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The Mass Velocity Effect on the Overtemperature Protection Limit in PWR Reactors

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Abstract

This paper analyzes the effect of the mass velocity on the overtemperature, ΔT, trip function in PWR reactors. The analyses were done with data from the Columbia University critical heat flux experimental test section and from the 1995 look-up tables for critical heat flux in tubes. The experimental conditions include mass velocities in the range of 500 to 4000 kg/sm^2, pressures from 12 to 16 MPa, and local quality from -40% to 30 %. The results show that, for mass velocities higher than 2500 kg/sm^2, a pressure reduction implies in a more restrictive condition in terms of DNB. For mass velocities below 1500 kg/sm^2, an inversion of this behavior is verified. As the general approach used to define the protection curves was developed for reactors designed for higher mass velocities, the observed behavior change indicates the need for a new methodology for other projects. The preliminary results showed that, for a design with low mass velocity, it would be better to divide the overtemperature curve into two first grade equations; the first one for the DNB thermal limit, and the second one to the saturation temperature limit. The suggested approach allows for the elimination of unnecessary safety margins in the reactors designs with low mass velocities.

1. INTRODUCTION

The concept of Overtemperature Protection Curves has been largely employed in the protection of PWR nuclear power plants. The operation is kept distant from the thermal limits of DNB (Departure from Nucleate Boiling) and saturation temperature in the reactor outlet and the reactor is shutdown if operation reaches these limits.

The methodology for the construction of protections curves, developed by Westinghouse [1], considers reactors with high mass velocities in the core, generally over 2,500 kg s^{-1}m^{-2}. In the case of reactors designed for lower mass velocities, as 1,500 kg s^{-1}m^{-2}, like the IRIS Advanced Reactor, or even for lower values, as those considered in several small reactors designs, few adaptations in this methodology are necessary.

The objective of this paper is to present an investigation of the effect of the mass velocity on the behavior of the thermal limit of DNB, thus on the overtemperature protection curve.

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Section 2 analyzes the behavior of DNB as a function of the mass velocity. Data from the Test Section #53 of the Columbia University [3] and from the 1995 Look-up Tables [4] were used.

Section 3 shows a case study of an hypothetic small reactor to demonstrate the effect of the low mass flow velocity, of 800 kg $s^{-1}m^2$, on the behavior of the protection curves and on its construction.

Section 4 presents the main conclusions of the present study.

2. DNB AS A FUNCTION OF PRESSURE AND MASS VELOCITY

The overtemperature protection curve is designed to protect the reactor with respect to the thermal limits of DNB and saturation temperature (T_{sat}) at the reactor outlet. The last limit is necessary to keep the proportionality between Power and Temperature difference, ΔT. Equations of ΔT as a function of the mean temperature (T_{avg}) and pressure (P) are set. The temperature difference is related with the reactor thermal power and T_{avg} with the inlet and outlet temperatures.

It can be seen that, with a fixed power, then a constant ΔT, any increase in the pressure will allow an increase in the T_{avg} to reach the saturation temperature limit, T_{sat}. By other side, with the DNB limit this is not true. The critical heat flux is related with many other factors like the local conditions as temperature and pressure (the local quality), mass flow velocity and also with the heat flux.

To study the behavior of the DNB with respect to the ΔT, T_{avg} and pressure, data from critical heat flux experiments were chosen from the "*The 1995 look-up tables for critical heat flux in tubes*"[4] and from the Test Section # 53 from the Columbia University [3].

2.1. The 1995 look-up tables for critical heat flux in tubes

The 1995 look-up tables for critical heat flux in tubes gives many data based on experimental critical heat flux studies. Table 1 presents data from a set of points from this reference. The data considers only subcooled conditions. Table 1 shows the local subcooled quality as a function of pressure for six different values of mass flow velocities. The table also shows the calculated outlet temperatures as a function of quality and pressure.

Figures 1 and 2 show, respectively, the local quality and outlet temperature as a function of pressure for each mass flow velocity.

Fig. 1 shows that the tendency of the critical quality, for every test, is to reduce with the increase in the pressure. The critical quality seems to be more feasible to represent the behavior of the critical heat flux.

Table 1- Local qualities and temperatures for Critical Heat Flux as a function of Pressure [4].

Pressure	G=500		G=1000		G=1500		G=2000		G=2500		G=3000		G=4000	
	Q"= 3.919		Q"=3.372		Q"= 3.177		Q"= 3.172		Q"= 3.225		Q"= 3.274		Q"= 3.390	
	Xloc	Tout	Xloc	Tout	Xloc	Tout	Xloc	Tout	Xloc	Tout	Xloc	Tout	Xloc	Tout
12	0.0	324.6	0.0	324.6	0.0	324.6	0.0	324.6	0.0	324.6	0.0	324.6	0.0	324.6
13	-13.2	307.4	-10.0	313.6	-4.7	323.1	-3.1	325.8	-2.7	326.5	-2.1	327.5	-1.0	329.3
14	-18.2	306.8	-11.9	318.1	-7.1	326.1	-4.7	329.8	-3.7	331.3	-2.8	332.7	-2.2	333.6
15	-39.0	277.3	-13.7	323.1	-10.3	328.3	-8.3	331.2	-6.2	334.2	-4.4	336.7	-3.9	337.2
16	-	-	-22.9	317.4	-13.2	331.6	-11.3	334.2	-9.3	336.7	-7.8	338.6	-6.2	340.5

[P] - MPa; [G] - kg s^{-1}m^2; [Q"] - MW m^2; [T] - °C; [X] - %.

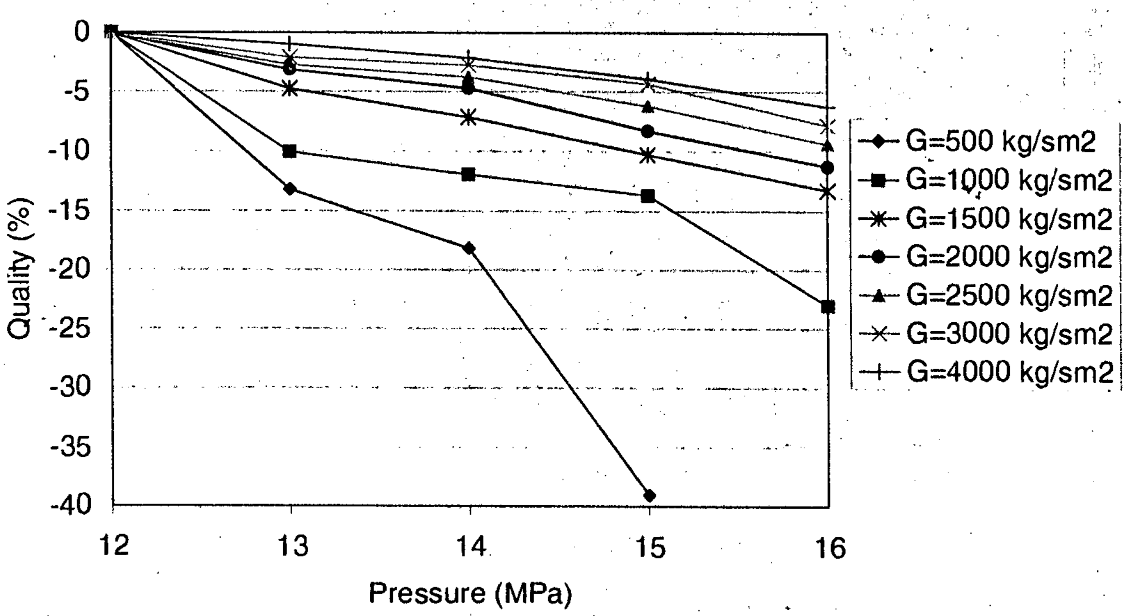

Figure 1 – Local Quality versus Pressure.

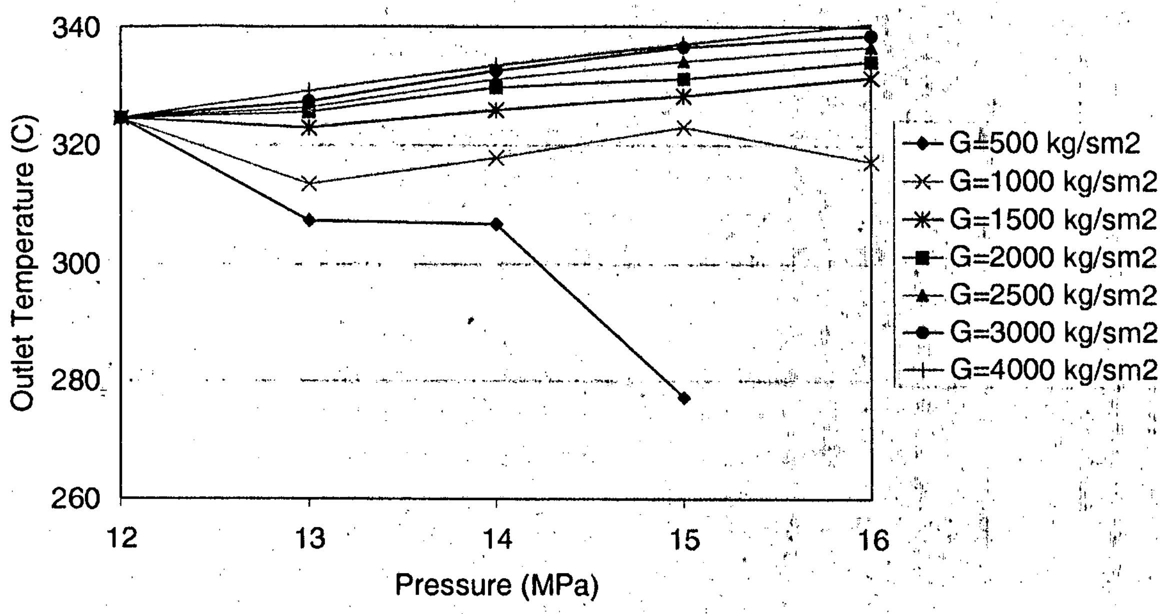

Figure 2 – Outlet Temperature versus pressure.

Taking the behavior of the outlet temperature (Fig. 2) into consideration, different tendencies are verified: for mass flow velocities higher than 1,500 $kg.s^{-1}m^2$, the outlet temperature increases with the increase in the pressure; for lower values there are regions were the behavior is quite different, the outlet temperature reduces with an increasing pressure; and, for values below 1,000 $kg\ s^{-1}m^2$, the tendency is the reduction in the outlet temperature with an increasing pressure for the full pressure range.

2.2. Columbia University Test Section #53 – Combustion Engineering

The experimental results obtained with the Columbia University Test Section #53 [3] confirm the observations above. Fig. 3 and 4 show the reduction of the critical quality and inlet temperature (T_{in}) with the pressure, for a G value around 1,370 $kg\ s^{-1}m^2$. Fig. 4 also shows the values of T_{in} calculated with COBRA3P[5] for DNBR equal unity, with the EPRI correlation [6].

EPRI correlation presented a coherent behavior in reproducing the experimental results with an increasing with pressure, but conservative, detachment from the measured values. This analysis has only numerical meaning as we always can find, for the same inlet temperature, a DNBR value below 1.3.

In Fig. 5 and 6 the conditions are equivalent to that of Fig. 3 and 4 but with a mass flow velocity of 2,670 $kg\ s^{-1}m^2$. Both, experimental and analytical results are in accordance with that observed with data from the Look-up tables.

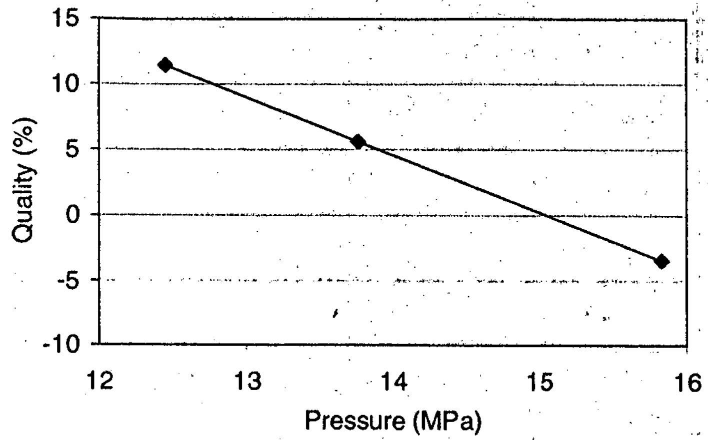

Figure 3 – Critical quality versus pressure for constant heat flux and G ≅ 1,370 kg $s^{-1}m^{2}$.

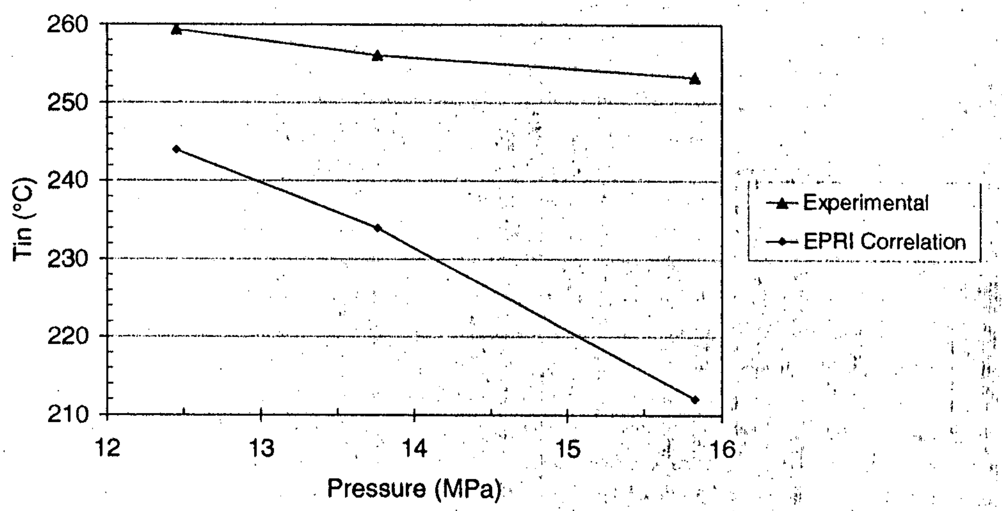

Figure 4 – Inlet temperature versus pressure for DNBR=1 and G ≅ 1,370 kg $s^{-1}m^{2}$.

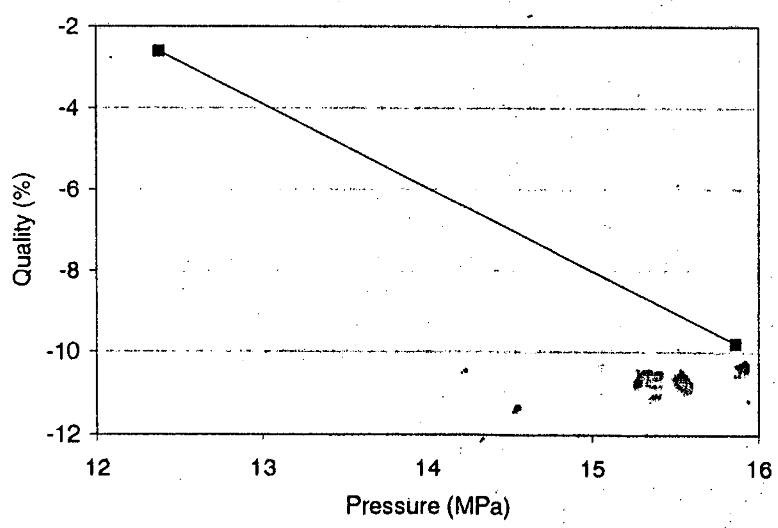

Figure 5 – Critical quality versus pressure – G ≅ 2,670 kg $s^{-1}m^{2}$.

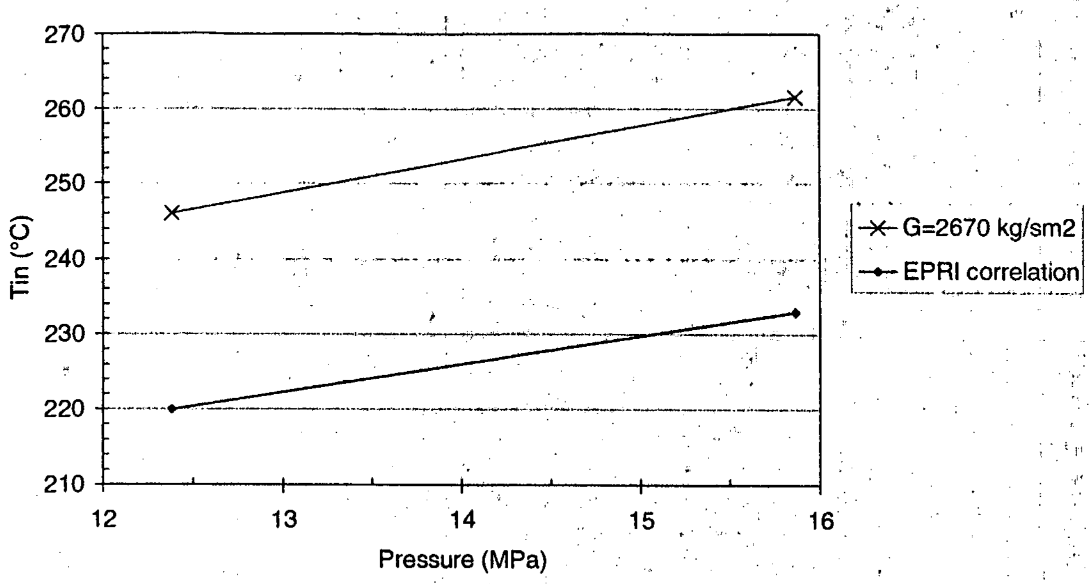

Figure 6 – Inlet temperature versus pressure, DNBR=1 and G ≅ 2,670 kg $s^{-1}m^2$.

Fig. 7 and 8 show the experimental results of critical quality and critical heat flux for 720kg $s^{-1}m^2$ with a constant inlet temperature. Fig. 9 shows the DNBR calculated with COBRA3P and the EPRI correlation for the conditions presented in Fig. 8. Observe that Fig. 7 and 8 show the same tendency of decreasing critical quality and the decreasing in the critical heat flux with the increasing pressure. Fig. 9 shows the tendency of EPRI correlation in produce more conservative results with the increase in pressure.

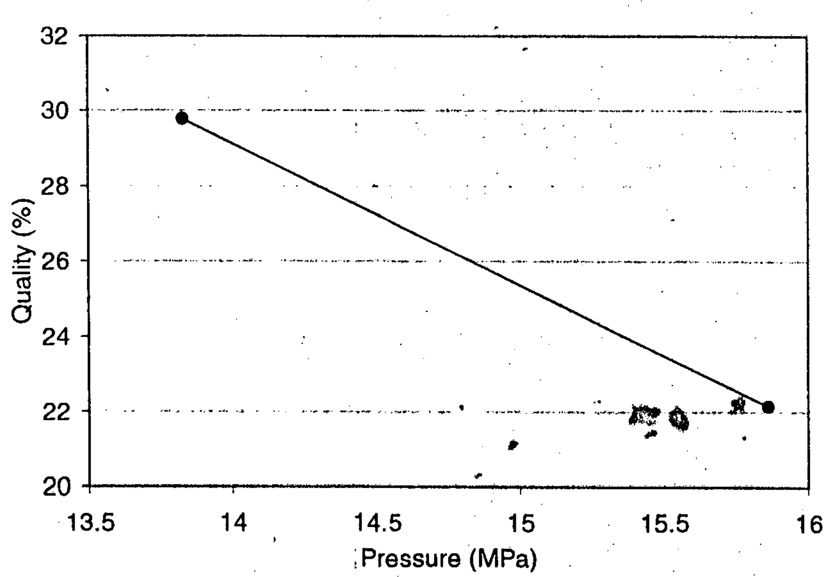

Figure 7 – Critical quality versus pressure for Constant Tin and G ≅ 720 kg $s^{-1}m^2$.

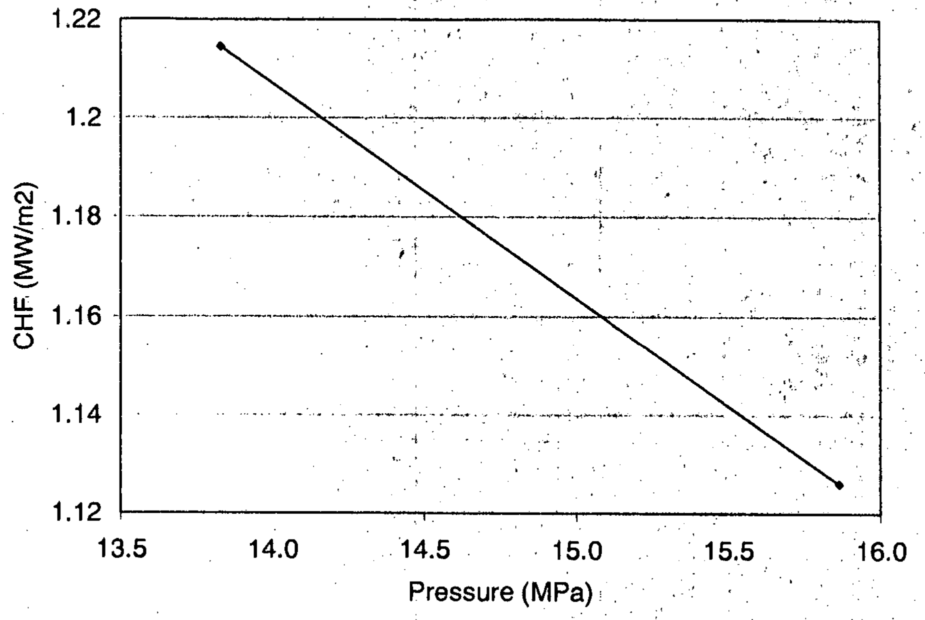

Figure 8 – Critical heat flux versus pressure for Constant Tin and G ≅ 720 kg $s^{-1}m^2$.

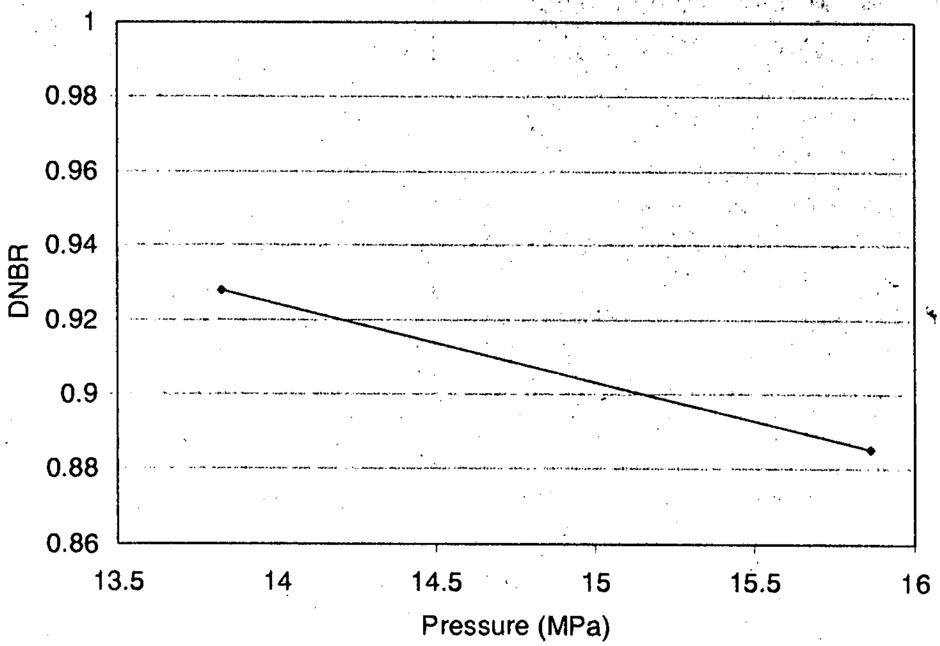

Figure 9 – DNBR (EPRI) versus pressure for Constant Tin and G ≅ 720 kg $s^{-1}m^2$.

3. CASE STUDY OF AN OVERTEMPERATURE PROTECTION CURVE

This section presents a case study based on a hypothetical small reactor of ~50MW(t), designed for a low mean mass flow velocity. The purpose is to check the effect of this low velocity on the overtemperature protection curve.

Figs. 10 to 12 show the normalized overtemperature, overpower and steam generators overpressure curves for the primary system pressures of 12, 14 and 15.5 MPa, at nominal flow conditions. The values of ΔT and T_{avg} were normalized with respect to the nominal conditions. The protection curves philosophy is based on the methodology presented in reference [1]. The analyses to find the limiting DNB were performed with COBRA IV [6]. These figures also show the proposed curves to increase the permissible operating area.

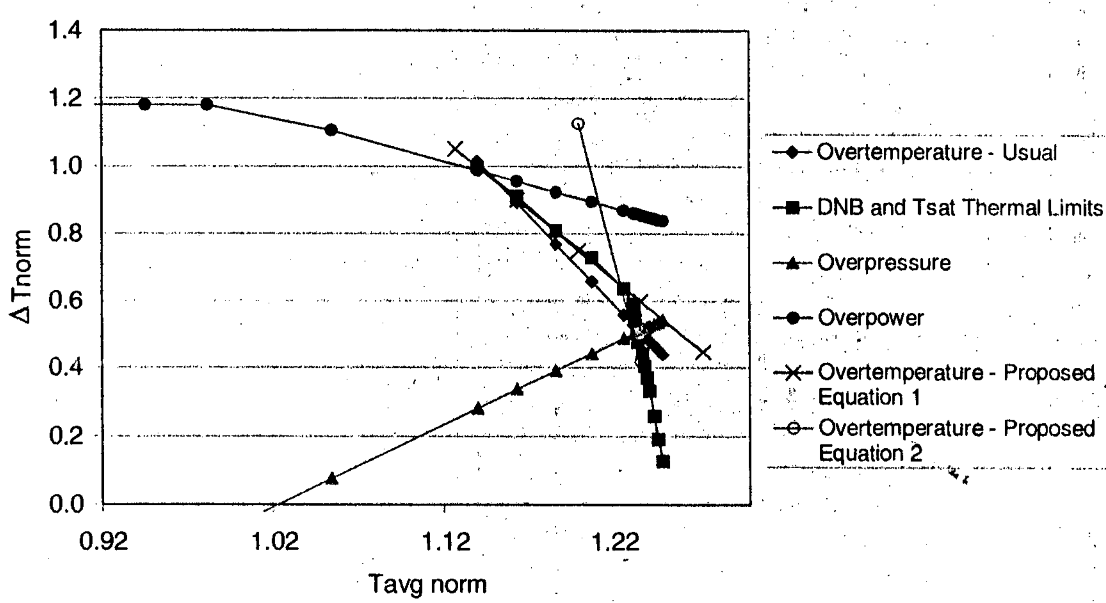

Figure 10-Normalized Protection Curves and DNB and T_{sat} Limits– Pressure 15.5 MPa

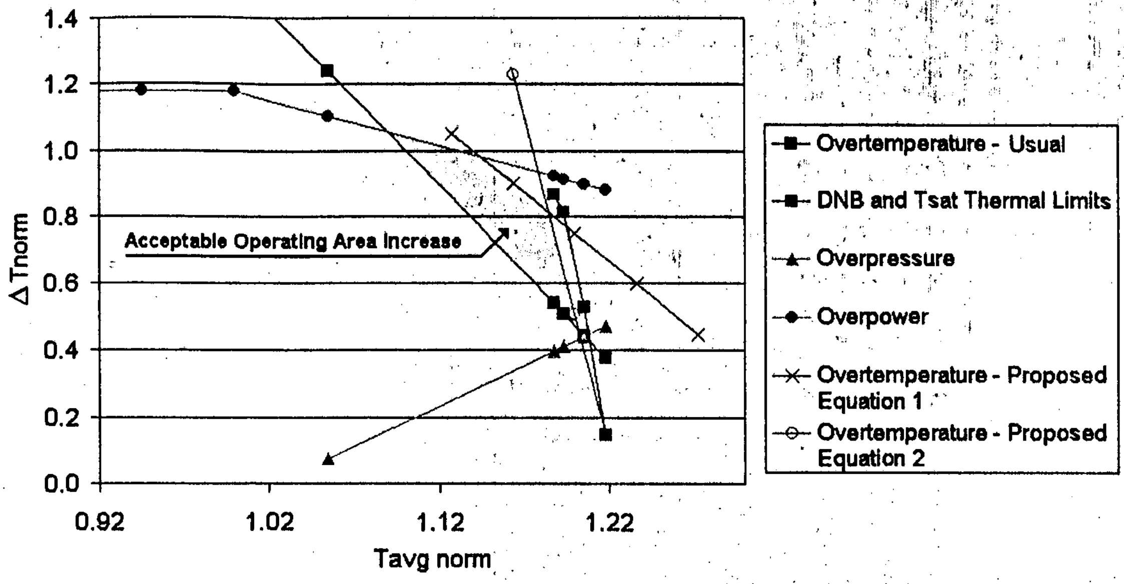

Figure 11 - Normalized Protection Curves and DNB and T_{sat} Limits – Pressure 14 MPa

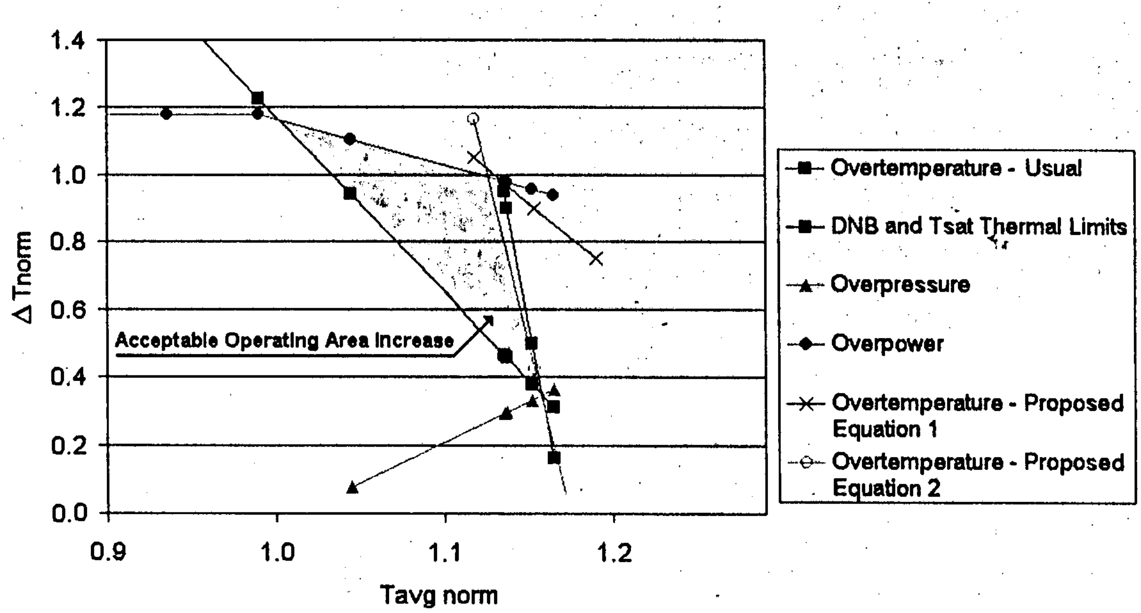

Figure 12- Normalized Protection Curves and DNB and T_{sat} Limits – Pressure 12 MPa

4. CONCLUSIONS

The main reason for this paper is to demonstrate the need of a carefully analysis of the plant operating conditions prior to the development of protection curves.

Analysis of experimental data show that the behavior of the temperature (not of the critical quality) correspondent to the DNB conditions, with pressure, changes according to the range of mass flow velocity. This change in behavior is important in the definition of the overtemperature protection curves.

The study case presented showed a possible loss of permissible operating area as a consequence of this behavior.

For the specific case of a nuclear reactor operating at low mass flow velocities, the proposed methodology allows for an increase in the operating area without loss of safety. However it is important to state that this methodology is subject to specific control characteristics of the plant in design.

It is also important to observe the need for a correct choice of DNB data and correlations to design and analyze a new PWR concept mainly in the case of lower mass flow velocities, lets say below 1,500 kg $s^{-1}m^2$.

Nomenclature

ΔT – vessel average temperature difference (°C)

CHF – Critical Heat Flux (MW/m^2)

DNB - (Departure from Nucleate Boiling)

DNBR - (Departure from Nucleate Boiling Ratio)

K - constant

P - Pressure (MPa)

T - Temperature (°C)

X – Quality (%)

G – Mass Velocity (kg $s^{-1}m^2$)

Q" – Heat flux (MW/m^2)

Subscripts

$_{1; 2; ...9}$ - constants index numbers

$_{avg}$ - average

$_{cr}$ - critical

$_{in}$ inlet

$_{loc}$ - local

$_{nom}$ – nominal

$_{norm}$ – normalized

$_{out}$ - outlet

$_{sat}$ – saturation

5. REFERENCES

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