ANALYSE DE DONNEES DE FLUX CRITIQUE EN R12 : INFLUENCE DU DIAMETRE HYDRAULIQUE ET DE LA LONGUEUR CHAUFFANTE ; TEST DU MODELE DE WEISMAN

ANALYSIS OF IN-R12 CHF DATA : INFLUENCE OF HYDRAULIC DIAMETER AND HEATING LENGTH ; TEST OF WEISMAN BOILING CRISIS MODEL

EDF

Electricité de France

Direction des Etudes et Recherches

Service Information Prospective et Normalisation

Département Systèmes d'information et de documentation

Groupe Exploitation de la Documentation Automatisée

1, avenue du Gal de Gaulle
92141 CLAMART Cedex
tel : 47 65 56 33

CLAMART Le 12/10/94

MME GAGNEBIEN G.
CEA - CE SACLAY

MIST-SBDS-SPRI

91191 GIF SUR YVETTE CEDEX

à l'attention de :

MEMOIRE TECHNIQUE ELECTRONIQUE

****
Cette feuille est détachable grâce à la microperforation sur le coté droit.
****

Référence de la demande : **F488770** Votre commande :

Origine : **AVIS DE PARUTION NORMES E**

Numéro du document : **93NB00148**

Titre : **ANALYSE DE DONNEES DE FLUX CRITIQUE EN R12 : INFLUENCE DU DIAMET RE HYDRAULIQUE ET DE LA LONGUEUR CHAUFFANTE ; TEST DU MODELE D: WEISMAN**

Auteurs : **CZOP V./HERER CH./SOUYRI A./GARNIER J.**

Source : **COLL. NOTES INTERNES DER. PRODUCTION D'ENERGIE (HYDRAULIQUE, THE**
Serial :

Référence du document : **SANS**

Nombre de pages: **0018** Nombre d'exemplaires : **001** Support : **P**

EDF Electricité de France

Direction des Etudes et Recherches

SERVICE RÉACTEURS NUCLÉAIRES ET ECHANGEURS
Département Transferts Thermiques et Aérodynamique

Septembre 1993

CZOP V.
HERER CH.
SOUYRI A.
GARNIER J.

ANALYSE DE DONNEES DE FLUX CRITIQUE EN R12 : INFLUENCE DU DIAMETRE HYDRAULIQUE ET DE LA LONGUEUR CHAUFFANTE ; TEST DU MODELE DE WEISMAN

ANALYSIS OF IN-R12 CHF DATA : INFLUENCE OF HYDRAULIC DIAMETER AND HEATING LENGTH ; TEST OF WEISMAN BOILING CRISIS MODEL

Pages : 18

93NB00148

Diffusion : J.-M. Lecœuvre
EDF-DER
Service IPN. Département SID
1, avenue du Général-de-Gaulle
92141 Clamart Cedex

ISSN 1161-0611

V. CZOP (1), Ch. HERER (2), A. SOUYRI (1) and J. GARNIER (3)

(1) EDF/DER/TTA, 6 quai WATIER - BP 49 - 78401 CHATOU Cedex (FRANCE)
(2) FRAMATOME, Tour FIAT - Cedex 16 - 92084 PARIS-LA-DEFENSE (FRANCE)
(3) CEA/DRN/STC, 85 X - 38041 GRENOBLE Cedex (FRANCE)

SYNTHÈSE :

Dans le but d'améliorer la connaissance du phénomène de crise d'ébullition, EDF, le CEA et FRAMATOME ont engagé des programmes expérimentaux en R12 : les programmes APHRODITE (EDF) et DEBORA (collaboration CEA-EDF-FRAMATOME). L'objectif de la première étape de ces programmes est l'acquisition de banques de données de flux critique pour une gamme étendue de paramètres thermohydrauliques, dans des configurations tubulaires et annulaires, pour différentes valeurs du diamètre hydraulique et de la longueur chauffante.

De fait, trois banques de données de flux critique obtenues en R12 et en tube ont été analysées dans cette note :

- les données APHRODITE acquises par EDF avec un diamètre interne de 13 mm,

- les données DEBORA obtenues par le CEA avec un diamètre interne de 19,2 mm,

- les données KRISTA acquises par KfK avec un diamètre interne de 8 mm.

L'analyse de ces résultats, faite à l'aide de corrélations de flux critique ainsi que d'un récent outil mathématique d'interpolation par fonctions spline pseudo-cubiques, conduit aux conclusions suivantes :

- aucune influence de la longueur chauffante sur le flux critique n'est notée,

- l'influence du diamètre ne peut se traduire simplement par une relation type exponentielle, les paramètres thermohydrauliques jouant également un rôle important.

Des calculs avec le modèle théorique de WEISMAN & PEI ont été comparés aux valeurs expérimentales : un assez bon accord est obtenu mais une meilleure prise en compte des effets de la pression et du débit est nécessaire.

EXECUTIVE SUMMARY :

In order to progress on the comprehensive modelling of the boiling crisis phenomenon, Electricité de France (EDF), Commissariat à l'Energie Atomique (CEA) and FRAMATOME have set up experimental programs involving in-R12 tests : the EDF APHRODITE program and the CEA-EDF-FRAMATOME DEBORA program. The first phase in these programs aims to acquire critical heat flux (CHF) data banks, within large thermal-hydraulic parameter ranges, both in cylindrical and annular configurations, and with different hydraulic diameters and heating lengths. Actually, three data banks have been considered in the analysis, all of them concerning in-R12 round tube tests :

- the APHRODITE data bank, obtained at EDf with a 13 mm inside diameter,

- the DEBORA data bank, obtained at CEA with a 19.2 mm inside diameter,

- the KRISTA data bank, obtained at KfK with a 8 mm inside diameter.

The analysis was conducted using CHF correlations and with the help of an advanced mathematical tool using pseudo-cubic thin plate type spline functions. Two conclusions were drawn :

- no influence of the heating length on our CHF results,

- the influence of the diameter on the CHF cannot be simply expressed by an exponential function of this parameter, as thermal-hydraulic parameters also have an influence.

Some calculations with Weisman & Pei theoretical boiling crisis model have been compared to experimental values : fairly good agreement was obtained, but further study must focus on improving the modelling of the influence of pressure and mass velocity.

1. INTRODUCTION

For nuclear power reactor designers and utilities, it is essential that the nuclear fuel is adequately cooled. In the case of pressurised water reactors, the CHF is a limiting parameter beyond which there is a rapid degradation in the heat transfer between the fuel rod and the cooling water that may lead to the loss of the integrity of the fuel clad and the release of fission products into the reactor coolant system. The calculation of the margin to CHF is thus a crucial problem in designing and operating these reactors.

For this reason, a great number of studies of this phenomenon were undertaken in the 1960s and 1970s. These studies were aimed at developing ways of predicting the CHF and permitting establishing the design limits and the operating point for PWRs using an experimental and statistical approach. This type of approach is indispensable and, for this reason, is still applied today. It involves the use of overall CHF data banks with computer codes and statistical analysis tools. Work is continuing in all three areas and is aimed at qualifying new fuel assembly designs, refining the modelling and improving the accuracy of the CHF prediction.

In such fields, where state-of-the-art techniques are predominant, recent results seem to indicate the possibility of significant improvements in the design and operation of PWRs. From this point of view, to develop a more physical model, it is necessary to improve our knowledge and understanding of the boiling crisis phenomenon, by, among other things, improving the list of external determining factors and identifying the basic mechanisms.

In this context, two complementary programs were initiated in France :

- EDF's APHRODITE program,
- the DEBORA program, a joint CEA/FRAMATOME/EDF project.

These two programs involve running CHF tests, with tubes of different lengths and diameters, using R12 as the coolant fluid. In this paper, we present our analysis concerning the first DEBORA and APHRODITE tests, which, with recent R12 data available in the literature (KfK data bank, obtained on KRISTA test facility), permitted evaluating the influence of two geometric parameters, the heating length and the tube diameter. Lastly, the theoretical approach of Weisman and Pei was tested using the ENEE data (APHRODITE program).

2. BASIC ELEMENTS OF THE ANALYSES

2.1 Three in-R12 CHF data banks have been used

The following paragraphs mainly focus on ENEE and DEBORA framework and give the main features of the three data banks used, obtained with vertical up-flow inside a ***uniform*** direct heating round tube. The thermal-hydraulic parameter ranges investigated for the three data banks are shown in Table 1.

a) the ENEE data bank

For a few years, EDF has been working on the development of a comprehensive and refined modelling of the boiling crisis phenomenon. To face this long-term and ambitious objective, EDF has set up a program which associates both experimental and numerical techniques:

- the numerical technique is based on the three-dimensional two-fluid eulerian ASTRID code, presently under development, which aims the simulation of boiling two-phase flows [1] ,

- the experimental approach involves specific experiments performed as part of the EDF's APHRODITE program or carried out through collaboration with other laboratories.

The ENEE data bank was obtained on the first mock-up (referred to as ENEE) installed on the APHRODITE loop. This mock-up is an electrically heated tube, with a variable heating length and a tube inside diameter of 13 mm, which is used to calibrate the experimental apparatus, in view of subsequent and more complex experiments ***dealing with local analysis of two-phase flow***. An associated program comprises :

- tests of the influence of the operating procedure used for CHF measurements,

- creation and development of a CHF data bank, the quality of which being very well controlled. This data bank has been obtained for three heating lengths (6, 3.5 and 1.2 m) .

Both the APHRODITE loop and the ENEE test section as well as the experimental procedures tested, have been previously described in [2] and [3].

b) the DEBORA data bank

For several years, FRAMATOME has performed numerous CHF tests in rod bundles with water or R12 as coolant fluids. These tests are carried out at the CEA centre in GRENOBLE on the OMEGA and GRAZIELLA loops. The development of optimised nuclear fuel and the evaluation of thermal-hydraulic margins now requires a better understanding of the boiling crisis phenomenon.

The FRAMATOME's R&D strategy has resulted in a comprehensive program, based on numerical simulations, experimental work and mathematical tools. The experimental program, jointly performed with the collaboration of the CEA, involves the AGATE project [4] for studying the hydrodynamic effect of the fuel mixing grids, and the DEBORA program [5] dedicated to handling all the heat transfer modifications due to the specific environment of the nuclear rod bundles, including the effect of a cold wall, of the grid mixing vanes and the geometry. The first DEBORA CHF data bank was obtained in a 19.2 mm diameter, with two heating lengths : 3.5 and 1 m.

All this information will help in qualifying the new code version FLICA IV (real 3-D), FLICA III-F being the current sub-channel analysis code used by FRAMATOME.

Furthermore, as the highest accuracy is always obtained by specific tools applied to a single product, FRAMATOME has developed a correlation [6] for its new AFA-2G nuclear fuel.

c) the KfK data bank

This data bank, published by Cheng X. in [7], has been obtained using a 8 mm inside diameter tube, with a 0.688 m heating length.

2.2 The statistical analyses are performed using a newly developed tool

The thermal-hydraulic operating parameters (i.e. mass velocity, outlet pressure, **outlet quality**) investigated in the three above mentioned data banks are in the same ranges, but not the same individual values. As a consequence, a direct comparison between the raw CHF data is not sufficient to get a reliable quantitative insight into the effect of the two geometrical parameters involved : heating length and tube diameter.

To do so, we have to define CHF predictors for each of these data banks and apply them to the others or use them to interpolate experimental values for specific thermal-hydraulic parameter values (same values for all three data banks). These predictors have been obtained using an advanced statistical method jointly developed by the CEA and FRAMATOME. For the last two years, EDF has been also supporting this project.

This method, called PLAQUE [8], is a mathematical tool, using pseudo-cubic thin-plate type spline functions. It has two main features :

- no a priori CHF model has to be given,

- the residual standard deviation obtained is smaller than the one given by a classical least square regression.

2.3 Be careful when using the R12 thermodynamic property tables !

The analysis of the CHF data has been conducted considering the so-called "local conditions hypothesis", i.e. using the local thermal-hydraulic parameters values calculated at the boiling crisis location (usually close to the tube outlet). The quality is obtained from a heat balance over the tube, which requires the use of R12 thermodynamic properties.

Outlet quality calculations performed with two different R12 thermodynamic property tables [9] and [10] showed significant differences between results that would have biased the CHF data bank analyses. Thus, for the comparative studies described in this paper, the outlet quality was calculated using the ASHRAE tables, regardless of the data bank. Since the parameters given in the published KfK data bank are outlet pressure, mass velocity and inlet quality, our outlet quality calculations cannot be free of possible differences due to the property values at the inlet. In order to perform better comparative analyses using various data banks, we must know ***the raw experimental parameters*** : inlet and outlet pressure, ***inlet temperature***, mass velocity (and, of course, the associated CHF).

3. PRELIMINARY ANALYSIS USING CORRELATIONS

Initially, we wanted to globally situate the data banks with respect to previous data banks using the most frequently employed non-propriety correlations, i.e. W3 [11], Biasi [12], CISE-4 [13], Bowring[14] and the Doroschuk tables [15]. This required employing a scaling law to relate the characteristics of R12 to equivalent water values. The Stevens [16] method was used, although the Ahmad [17] method gives similar results.

These calculations are useful to verify the validity of these correlations and of the scaling laws and in the same time, to observe the general effects of varying the heating length and the tube diameter.

It turns out that only the Biasi correlation can be applied to all the data in Table 1. The 19.2 mm diameter tube in the DEBORA tests and the 6 m heating length in the ENEE.A&B tests fall outside the geometrical validity ranges of the other correlations. We have, however, performed the calculations respecting only the validity range for the thermal-hydraulic conditions specified in Table 2.

Table 2 also contains the statistical values characterising the quality of the prediction, i.e. the average value of the ratios of the predicted fluxes to the measured CHF, the associated standard deviation, and the number of tests validated. In most cases, the values are of the right order of magnitude. However, it is easily seen that none of the methods for predicting the CHF is very accurate. These results demonstrate the weaknesses of these correlations for taking into account the effects of the heating length (DEBORA 1 and 2 comparison and ENEE.A&B and ENEE.C comparison) and hydraulic diameter (DEBORA 1 and ENEE.C comparison).

4. THE EFFECT OF HEATING LENGTH ON CHF

Most authors agree on the fact that, when the heating length to diameter ratio is greater than about 80, the length has no influence on the CHF in uniformly heated tubes, i.e. the local conditions hypothesis is valid. The experimental proof is not easy to obtain , due to the technical difficulties in covering the same parameter ranges for all the lengths.

Nevertheless, both on DEBORA and ENEE, some tests were achieved with the same thermal-hydraulic parameter values with different lengths. Examples are given in Figure 1 for DEBORA and in Figure 2 for ENEE , where the CHF is plotted versus the quality. The values obtained for one length seem to follow the same curve as those obtained for other lengths, for the same pressure and mass velocity ; but this visual observation is not sufficient.

Therefore, the mathematical tool PLAQUE was used to confirm this observation. First, we have checked the quality of our predictors by comparing the predicted values with the experimental ones used to calculate each predictor. Generally speaking, the predictors we have obtained for the data banks studied are not reliable for mass velocity values of less than 2000 kg/m^2s (probably due to the phenomenon itself). Furthermore, for the ENEE data bank, the predictions are not very good at high values of CHF (greater than 200 kW/m^2) because only a few points are available, but however contribute in calculating the predictor. As in all statistical methods, the experimental points must be regularly spread out over the parameter field.

Due to the number of tests for each length of the ENEE and DEBORA data banks, only ENEE.A&B (6 m) and ENEE.C (3.5 m) have been statistically compared with a good confidence level. In a first phase, the intersection between the two parameter fields has been defined and called "the common field". This common field is composed of 5 values of pressure (1.5, 2., 2.5, 3. and 3.5 MPa) , 4 values of mass velocity (1000, 2700, 4000 5500) and qualities from -0.06 to 0.4.

One predictor has been calculated for each of the two data banks limited to the points in this common field (PLAQUE-6r for 6 m, calculated with 106 points and PLAQUE-3.5r for 3.5 m, with 73 points). Then, each of them was qualified, by comparison with the experimental values. The prediction-to-measurement ratio is good (as illustrated in Figures 3 and 4) and the best agreement was obtained for the 6 m heating length.

Finally, the values calculated with these two predictors, for the two data banks, have been compared. This comparison is summarised in Table 3, where the prediction-to-measurement-ratio is given (averaged value and RMS) for both lengths and predictors. Of course, 6 m data are more accurately calculated with PLAQUE-6r and 3.5 m data with PLAQUE-3.5r. The small differences between the calculations made with the two predictors on the same data bank are not significant, because of the differences between the thermal-hydraulic parameter distribution in the two banks.

These results confirm that no effect of the heating length on the CHF is noted on ENEE data bank.

The largest difference between the two predictors is obtained when the parameters are near the boundary of the parameter fields, as it is shown in the examples given in Figures 5 and 6, where the ratio of calculations made with PLAQUE-3.5r to those made with PLAQUE-6r is plotted versus quality and mass velocity. This behaviour is probably due to the experimental CHF point distribution.

5. THE EFFECT OF DIAMETER ON CHF

To express the relationship between the CHF value for 2 different diameters (D and D_0), we generally state, as reported for instance in [18] :

$$(1) \qquad \phi_c(D) = \phi_c(D_0)\left(\frac{D_0}{D}\right)^{\varepsilon}$$

where ε is either constant (0.5 in [15] or 1/3 in [19]) or depends on the local thermal-hydraulic parameters. For example, the correlations used in chapter 3 include a CHF versus diameter variation leading to calculated values of ε in the range of 0.2 to 0.7 (as shown in Figure 7).

For the current study, the effect of diameter was studied with the experimental CHF values obtained for 8 mm, 13 mm and 19.2 mm. Due to the differences between the thermal-hydraulic parameters investigated in the three data banks, PLAQUE was used to calculate CHF for the three diameter values and for specific thermal-hydraulic parameter values inside the common parameter field. So, three predictors have been calculated, one for each diameter. Moreover, since no heating length effect was found, these predictors have been calculated using all the experimental points for each tube data bank.

Figure 8 shows the as above mentioned calculated CHF versus tube diameter variation. For a given mass velocity and pressure, the CHF decreases versus diameter at low quality, but when the quality reaches a certain threshold, the CHF increases first and then decreases ; it is maximum for the 13 mm tube diameter. This threshold value, which could be linked to the two different types of boiling crisis, depends on pressure and mass velocity value : it decreases when the pressure or the mass velocity increase ; the effect of these two latter parameters could be connected to the size of the bubbles as compared to the size of the tube.

Thus, it turns out that the proposed equation (1) is not valid. Not only is the exponent ε a function of pressure, mass velocity and quality but also it varies with the tube diameter.

We wish to stress the point that the KfK values (8 mm inside diameter data) may be biased as previously pointed out in chapter 2.3. Actually, we have based our calculations, for ENEE and DEBORA on the raw inlet experimental parameters. On the contrary, for KfK data bank, inlet quality was used, and we cannot distinguish in the behaviour of 8 mm diameter data, what may be due to thermodynamic property table differences. Complementary studies must be performed to clarify this matter. In addition, three diameters are not sufficient and new investigations, for diameter values between 8 and 13 mm would be of great interest.

Let's consider now the two data banks ENEE & DEBORA, both parameters being calculated with the same tables. For all points, the CHF value is higher for 13 mm than for 19.2 mm. A straightforward calculation of ε indicates that it varies from 0.1 to 0.5 (table 4).

Finally, these results indicate a need in local data to improve a mechanistic approach of the boiling crisis phenomenon ; APHRODITE and DEBORA programs should meet such a need.

6. PRELIMINARY TEST OF THE WEISMAN MODEL

A critical review of different theoretical models is being carried out. This study reveals two deficiencies :

- a lack of physical information to understand the mechanisms involved in CHF,

- a lack of validated constitutive laws (based on local data) to get reliable closure relationships.

Two models seemed to be interesting to be tested : Katto's model [20] and Weisman & Pei's one [21]. In a first phase, we have tested Weisman & Pei model . In this model, the flow is supposed to be separated into two parts : the bubbly layer and the core region. Turbulent exchange between these regions is considered as the limiting mechanism leading to CHF, which is supposed to occur when the void fraction is equal to 0.82 close to the heating wall. The calculations have been compared with the ENEE experimental values in the parameter ranges located in the validity field of the model. For 175 tested points, the averaged calculated to experimental CHF ratio is 1.007 and the RMS equals 0.311, (as illustrated in Figure 9). This is not so bad regarding the fact that the data have been obtained in R12. Different friction factor correlations have been used, they appeared to have no influence on the results.

Then, to improve this model, the prediction-to-measurement ratios were plotted successively versus CHF and the thermal-hydraulic parameter values to identify the weak points. As far as CHF and quality are concerned, no link could be found (see in Figure 10). But, it appears that this ratio decreases when the mass velocity or the pressure increases (Figures 11 and 12). Furthermore, the higher the pressure, the lower the scatter. So, future improvements of this model could be by better taking into account these two parameters.

7. CONCLUSION

Three R12 data banks for a vertical cylindrical tube, with pressure, mass velocity and quality in the same ranges, were analysed. A preliminary analysis of the results shows that great care must be taken in choosing the fluid thermodynamic property tables used for the calculations and that no acceptable results were obtained with classical CHF correlations.

This study shows interesting prospects for predicting and modelling the CHF. Some major assumptions such as the absence of a heating length effect (at least, for the studied length to diameter ratio, i.e. greater than 55) is clearly confirmed, on the basis of homogeneous and quality controlled data.

As far as the variation of CHF with the tube diameter is concerned, we have found that :

- this effect is closely linked to the thermal-hydraulic parameters,

- CHF does not always decrease with increasing diameter, as usually stated.

Some indications for studying the variation of CHF with the tube diameter are suggested : a more accurate analysis of the tube diameter effect would require more quality controlled CHF data banks, particularly with diameter in the range of 8 mm to 13 mm.

Finally, the first attempt made with the physically based Weisman & Pei model is encouraging. Nevertheless, this model has to be improved : a better modelling of the mass velocity and local pressure effects seems to indicate promising avenues of research. This model, as well as many correlations and CHF tables, may be used for rough calculations in most industrial applications. But, where very accurate predictions are required, such as for nuclear power plants, we have to rely on thermal-hydraulic and geometric parameters close to realistic values, and to use very specific predictors.

8. NOTATIONS

D	m	Tube diameter
D_0	m	Reference diameter
G	kg/m^2s	Mass velocity
L	m	Tube length
P	Pa	Pressure
x		quality
ϕ_c	W/m^2	Critical heat flux
ε		exponent in (1)

CHF	stands for Critical heat flux
RMS	stands for Root Mean Square
PLQ	stands for PLAQUE

9. REFERENCES

[1] BOREE J., FABRE J., CHARNAY G., FREYDIER P., CHEN O. *Boiling water flows. A local wall heat transfer model for use in an eulerian 3-D computer code.* 2nd Icone Conference, SAN FRANCISCO (1993).

[2] SOUYRI A., CONAN S., PORTESSE A., TREMBLAY D. *Mean features of the Aphrodite boiling crisis experimental program and analysis of the CHF tests performed on a vertical tube mock-up.* European two-phase flow group meeting. STOCKHOLM (1992).

[3] SOUYRI A., CONAN S., PORTESSE A., TREMBLAY D. *The Aphrodite program. Analysis of the first CHF tests performed on a vertical tube.* NURETH 6 meeting . GRENOBLE 1993. (to be published).

[4] HERER C. *3-D measurements in nuclear fuel bundles using laser Doppler velocimetry.* ASME/JSME Fluids engineering conference. PORTLAND, OREGON (1991).

[5] GARNIER J. *Measurements of local thermal-hydraulic parameters in R12 simulating PWR conditions from one-phase flow until critical heat flux conditions.* European two-phase flow group meeting. HANOVRE (1993). (to be published).

[6] AYED R., BOURTEELE J.P. *FC, the FRAMATOME correlation for critical heat flux in pressurized water reactor rod bundles.* European two-phase flow group meeting. HANOVRE (1993). (to be published).

[7] CHENG X. *Experimentelle Untersuchungen zur kritischen Heizflächenbelastung in 8 mm-Kreisrohren und in 7-Stabbündeln.* Institut für Reaktorbauelemente. Projekt Nukleare Sicherheitsforschung. Kernforschungszentrum KARLSRUHE. (1991).

[8] de CRECY F. *Pseudo-cubic thin plate type spline method for analysing experimental data.*
European two-phase flow group meeting. ROME (1991).

[9] STEWART R.B., JACOBSEN R.T., PENONCELLO S.G. *ASHRAE. Thermodynamic Properties of Refrigerants.* American Society of Heating, refrigerating and Air Conditioning Engineers, Inc. (1986).

[10] ATOCHEM *Propriétés thermodynamiques du FORANE 12.* Centre d'Application de Levallois. AC 665.

[11] TONG L.S. *Heat transfer mechanisms in nucleate and film boiling.*
Nucl. Eng. Design 21:1 (1972).

[12] BIASI L., et al. *Studies on burnout. Part 3.*
Energy Nucl. 14:530 (1967).

[13] GASPARI G.P., et al. *A rod-centered subchannel analysis with turbulent (enthalpy) mixing for critical heat flux prediction in rod clusters cooled by boiling water.*
Proceedings 5th International Heat Transfer Conference, TOKYO, JAPAN (1974).

[14] BOWRING R.W. *Simple but Accurate Round Tube, Uniform Heat Flux Dryout Correlation over the Pressure Range 0.7 to 17 MPa.*
AEEW-R-789. U.K. Atomic Energy Authority (1972).

[15] DOROSHCHUK *Recommendations for calculating BO in a round tube with uniform heat release.*
Teploenergetika 22 (12) 66.70 (1975).

[16] STEVENS G.F., ELLIOTT D.F., WOOD R.W. *An experimental investigation into forced convection burnout in freon, with reference to burn out in water. Uniformly heated round tubes with vertical upflow.*
AEEW-R237 (1964).

[17] AHMAD S.Y. *Fluid to fluid modelling of critical heat flux : a compensated distortion model*
Int. J. Heat Mass Transfer, vol. 16, pp 641-661 (1973).

[18] ZEGGEL W., BETHKE S., GROENEVELD D.C., ERBACHER F.J. *Analysis of round tube CHF tables.*
European two-phase flow group meeting. STOCKHOLM (1992).

[19] GROENEVELD D.C., CHENG S.C., DOAN T. *1986 AECL-UO critical heat flux lookup table.*
Heat transfer Engineering, vol7, N°1-2 pp46-61 (1986).

[20] KATTO Y. *Prediction of critical heat flux of subcooled flow boiling in round tubes.*
Int. J. Heat Mass Transfer, vol. 33, N°9, pp 1921-1928 (1990).

[21] WEISMAN J., PEI B.S. *Prediction of critical heat flux in flow boiling at low qualities.*
Int. J. Mass Transfer, vol. 26, pp 1463-1476 (1983).

Data bank	Tube diameter (m)	Length (m)	Pressure (MPa)	Mass velocity (kg/m2s)	Quality	Number of points
CHENG	0.008	0.688	1. to 3.	1000. to 6000.	- -0.4 to 0.3	72 *
DEBORA 1	0.0192	3.5	1.5 to 3.	1000. to 5000.	-0.4 to 0.4	146
DEBORA 2	0.0192	1	1.5 to 3.	1000. to 5000.	-0.8 to 0.2	35
ENEE.A&B	0.013	6	1. to 3.5	700. to 5500.	-0.1 to 0.5	257
ENEE.C	0.013	3.5	1. to 3.5	700. to 5500.	-0.4 to 0.5	246
ENEE.D	0.013	1.2	1.5 to 3.5	2700. to 5500.	-0.5 to 0.0	19

Table 1 : Comparison of the three CHF Data bank parameter ranges.
(only 72 selected points were used from all the available data.)*

Effect	Data bank	W3	BIASI	CISE-4 c	BOWRING	DOROSHCHUK	
HEATED LENGTH EFFECT →	DEBORA 2	1.249	0.964	0.928	0.925	1.138	mean value
		0.253 a	0.100	0.129	0.109	0.175 a	standard deviation
		19	7	23	35	22	validated data
→ / TUBE DIAMETER EFFECT →	DEBORA 1	0.877	0.942	0.991	1.101	0.940	mean value
		0.091 a	0.190	0.112	0.107	0.141 a	standard deviation
		65	56	103	146	118	validated data
→ / HEATED LENGTH EFFECT →	ENEEC	0.741	0.904	1.118	1.116	0.838	mean value
		0.160	0.251	0.272	0.233	0.143	standard deviation
		55	30	127	197	125	validated data
→	ENEE A&B	0.752	1.155	1.229	1.269	0.954	mean value
		0.185 b	0.514	0.302 b	0.266 b	0.208 b	standard deviation
		26	81	119	197	96	validated data
	CHENG X.	0.860	0.861	0.991	0.985	0.847	mean value
		0.080	0.123	0.275	0.230	0.076	standard deviation
		32	24	59	72	62	validated data

a) limiting range for diameter : 17.8 mm
b) limiting range for heated length : 3.7 m
c) limiting range for pressure : 5.0-6.9 MPa

VALIDITY RANGE CONSIDERED FOR CALCULATIONS (in water):

	W3	BIASI	CISE-4 c	BOWRING	DOROSHCHUK
P (MPa)	< 14.5	< 14.5			
G (kg/m2/s)	< 6800	< 6000	< 4100		
X (%)	-25; +15	0;100			

Table 2 : Application of in-water correlation to in-R12 CHF test in tube using the STEVENS scaling laws in conjunction with ATOCHEM R12 thermodynamic tables

Length	Prediction/ Measurement	
	PLAQUE-6r	PLAQUE-3.5r
6 m 106 points	average = 1. RMS = 0.003	average = 0.987 RMS = 0.063
3.5 m 73 points	average = 1.01 RMS = 0.075	average = 1.001 RMS = 0.024

Table 3 : Comparison of the calculations made with two predictors, built with two different length data banks.

Pressure	Mass velocity	Critical quality			
(MPa)	(kg/m2s)	-0.1	0.0	0.1	0.2
2.3	3000		0.3	0.5	0.3
2.3	4000	0.2	0.4	0.3	0.1
2.3	5000	0.2	0.4		
3	3000	0.2	0.3	0.3	0.4
3	4000	0.3	0.3	0.2	
3	5000	0.3	0.2		

Table 4 : Calculated value of ε to correct CHF for diameter changing from 13 mm to 19.2 mm (analysis of ENEE and DEBORA data banks)

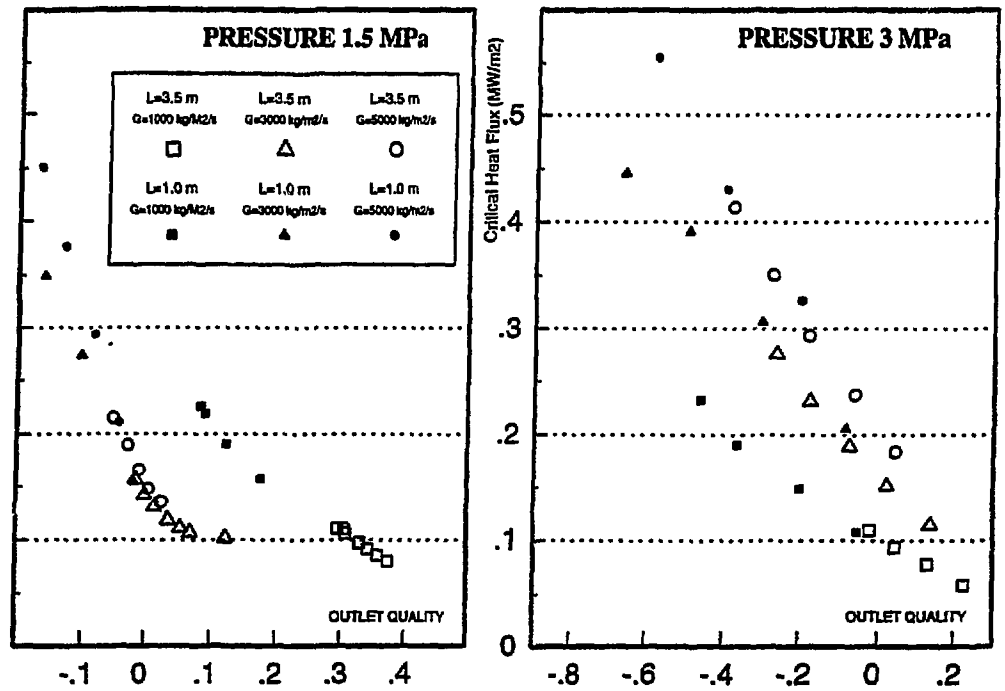

Figure 1 - Measured CHF on DEBORA for two different heating lengths

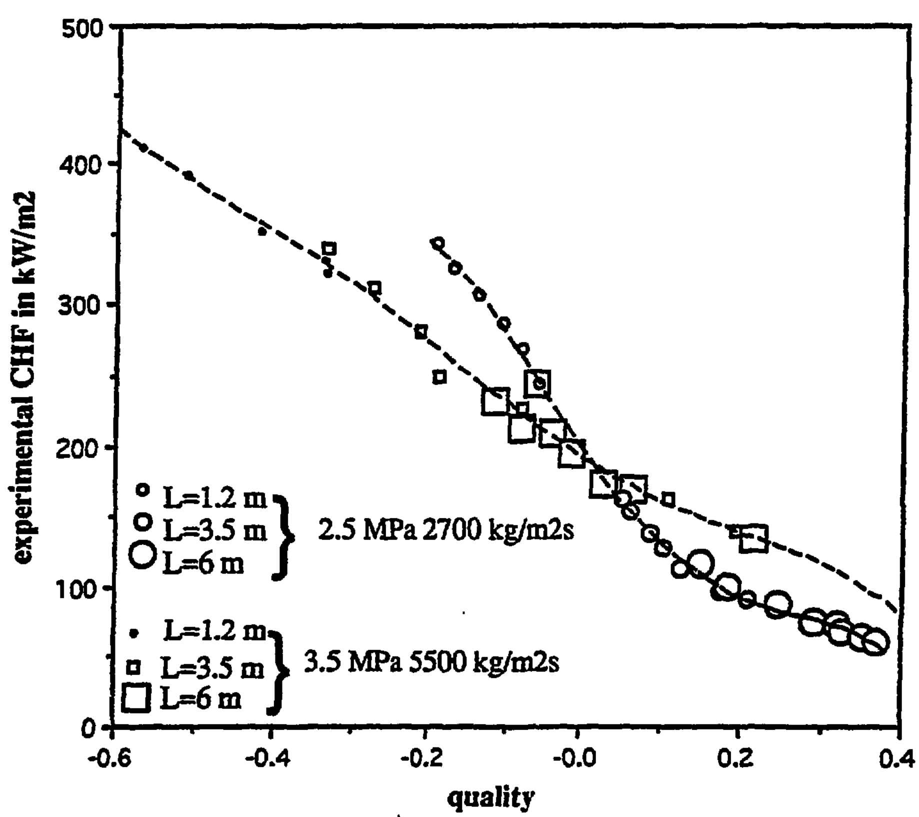

Figure 2 - Experimental CHF versus quality for ENEE experiments.

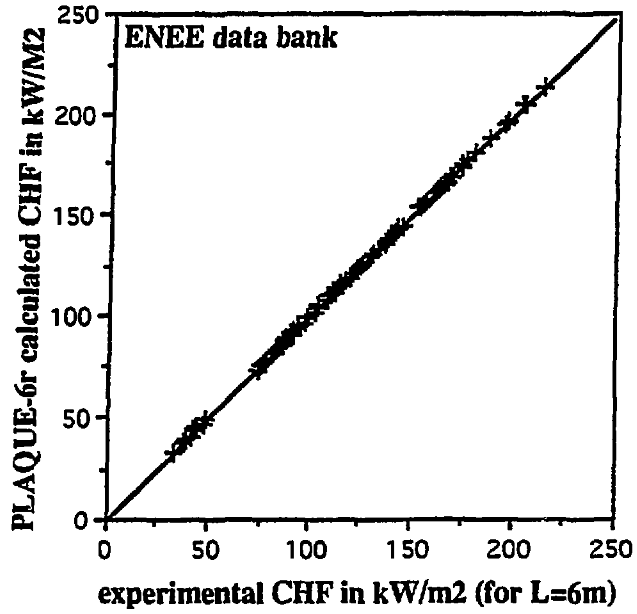

Figure 3- Comparison between calculations with PLAQUE-6r and measured CHF

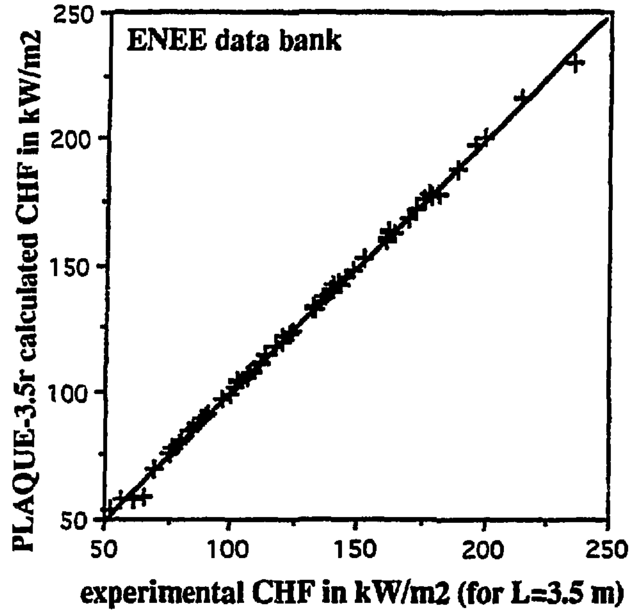

Figure 4- Comparison between calculations with PLAQUE-3.5r and measured CHF

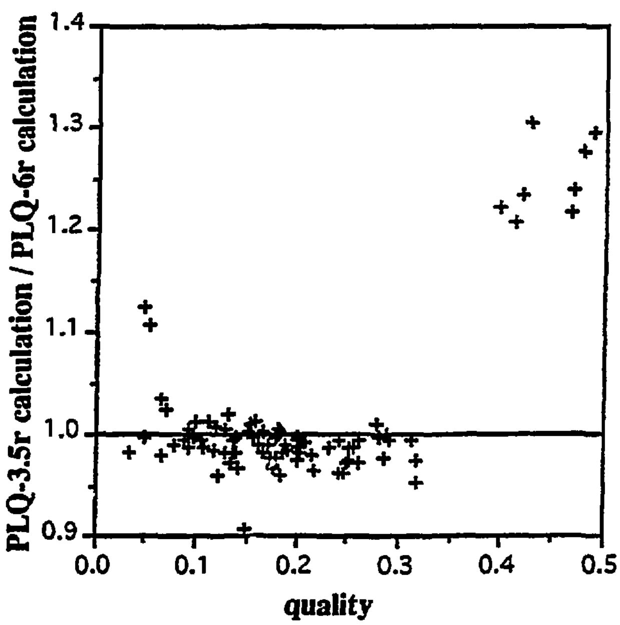

Figure 5- PLAQUE-3.5r over PLAQUE-6r ratio versus quality

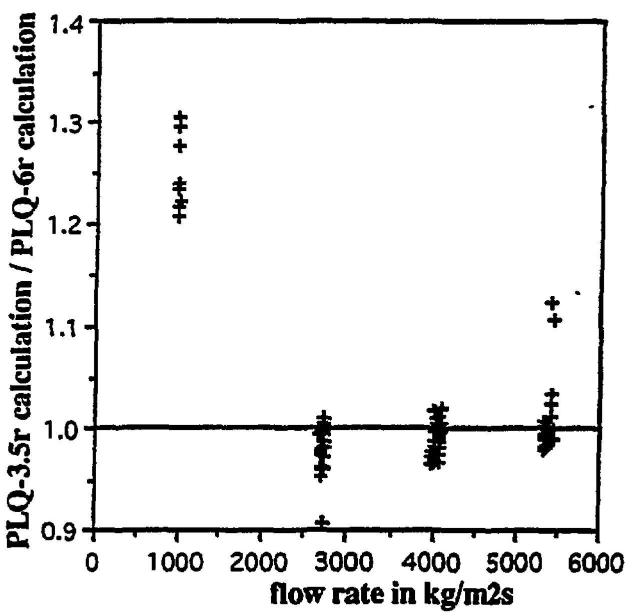

Figure 6- PLAQUE-3.5r over PLAQUE-6r ratio versus mass velocity

For figures 5&6, the calculations were made with thermal-hydraulic parameter values of 3.5 m ENEE data bank, inside "common field"

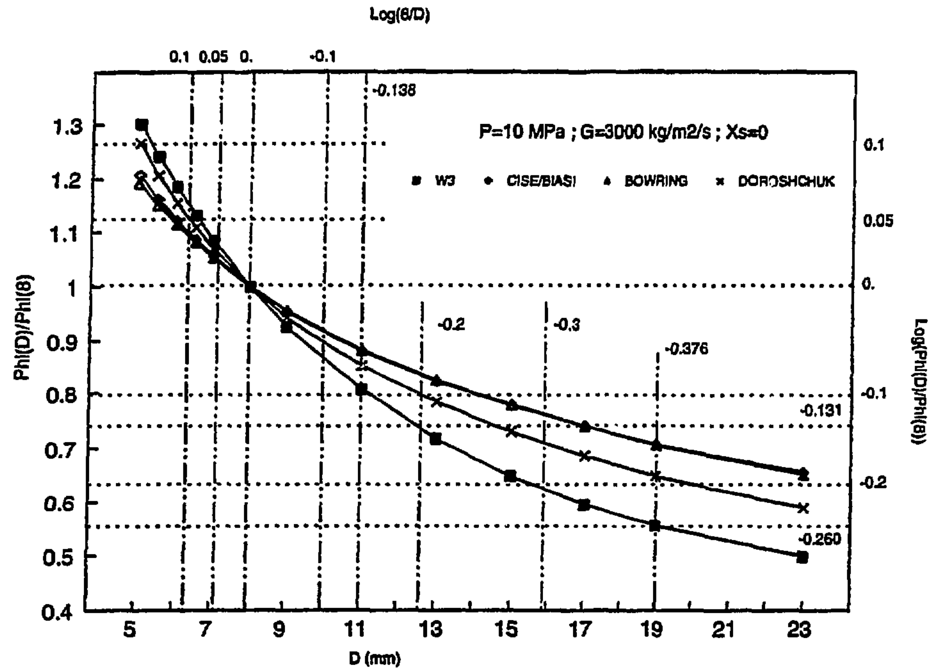

Figure 7 - Variation of predicted CHF versus hydraulic diameter for several correlations

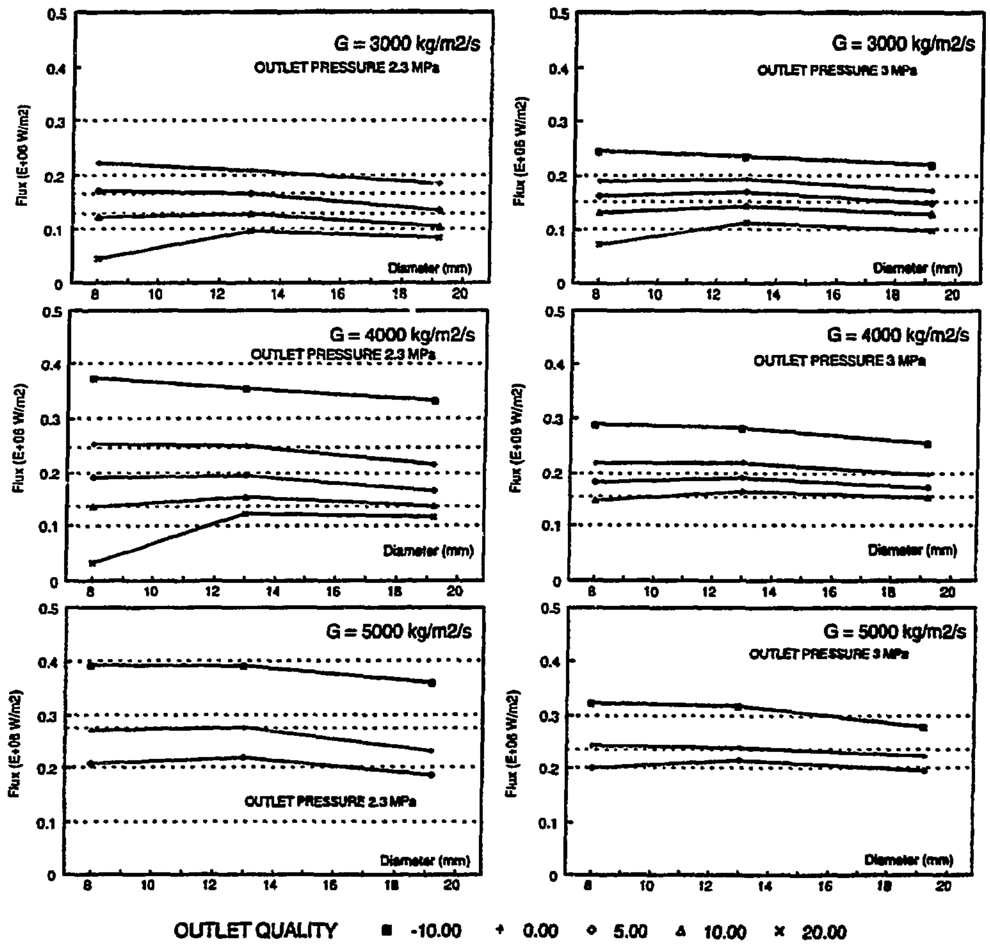

Figure 8 - Measured CHF versus tube diameter as interpolated by PLAQUE

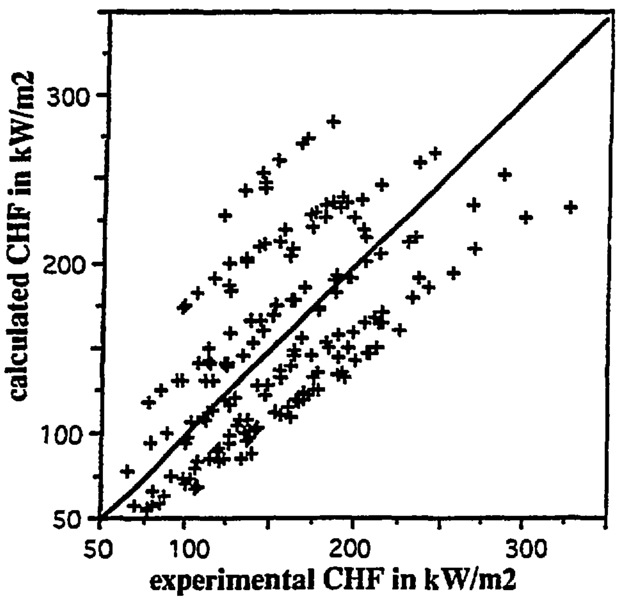

Figure 9- Comparison between calculations with Weisman & Pei model and experimental data

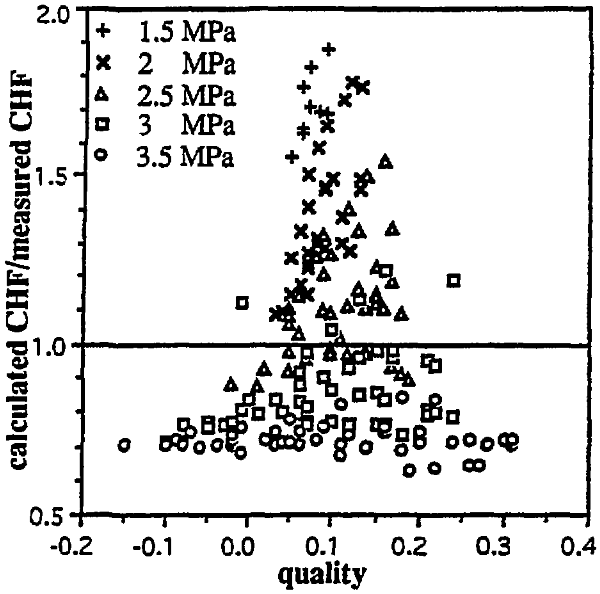

Figure 10- Calculations withWeisman & Pei model to experimental data ratio versus quality

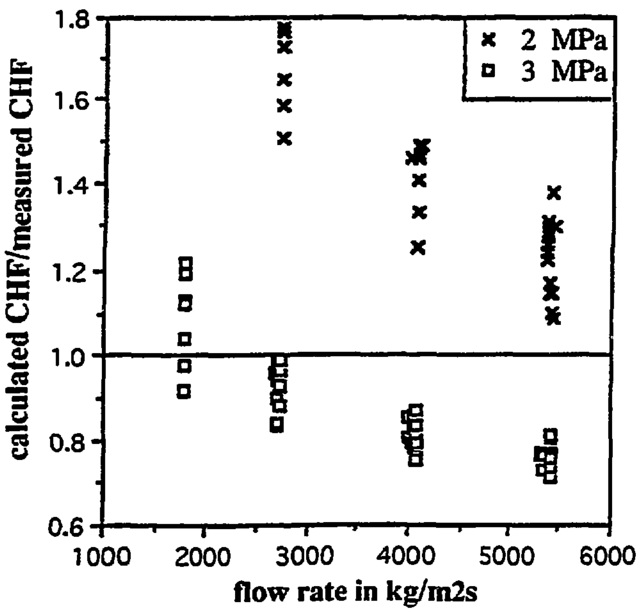

Figure 11- Calculations withWeisman & Pei model to experimental data ratio versus mass velocity

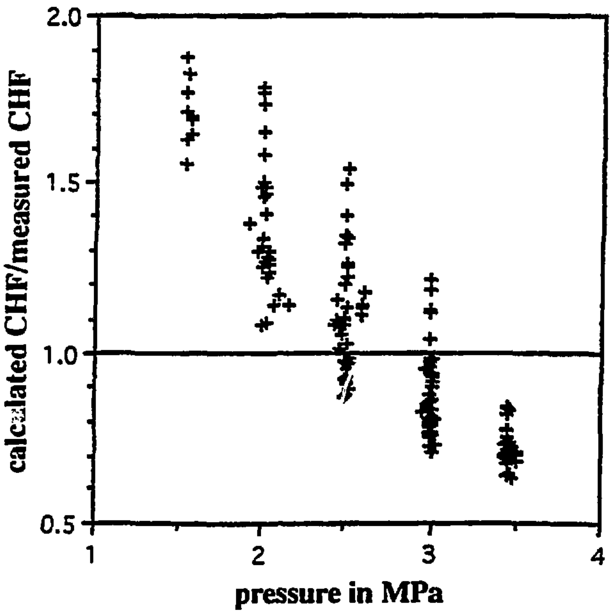

Figure 12- Calculations with Weisman & Pei model to experimental data ratio versus pressure