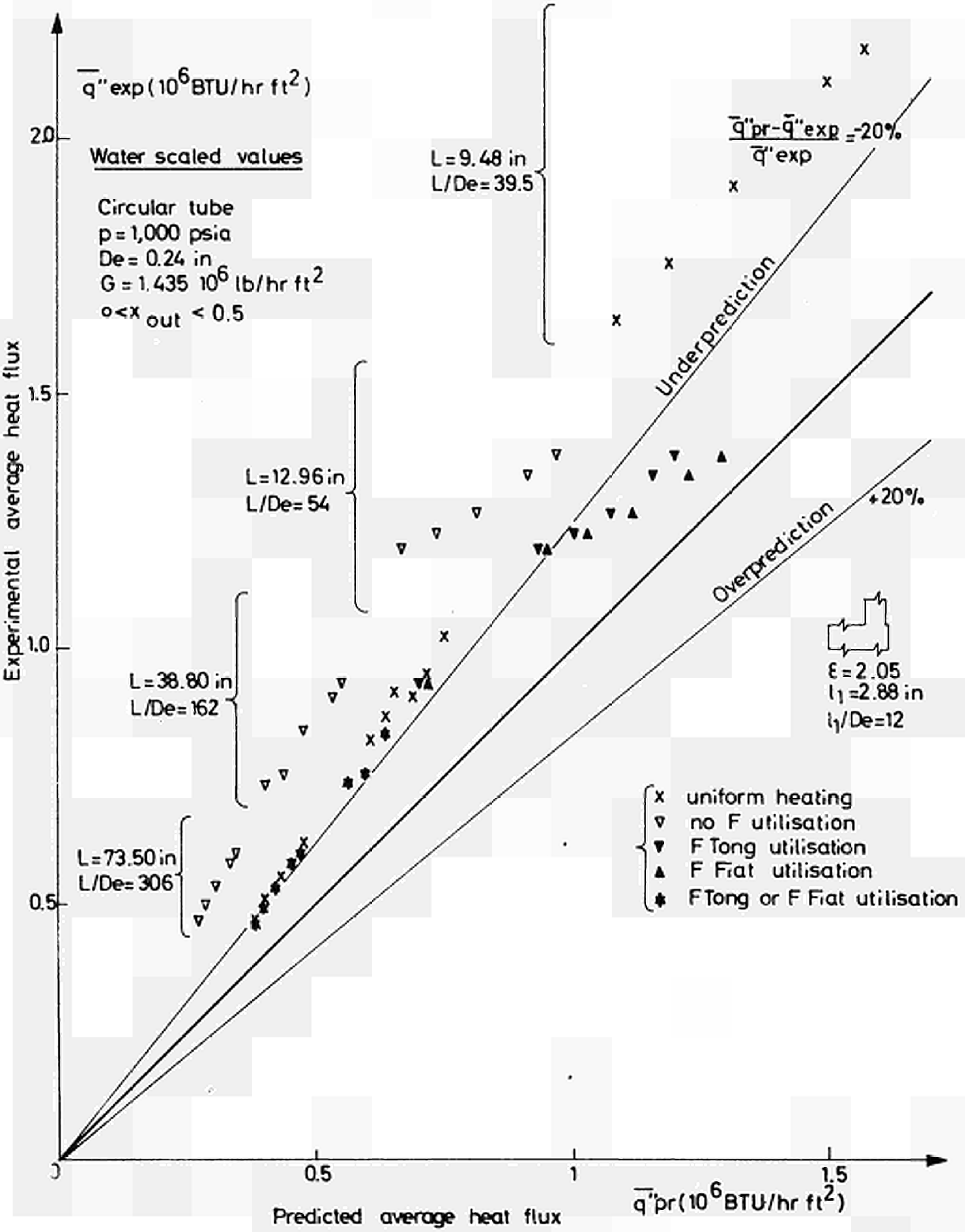


Fig. 1

COMPARISON OF RESULTS FROM AEEW-426 WITH THE W-2 CORRELATIONS(ΔH_{DHB})

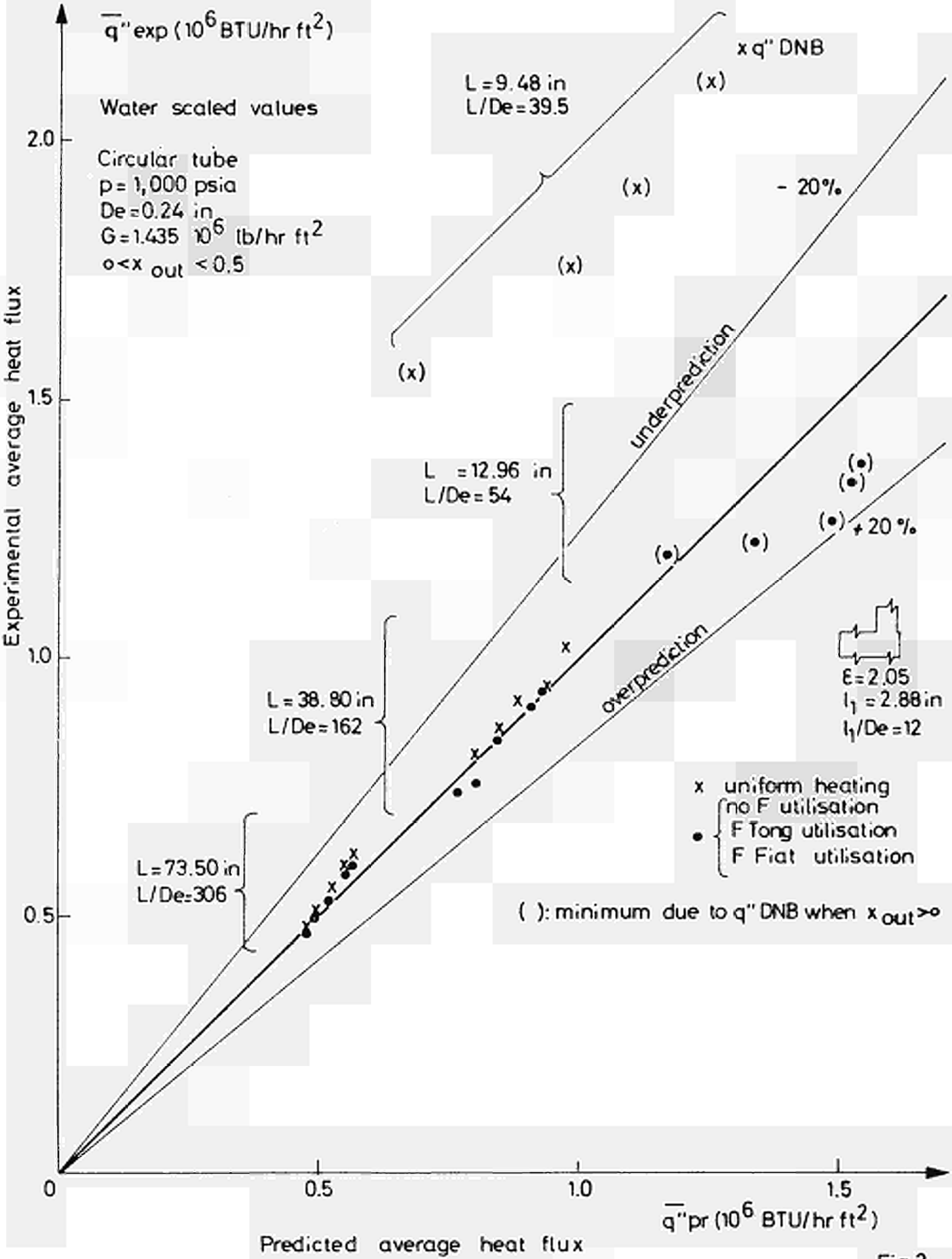


Fig.2

COMPARISON OF RESULTS FROM AEEW-R426 WITH THE W-3 CORRELATION

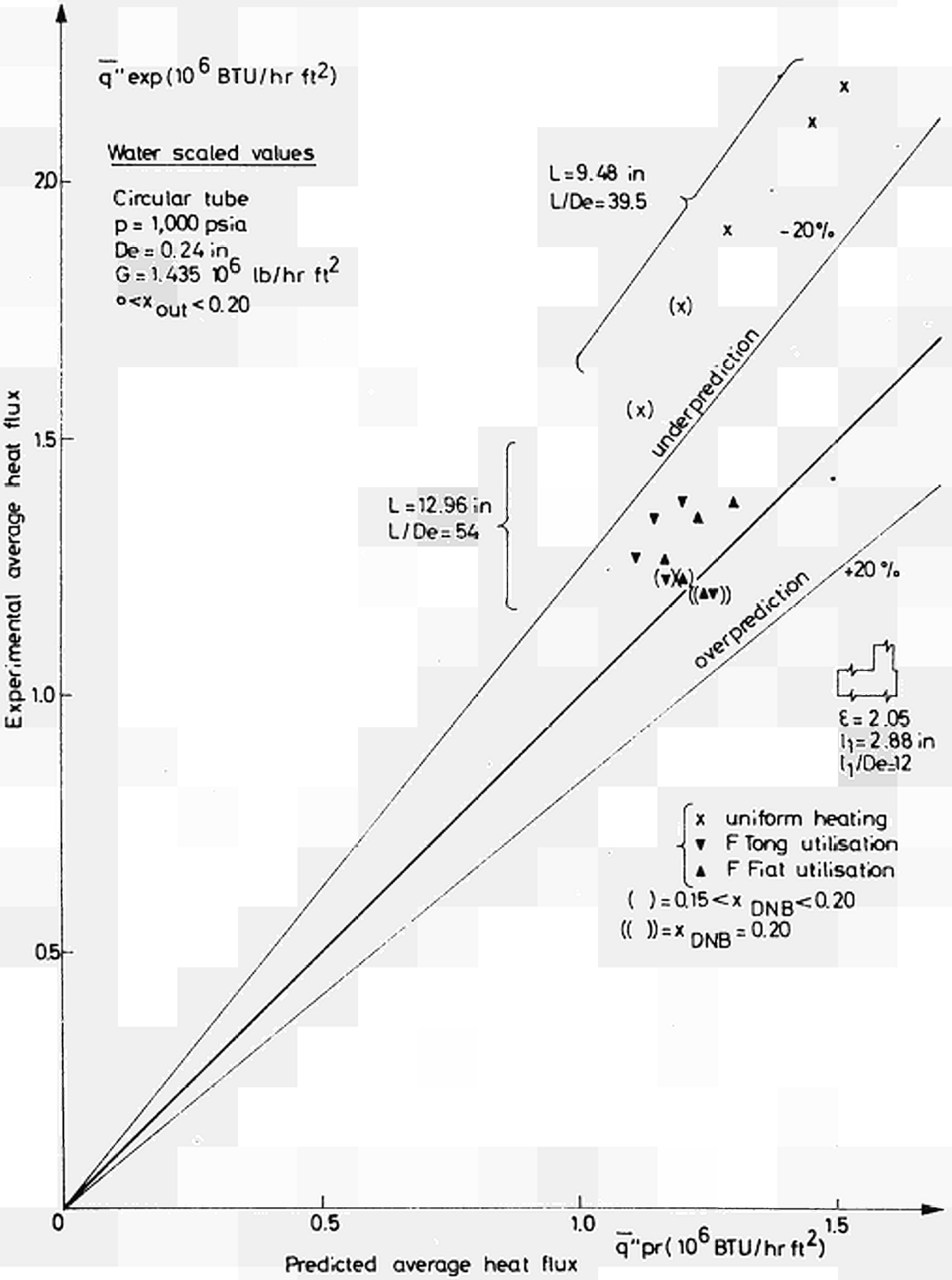


Fig. 3

COMPARISON OF RESULTS FROM WAPD-TH-338 WITH THE WAPD-188 CORRELATION

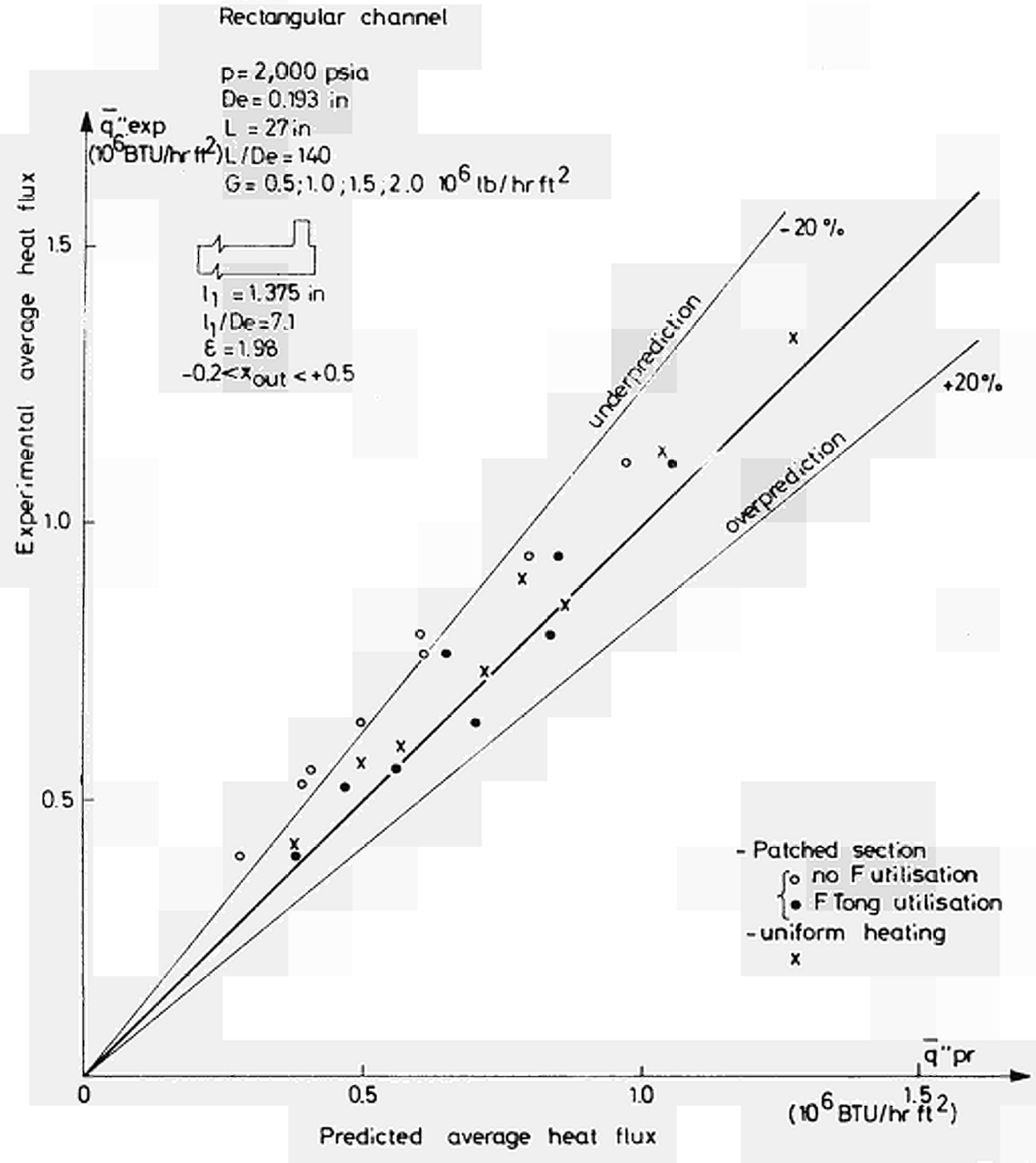


Fig. 4

COMPARISON OF RESULTS FROM WAPD-TH-338 WITH THE W-2 CORRELATIONS

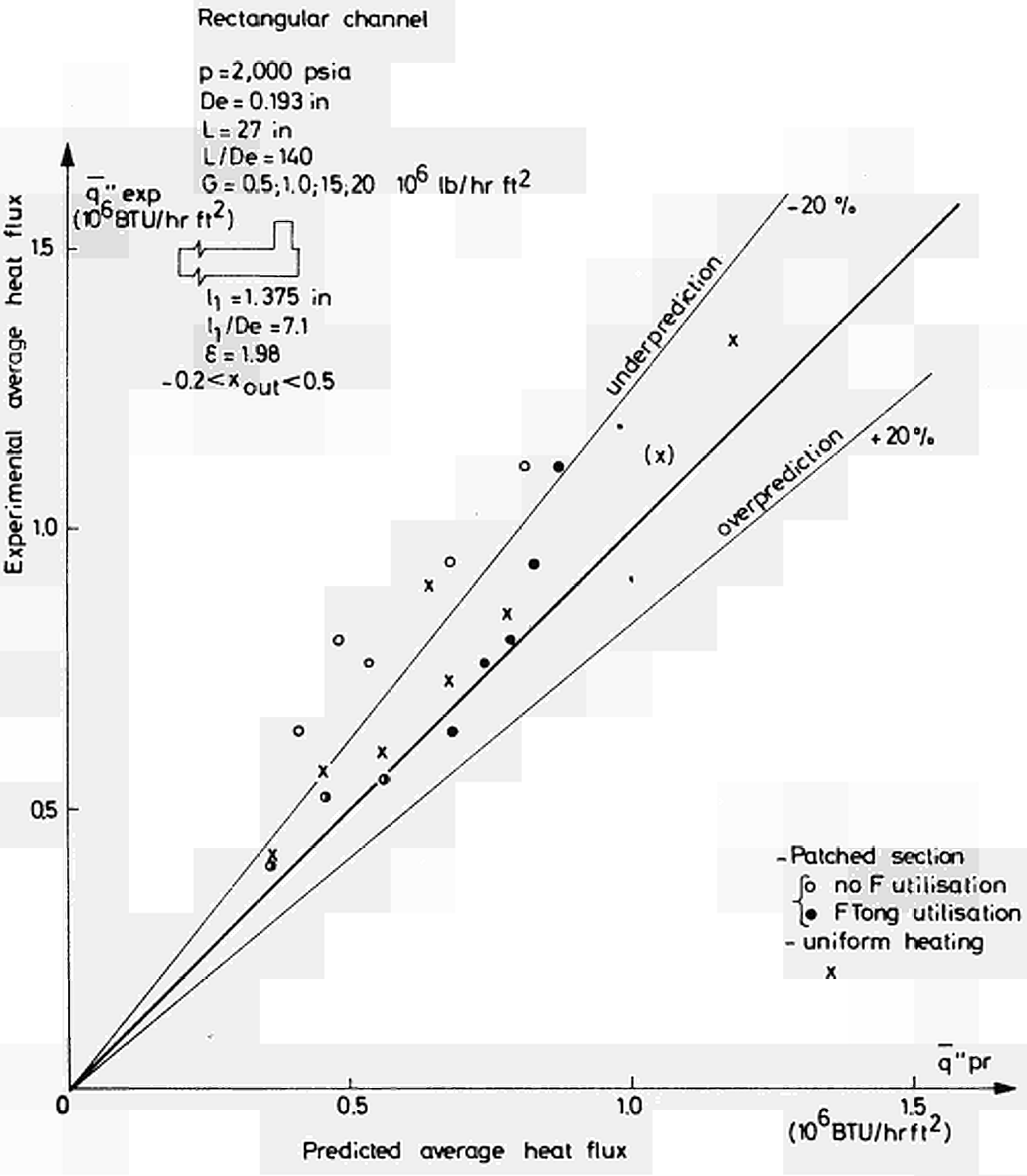


Fig. 5

COMPARISON OF RESULTS FROM WAPD-TH-338 WITH THE W-3 CORRELATION

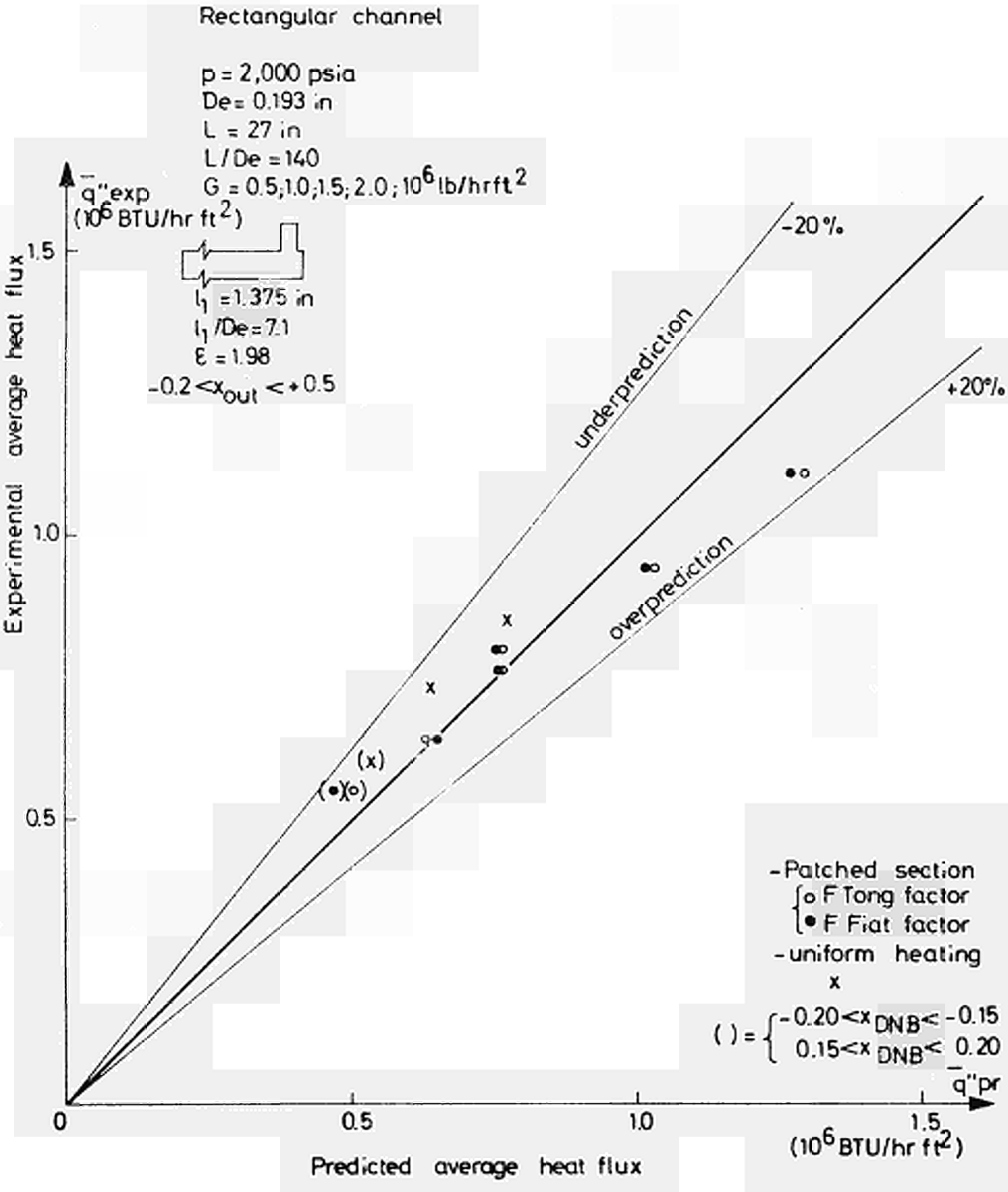


Fig. 6

COMPARISON OF RESULTS FROM DOKLADY VOL.7 Nº 7 WITH THE WAPD 188 CORRELATION

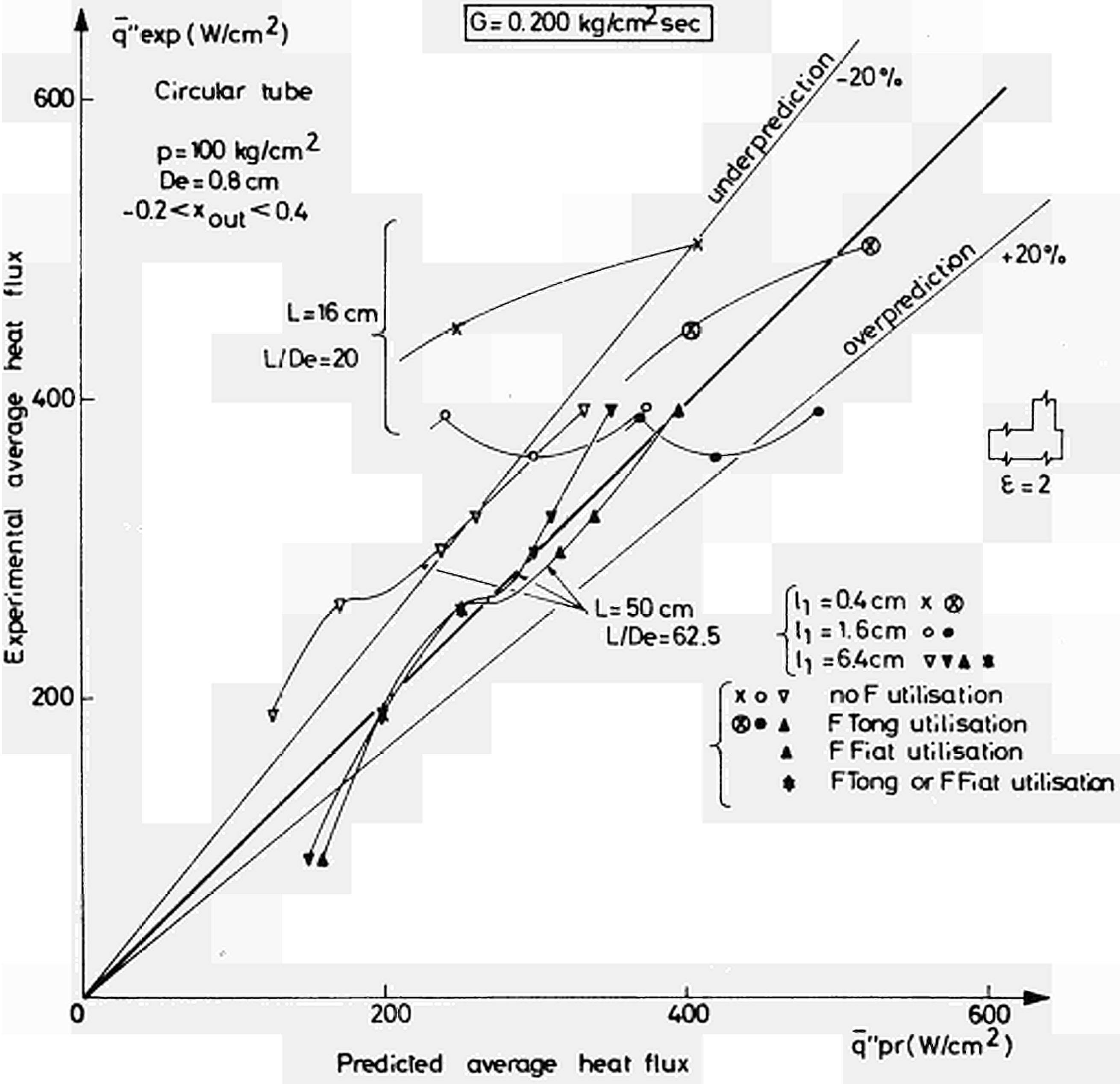


Fig.7.

COMPARISON OF RESULTS FROM DOKLADY VOL. 7 Nº 7 WITH THE WAPD-188 CORRELATION

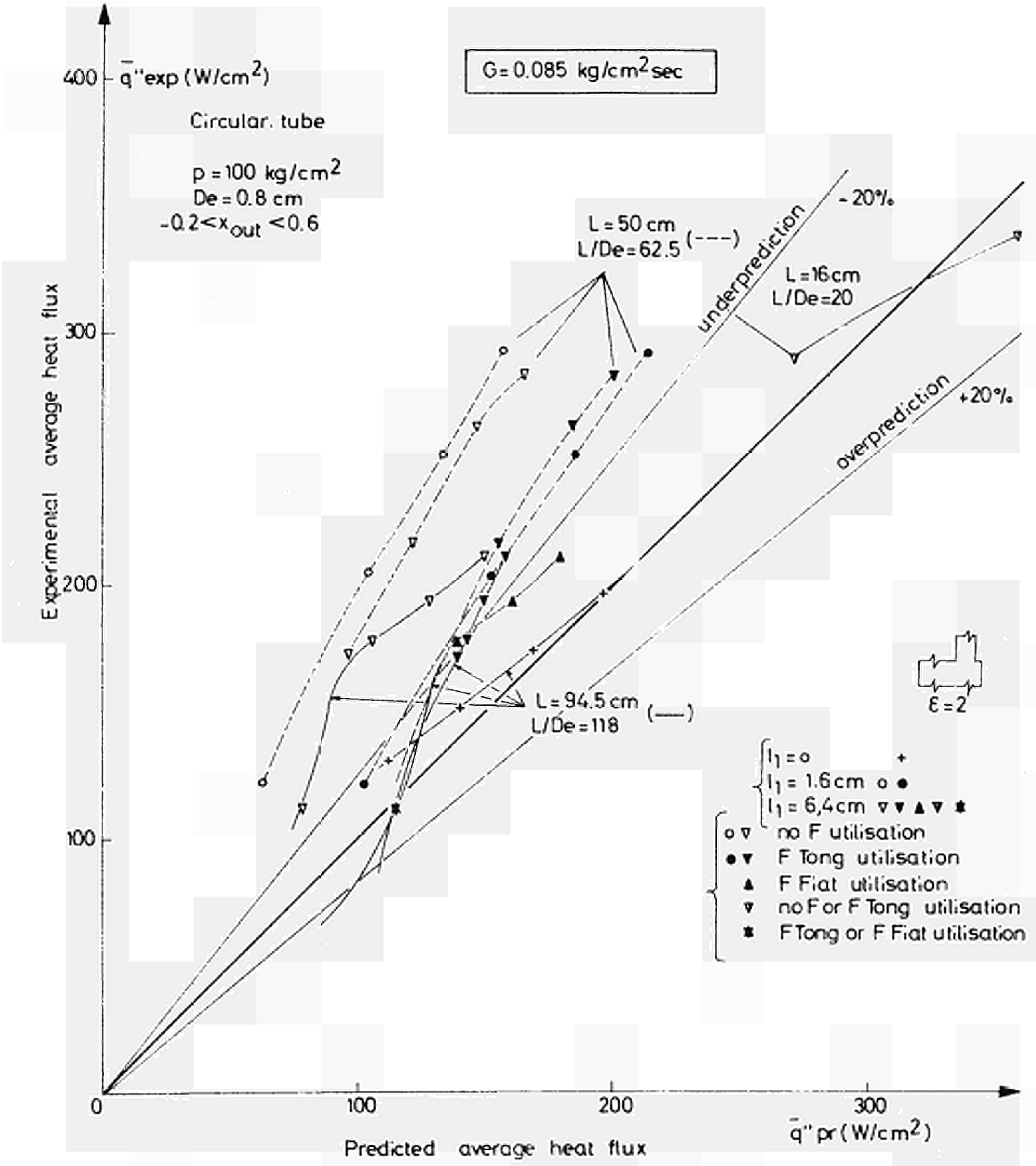


Fig. 8.

COMPARISON OF RESULTS FROM DOKLADY VOL.7 Nº7 WITH THE W-2 CORRELATIONS

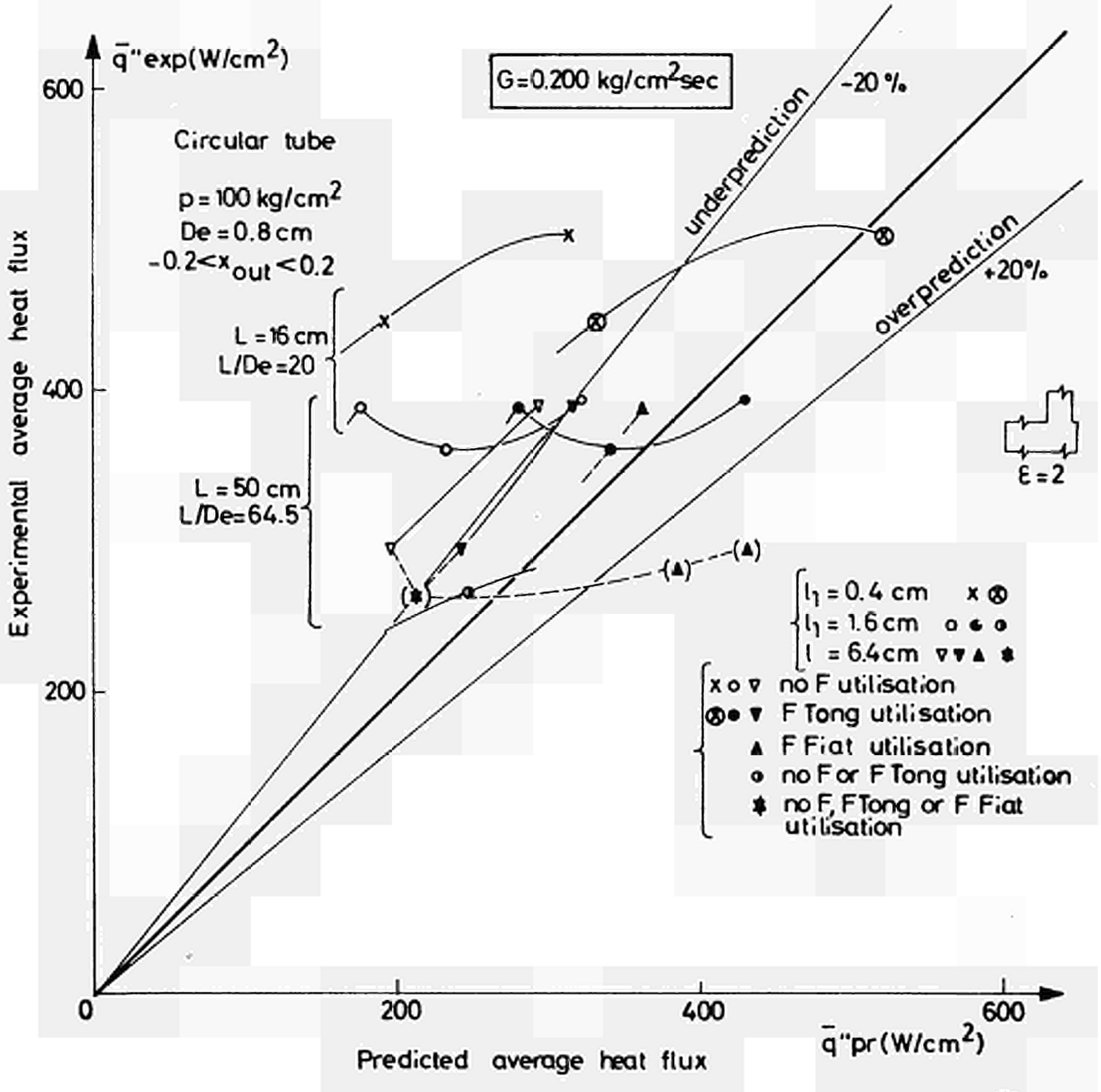


Fig. 9.

COMPARISON OF RESULTS FROM DOKLADY VOL.7 Nº7 WITH THE W-2 CORRELATIONS

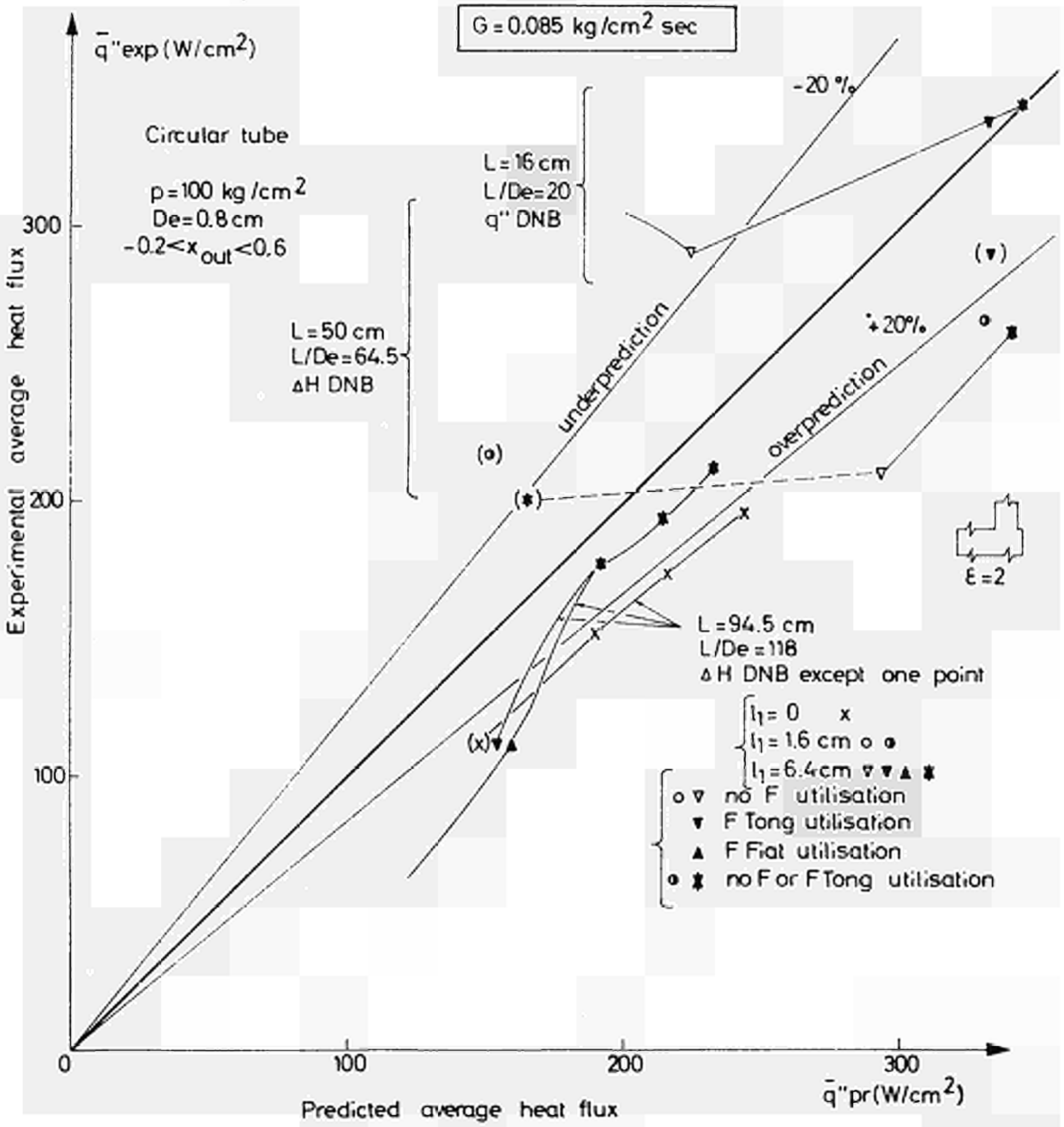


Fig.10.

COMPARISON OF RESULTS FROM DOKLADY VOL.7 Nº 7 WITH THE W-3 CORRELATION

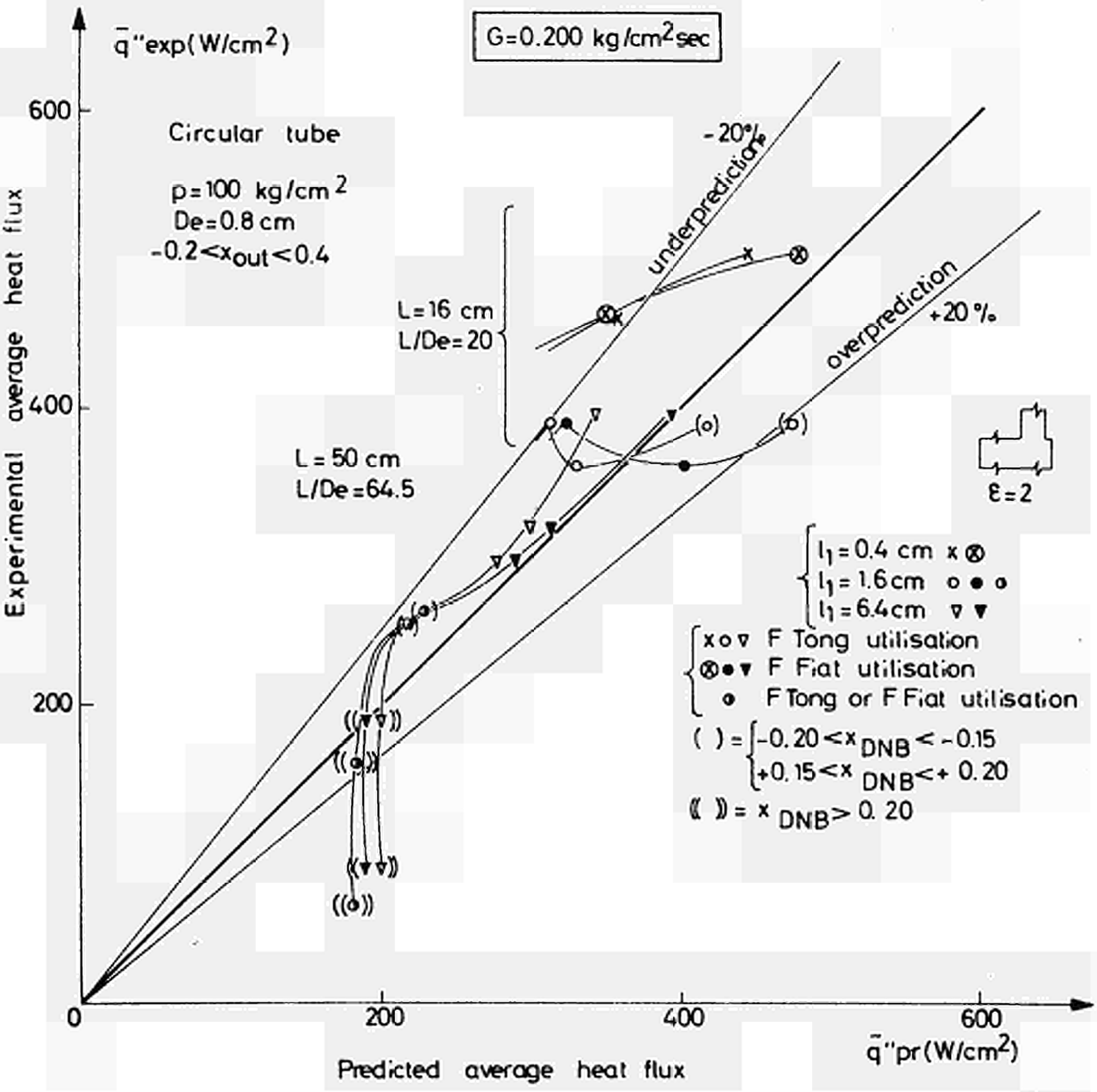


Fig.11

COMPARISON OF RESULTS FROM DOKLADY VOL.7 N°7 WITH THE W-3 CORRELATION

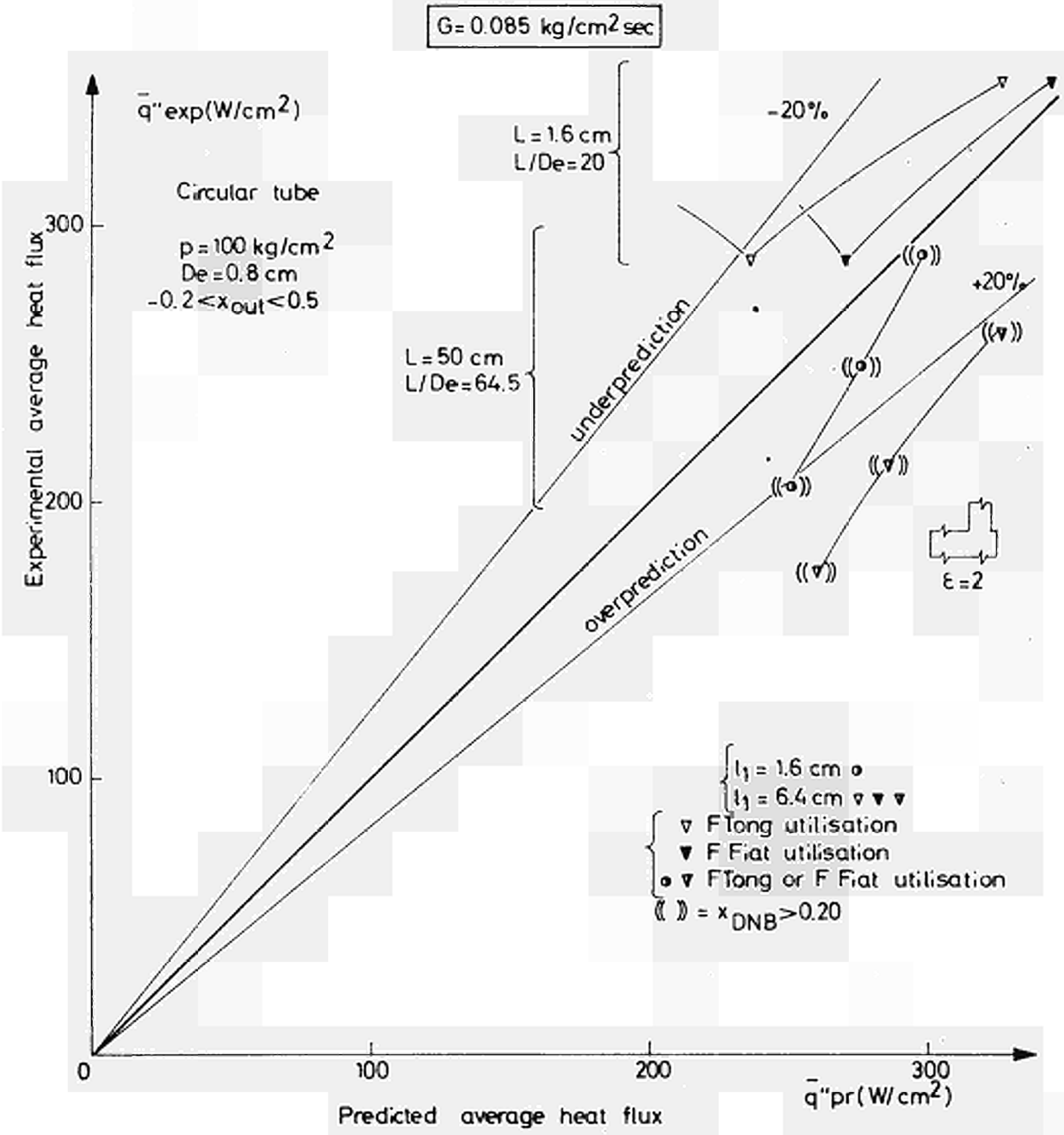


Fig. 12

COMPARISON OF RESULTS FROM EUR 2490e WITH THE WAPD-188 CORRELATION

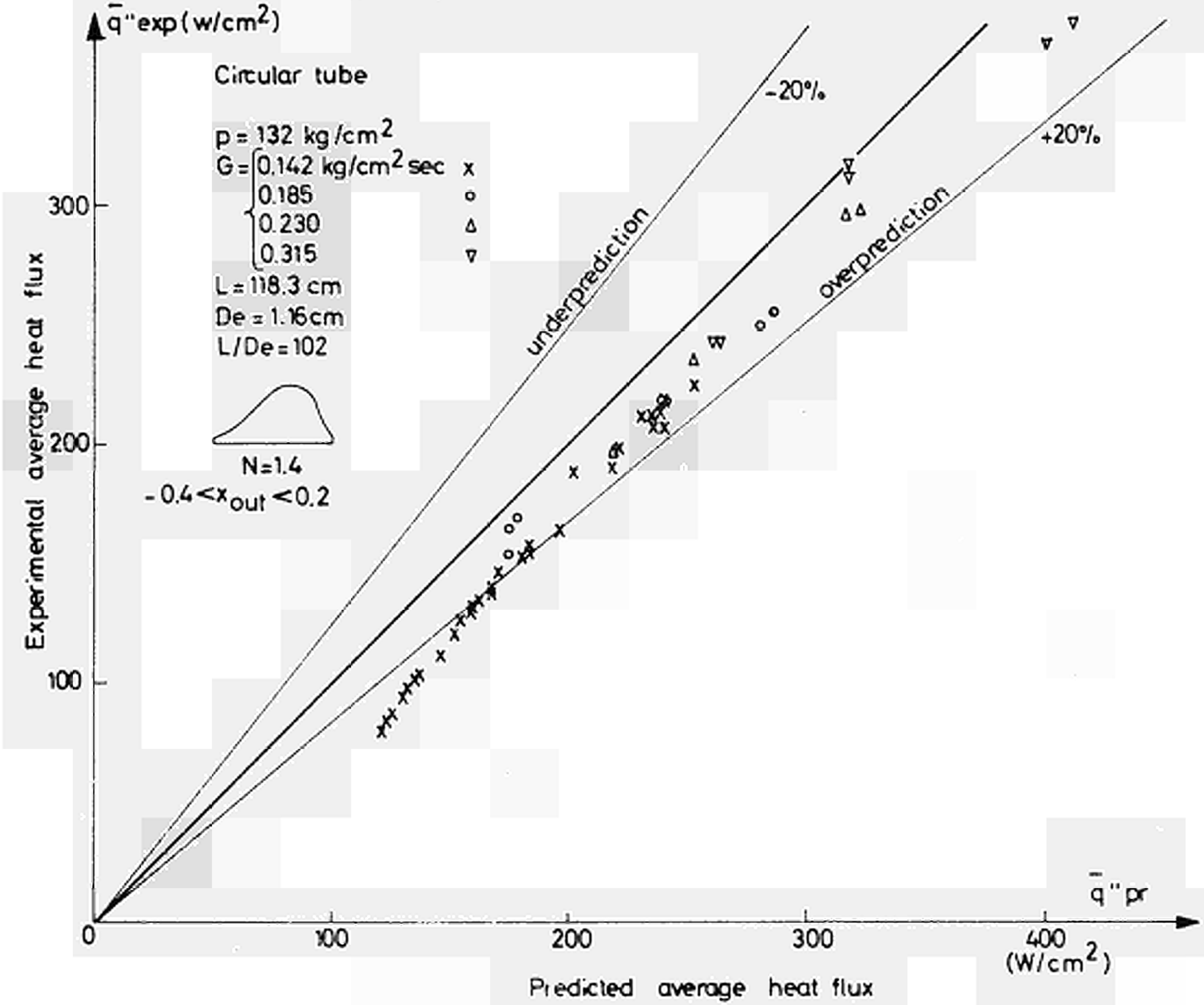


Fig. 13.

COMPARISON OF RESULTS FROM EUR 2490 e WITH THE W-2 CORRELATIONS

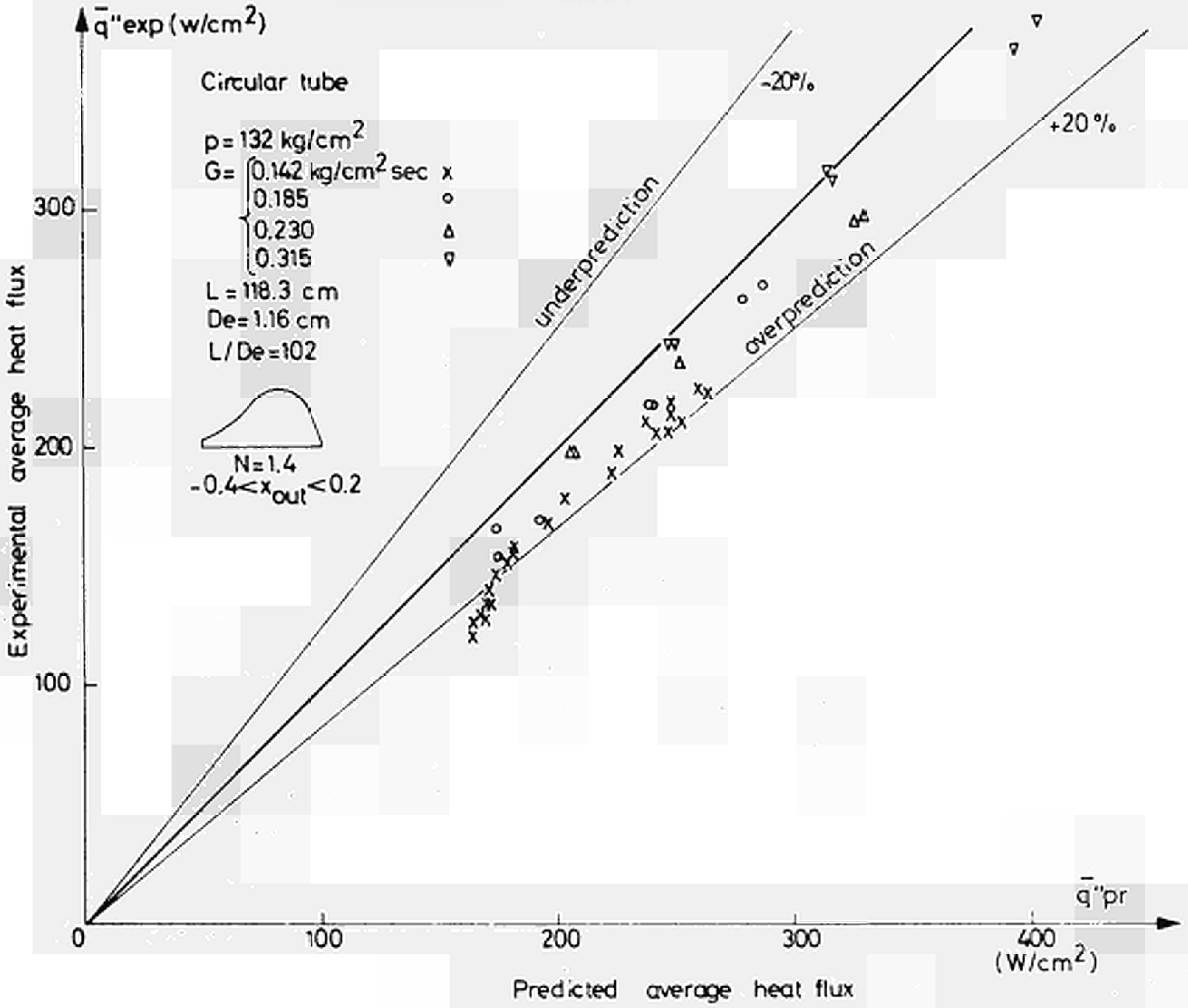


Fig.14.

COMPARISON OF RESULTS FROM EUR 2490e WITH THE W-3 CORRELATION

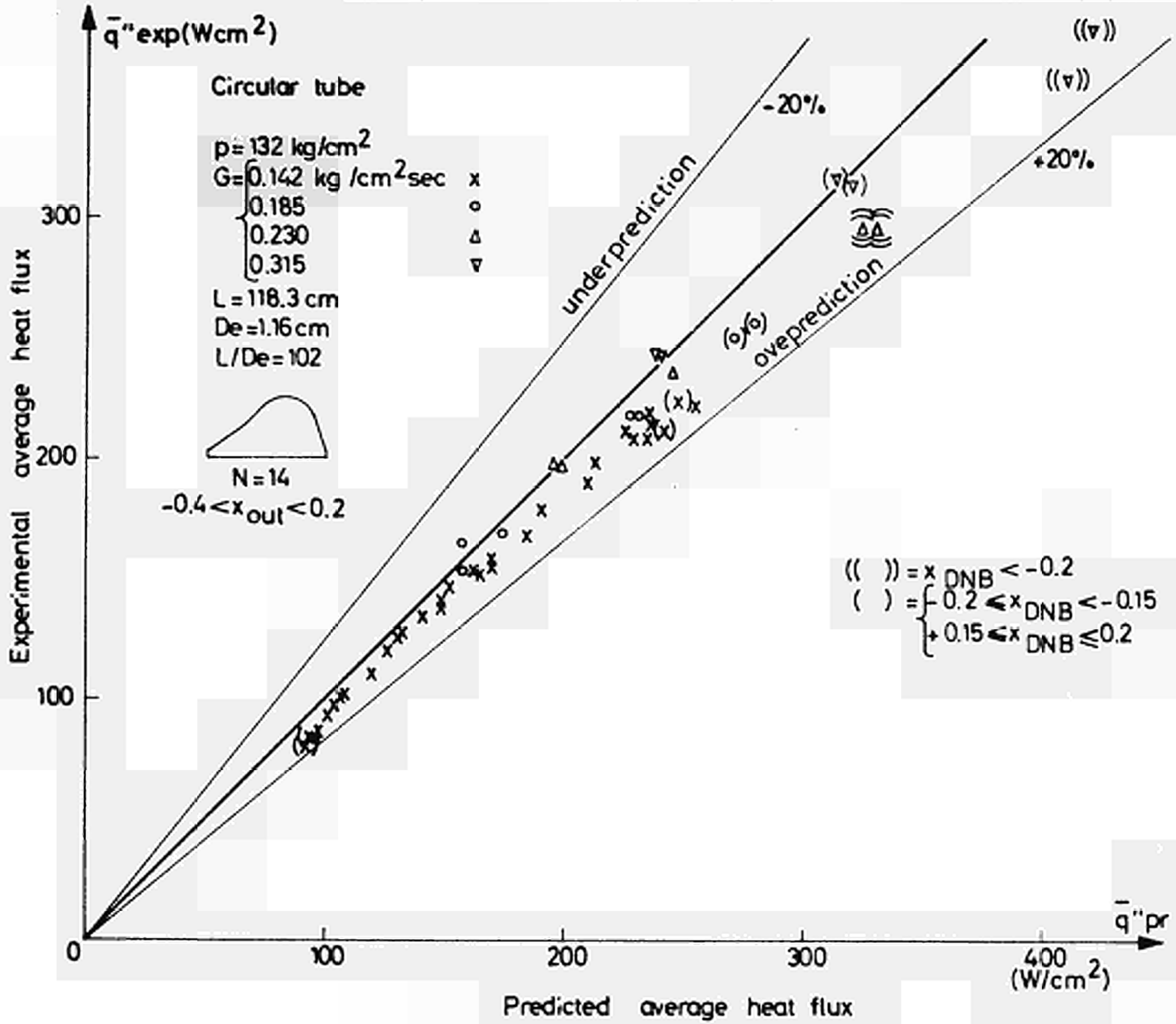


Fig.15.

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>
> **Alfred Nobel**

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