CORE DEBRIS COOLING WITH FLOODED VESSEL OR CORE CATCHER

HEAT EXCHANGE COEFFICIENTS UNDER NATURAL CONVECTION

Report by an NEA Group of Experts

September 1994
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Pursuant to Article 1 of the Convention, the OECD shall promote policies designed:

-- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;

-- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and

-- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The current Signatories of the Convention are Australia, Austria, Belgium, Canada, Denmark, Finland, France, the Federal Republic of Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

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The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of scientists and engineers. It was set up in 1973 to develop and coordinate the activities of the OECD Nuclear Energy Agency concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations. The Committee's purpose is to foster international co-operation in nuclear safety amongst the OECD Member countries.
FOREWORD

The attached report has been prepared by S. Rougé and J.M. Seiler on the basis of information made available and discussed by members of the Task Group on Severe Accident Phenomena in the Containment (SAC) of CSNI's Principal Working Group on the Confinement of Accidental Radioactive Releases (FWG4). It has been endorsed by the SAC and FWG4, at meetings held in March and September 1994 respectively. The report has been approved by CSNI for publication in the series of CSNI Reports in November 1994.

A list of SAC members is given in an Appendix.
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS (CSNI)

PRINCIPAL WORKING GROUP ON
CONFINEMENT OF ACCIDENTAL RADIOACTIVE RELEASES (PWG4)

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* As these results are very recent, they have intentionally not been included in the previous sections. The actual results need to be completed and analyzed in order to obtain a clear picture of the physics of boiling under conditions of interest.
ABSTRACT

External cooling by natural water circulation is necessary for molten core retention in LWR lower head or in a core-catcher. Considering the expected heat flux levels (between 0.2 to 1.5 MW/m²) film boiling should be avoided. This rises the question of the knowledge of the level of the critical heat flux for the considered geometries and flow paths.

The document proposes a state of the art of the research in this field.

Mainly small scale experiments have been performed in a very recent past. These experiments are not sufficient to extrapolate to large scale reactor structures. Limited large scale experimental results exist. These results together with some theoretical investigations show that external cooling by natural water circulation may be considered as a reasonable objective of severe accident R&D.

Recently (in fact since the beginning of 1994) new results are available from large scale experiments (CYBL, ULPU 2000, SULTAN). These results indicate that CHF larger than 1 MW/m² can be obtained under natural water circulation conditions.

In this report, emphasis is given to the pursuit of finding predictive models for the critical heat flux in large, naturally convective channels with thick walls. This theoretical understanding is important for the capability to extrapolate to different situations (various geometries, flow paths ...). The outcome of this research should be the ability to calculate Boundary Layer Boiling situations (2D), channelling boiling situations (1D) and related CHF conditions.

However, a more straightforward approach can be used for the analysis of specific designs.

Today there are already some CHF data available for hemispherical geometry and these data can be used before a mechanistic understanding is achieved.
1. INTRODUCTION

Severe accidents of Light Water Reactor (LWR) involving core melting give rise to extensive studies for late phase corium (i.e. molten material issued from the core) cooling. Molten corium may be arrested inside the reactor pressure vessel or outside on specific devices (core-catchers). Corium is "arrested" means: corium may be contained and cooled in or onto a structure which is mechanically able to contain the mass of corium. This structure may be the reactor lower head or the concrete floor of the reactor containment or a core-catcher.

Water is needed to freeze and cool the molten corium and to extract the decay heat. This water may be in direct contact with the corium or indirectly through a metallic wall (as in the case of corium contained in the lower-head).

Physical separation of corium and water by means of a metallic structure has some advantages: the risk of vapour explosion is minimised and the risk of long term lixiviation of radioactive material is also minimised.

Only the case of indirect cooling of corium is considered here.

The cooling of the lower head is a situation of particular interest.

The cooling of a metallic structure by water must ensure sufficient low surface temperature and sufficient residual thickness of the structure in order to avoid melt--through or mechanical ruin of the structure.

Recently, an analysis of the margin-to-failure has been made for the TMI-2 vessel [STICKLER et Al, 1993]. The Authors conclude that "The background, or global, temperature behaviour (of the lower head) is key to predicting PWR vessel failure at high pressure conditions". E.S. BECKJORD [1993], from the USNRC, considers that "Accident management procedures should recognise: (1) the importance of cooling water not only for the reactor core, but also for limiting the reactor vessel wall temperature; and (2) the need for controlling pressure to avoid vessel creep failure"; and further: "External reactor vessel cooling, by flooding the cavity surrounding the lower part of reactor vessel, could reduce the potential for reactor vessel failure".

Sufficiently low vessel temperatures means sufficiently high heat exchange.

2. GENERAL REACTOR CONDITIONS

From a thermohydraulic point of view, the situation related to the cooling of a corium-retention-structure by water is characterised by:

- low pressure conditions (ranging from atmospheric pressure to some bars depending on the pressure level within the containment during the accident sequence),
- large channel dimensions (ranging from a few centimetres to some meters depending on the geometries considered),
- imposed heat flux distribution (the heat flux distribution is related to the corium internal thermohydraulics),
- the base case is natural convection in water (passive safety designs).

The decay heat must be evacuated to a cooling device which may be located in the containment. In this case, vapour carries the decay heat to the condenser which may be the containment itself, as in the AP600 project. The structure containing the corium is only a part of the water circulation path. This circulation may generally be divided into two main parts: a hot leg [including 1- the structure containing corium: lower head or core-catcher 2- the flow path of the vapour to the containment (for instance the gap between reactor vessel and thermal insulation)] and a cold leg [including condenser, water sump and liquid water flow path to the structure containing corium]. The heat transfer on the structure containing corium depends on the water mass flow rate which is related to the general flow recirculation. As a consequence, the cooling of the structure can generally not be separated from the general recirculation problem; both problems must be considered together.

An Example of coupling is given by KYMÄLÄINEN et al. [1992-2] for the cooling of the lower head of the Loviisa reactor (figure 1). In this case, the sump level is considered to be above the top of the lateral thermal insulation of the reactor vessel. In other situations, the sump level may be lower than sketched on figure 2. Even in this later case, the vapour escapes between the reactor vessel and the thermal insulation; the boiling in this more or less narrow channel may have an effect on the recirculating flow rate and thus on the heat exchange on the surface of the lower head.

Mainly three characteristic boiling situations may be emphasised:

1) A situation in which the distance between the heating surface and the surrounding structures is small enough to allow for vapour to extend to the surrounding structures.

This situation tends to the situation of boiling in channels; thus general knowledge concerning boiling in channels may be used for the analysis of such situations.

This situation will be depicted in the following as "channelling".

This is typically the situation which may occur between the vessel and the thermal insulation if the gap is small enough (a few centimetres).

2) A situation in which the vapour stays nearby the downward facing vessel surface and does not extend to the surrounding structure.

Under such conditions a "two-phase boundary layer" develops onto the heating surface.

This is typically the case for the bottom of the lower-head in a situation as depicted on figure 2.

This situation will be depicted in the following as "Boundary Layer Boiling" or shorter as "BLB". This leads to strong 2D and even 3D effects in the considered fluid volume.
Figure 1. Flow routes along RPV wall in Loviisa. Many other paths away from the vessel allow water to flow back into the cavity

after KYMÄLÄINEN et al. [1992-2]
Figure 2. Flooded reactor cavity with presence of thermal insulation
3) A situation of upwards facing heat surface which will be depicted here as \textit{pool-boiling}.

The geometry of the thermal insulation which surrounds the reactor vessel may be arranged (optimised) in such a way that a "channelling" effect is produced when boiling appears. This tends to produce a buoyancy or "chimney" effect between the vessel and the insulation and is aimed to increase the mass flow rate in this space. Thus the heat removal capability from the lower head should be increased. An example of such an arrangement is given by HENRY & FAUSKE [1993] who consider the situation shown on figure 3.

In the BLB situation the boundary conditions for the Boiling Boundary Layer are rather simple: the two-phase boundary layer is driven by the liquid pressure gradient which in the general case is reduced to the buoyancy term:

$$\frac{dp}{dz} = D \cdot g$$

where:

- $D$ is the density of the liquid
- $g$ is the acceleration of gravity
- $z$ is the vertical coordinate

In the general real cases, both situations (channelling and Boundary Layer Boiling) may simultaneously be present; for instance considering the situation depicted on figure 1 or 2, one can expect a development of BLB (Boundary Layer Boiling) in the lower region of the vessel head (2D or 3D boiling) and a "channelling" type situation (mainly 1D) on the lateral cylindrical surface of the vessel.

\textit{Order of magnitude of Heat flux distribution to be considered:}

The heat flux distribution is an important input parameter for the analysis of the structure cooling and integrity; it is strongly related to the considered geometry.

For the case of a hemispherical lower head, the heat flux is expected to increase with the elevation as a consequence of the natural convection within the corium pool contained in the lower head. This problem has been addressed by OKKONEN [1992], with many pertinent references, for the case of oxydic corium.

The case of molten pool of oxydic material may not be the only reactor situation to be considered. Stratified pools of metallic and oxydic material or even pools of metallic material with solid oxydic debris should also be considered.
Figure 3. Water inflow and steam outflow through the gap between insulation panels

after HENRY and FAUSKE [1993]
The magnitude of the heat fluxes to be considered seems also to be subjected to some discrepancies. The magnitude depends mainly on:

- the mass of corium relocated within the lower-head,
- the structure of the debris and pool,
- the decay power level,
- the proportion of heat directed downwards and sidewards to the lower vessel head,
- the shape of the heat flux distribution,
- ...

We consider in the following only the situation of a molten pool of ceramic material.

The proportion of heat which is delivered to the lower head depends on the height of the pool and on the heat transfer at the upper surface of the pool.

Depending on different authors, this proportion varies between 25% to 80 or 90%:

* 80 to 90% corresponds to the situation of low heat transfer at the upper surface of the pool (due, for instance, to a low emissivity of steel structures).
* 25% corresponds to a shallow pool with maximum heat directed upwards.

For a hemispherical pool and a solid crust at the surface, the estimated proportion of heat which may be directed downwards is of the order of 45% to 55 %.

The natural convection within the pool is responsible for a non uniform heat flux distribution with a maximum nearby the upper level of the pool and a minimum at the bottom of the pool. Considering a turbulent boundary layer flow nearby the crust along the lower head surface, the estimated maximum heat flux is about equal to 1.5 times the average heat flux for a hemispherical pool.

The residual power to be considered lays around $1\text{MW/m}^3$ but may be considered as high as $3\text{MW/m}^3$.

All these considerations lead to an estimation of the average heat fluxes which may vary in the range $0.2$ to $1\text{MW/m}^2$ and peak heat fluxes in the range $0.3$ to $1.5\text{MW/m}^2$.

A typical heat flux distribution on a cylindrical lower-head is shown on figure 4 (result of proper calculations with the TRIO VF code, see [S. PIGNY, 1994]). Figure 5 shows a heat flux distribution measured on the COPO facility (KYMÄLÄINEN et Al.,[1992-1]).

If a cylindrical container is considered, the heat flux profile is expected to show a weak linear function of the height (SCARABEE test BF1, BRETON et Al. [1990]).

For these examples, the maximum heat flux is located near the top of the heating height.
Figure 4 Heat flux distribution on a hemispherical lower-head after PIGNY (power = 32 MW)
Heat flux profile in run fh2.

Side-wall cooling unit numbering of the COPO facility.

Figure 5. Heat flux distribution from the COPO facility
3 FILM BOILING, NUCLEATE BOILING AND CRITICAL HEAT FLUX

As a first approach of the boiling heat transfer, the preceding heat flux levels have to be compared with 1 MW/m², the well known heat flux level which corresponds to the critical heat flux for a water pool boiling situation on a horizontal surface directed upwards at 1 atmosphere.

In the following it will be first be shown that an assumption of film boiling (worst situation for heat exchange which may be considered) will lead to unacceptable temperature levels and residual steel thicknesses for the considered heat flux range. It then will be shown that nucleate boiling is able to save the vessel. Nucleate boiling may be maintained as long as the critical heat flux level (CHF) is not exceeded; therefore an overview of the studies related to the determination of critical heat flux for the relevant situations is given. As the critical heat flux depends strongly on the development of two-phase flow on the heated wall, an overview about relevant work is proposed.

3.1 Vapour accumulation and film boiling

The fact that the surface of the lower-head is directed downwards is expected to be a non favourable situation. The vapour may accumulate by stratification along the downward boiling surface. Vapour accumulation is expected to lead to film boiling.

Film boiling however leads to very low heat exchange coefficients. Several theoretical and experimental developments concern heat exchange with film boiling (HAMILL and BAUMEISTER [1966], SURYANARAYAMA and MERTE [1972], LABUNTSOV and GOMELAUER I [1979], BUI and DHIR [1985-1], LIU et AL. [1992], SAUER and LIN [1974], HSU and WESTWATER [1960], NISHIO et AL. [1991], JUNG et AL. [1987], WALLIS and COLLIER (see HESTRONI [1982]).

The first established correlations (WALLIS and COLLIER, LABUNTSOV and GOMELAUER) considered laminar or turbulent stable film boiling

SURYANARAYAMA and MERTE [1972] evidenced interfacial instabilities which were also analysed by BUI and DHIR [1985] who sketched (figure 6) a repetitive phenomena leading to an average heat exchange coefficient which does not depend on the dimensions of the considered flat heating plate.

Effect of inclination was investigated, for instance, by SAUER et AL. [1974].

The order of magnitude of the expected heat exchange coefficients by film boiling is of the order of 100 to about 250 W/m² K (radiation plays some role at elevated temperatures). If the wall surface temperature has to stay below, say, 1000K, this would mean that the maximum allowed heat flux is, in this case, of the order of 0.05 to 0.1 MW/m², which is a rather low value.

One is thus led to the conclusion that film boiling and vapour accumulation nearby the wall surface has to be avoided unless the heat fluxes are lower than, say, 0.1 MW/m².
Figure 6. Configuration of the vapour-liquid interface after BUI and DHIR [1985-2]
However, HENRY et al., [1991], claim that the growth of interfacial instabilities (KELVIN-HELMHOLTZ type) may lead to local contacts between the vessel and liquid water and thus increase the heat transfer. This type of instabilities may be the same than the ones which were studied by BUI and DHIR and by NISHIO et al. and which do not lead to a significative increase of film boiling heat transfer.

3.2 Can nucleate boiling save the vessel?

Nucleate boiling implies very high heat exchange coefficients and this is equivalent to suppose that the external surface temperature of the vessel is equal to the saturation temperature.

Supposing now a heat flux level as high as 1.5 MW/m² it is possible to determine the residual vessel thickness.

This thickness is about 3.5 cm if a thermal conductivity of 30 W/mK is assumed. If it can be shown that the mechanical integrity of the vessel may be assured with a residual thickness of about 3.5 cm and an external surface temperature of about 100°C, it may be concluded that nucleate boiling is able to save the vessel.

3.3 Critical heat flux

Nucleate boiling can be maintained as long as the critical heat flux is not exceeded. The CHF is the maximum heat flux level which may be evacuated under nucleate boiling conditions. If the CHF is exceeded, the heat transfer coefficient will decrease and the surface temperature will drastically increase.

Critical heat flux: DNB or Dry-Out?

DNB and Dry-Out are two theoretical typical ways which correspond to the CHF.

Departure from Nucleate Boiling (DNB) is a situation which corresponds to vapour accumulation nearby the heating surface. The presence of numerous vapour bubbles leads to the progressive (transition boiling) formation of a continuous vapour film which isolates the heating surface from the liquid water.

Dry-Out corresponds to the evaporation of the liquid film on the heating surface at high quality boiling.

High quality boiling is generally associated with channel geometries and low coolant mass flowrates. This may typically be the situation for boiling between the vessel surface and the lateral thermal insulation.
A pool boiling situation, such as the development of a Boiling Boundary Layer under the lower-head in a large cavity may lead to CHF conditions which are closer to our definition of DNB. This corresponds however to a macroscopic point of view which considers the Boiling Boundary Layer as a vapour accumulation process.

If the physical processes within the Boiling Boundary Layer are examined with greater details, it may be considered that locally the flow pattern is changing from the location of the boiling front to the location of CHF. The location of CHF should correspond, locally, also to high void fractions and qualities which are characteristics of what has been previously defined as Dry-Out.

Thus the differences between DNB and Dry-Out should be considered as a secondary problem and the word CHF will mainly be used in the following.

3.4 Existing experiments on CHF with inclined surfaces

Several experiments have been performed in order to evaluate the level of the critical heat flux (CHF) in stagnant water pools with controlled temperature levels.

Up to now, mainly small surfaces (characteristic dimension of a few centimetres) have been tested in water pools with different inclinations (VISHNEV et Al. [1976], BUI and DHIR [1985-2], BEDUZ et Al. [1988], GUO and EL-GENK [1991], ISHIGAI et Al. [1961], CHU et Al. [1992], EL-GENK and GUO [1992]).

Figure 7 shows the critical heat flux as a function of the angle of inclination (this figure is taken from CHU et Al. [1992]). The critical heat flux is normalised by the critical heat flux obtained for a horizontal upward facing surface (0 degrees angle). It is found that there is a rapid decrease in the critical heat flux as the surface approaches the horizontal downward inclination (180 degree angle). TONG [1968], VISHNEV and Al., also EL GENK and GUO [1992] propose correlations for the determination of the critical heat flux.

ISHIGAI and Al. [1961] showed that the critical heat flux is decreasing with the increase in size of the heating surface.

Also BUI and DHIR [1985-2] concluded to a decrease of the critical heat flux when a transient heating situation is considered (see figure 8).

All these studies must be considered as indicative as they do not take into account the scale and shape (bended surfaces, etc...) effects and do not consider the effect of recirculating flow. To our opinion they cannot be used for extrapolations to all reactor situations as will be discussed in the next section.
Figure 7. Normalised critical heat flux versus angle of inclination (0° is upward facing and 180° is downward facing).

after CHU et al. [1992]
Figure 8. Effect of surface roughness and transient on boiling curve

after BUI and DHIR [1985]
4. ANALYSIS OF THE DIFFERENT BOILING SITUATIONS

From the previous section, it is concluded that the main emphasis must be devoted to the prediction of the occurrence of CHF in reactor situations.

Three typical situations have been identified:

- Situations with Channelling.
- Boiling Boundary layers for downward facing surfaces.
- Pool Boiling for upward facing surfaces.

4.1 Pool Boiling

For Pool Boiling with horizontal surfaces facing upwards the CHF is well known (about 1 MW/m² in saturated water at 1 atmosphere). This should also stand, as shown by previously described small scale experiments, for upwards facing inclined surfaces as the inclinations varies from horizontal towards the vertical situation.

As the inclination approaches the vertical position, vapour accumulation on surfaces of great size begins to play a role. For instance BUI and DHIR [1985-2] (figures 6 and 8) indicate CHF values reduced to 0.3 to 0.6 MW/m² for a vertical plate in saturated water at 1 atmosphere.

The limit of inclination for which vapour accumulation begins to play a role is not well known, but should not be very far from vertical position.

4.2 Boiling Boundary Layer

For Boiling Boundary Layer situations on large surfaces quite nothing is known.

CHEUNG and EPSTEIN [1985] proposed a model for the calculation of Two-Phase Gas Bubble-Boundary Layer Flow along vertical and inclined surfaces. The predictions of the boundary layer thickness determined by this model are in reasonable agreement with experiments performed by injecting argon through a porous inclined surface in stagnant water. But non-condensable gas does not behave as vapour. Vapour condensation plays a very important role on the development of the Boiling Boundary Layer.

Specific experiments for the validation of Boundary Layer Boiling models are necessary.
4.3 Channelling

The Channelling situation is a more classical situation.

We potentially can make use of the important knowledge gained for other reactor analyses. However, most of this material concerns situations characterised by high pressures (150 bar), small hydraulic diameters (a few millimetres), and vertical surfaces.

CHF correlations which have generally been developed for very restricted conditions cannot be used for CHF predictions for the situations of interest here.

Moreover the predictions of CHF needs the knowledge of the recirculation mass flow rate.

This mass flow rate corresponds to the equilibrium situation for which the pressures drops over the two-phase flow (hot leg) are equilibrated by the pressure drop in the feeding leg (cold leg).

The pressure drops in the two-phase flow depend on the void fraction distribution, the velocity distribution which, of course depend on the mass flow rate.

Thus one is led to the conclusion that the prediction of CHF in the channelling situation is strongly related to the ability to predict the void fraction distribution, velocities and pressure drops (in one word the characteristics of the two-phase flow) in the geometry of interest.

If the geometry is well defined, tests in a representative situation could be performed in order to obtain a direct measurement of the CHF limit under natural convection.

But this will not be sufficient for an optimisation of a design. Optimisation needs the ability to predict the two-phase flow characteristics for different geometries. This may only be done if analytical experiments are performed and mathematical models are developed and qualified.

A simplified model is proposed by HENRY and FAUSKE [1993] for the description of two-phase flow development between the lower head and the thermal insulation (a space of about 2 cm is supposed). This model is based on a 1D straight channel approach and supposes that the critical heat flux is reached for qualities lying nearby 1. The authors conclude that up to 20 MW may be evacuated without reaching critical conditions. This conclusion is quite encouraging but needs clearly improvements and qualifications.

4.3.1 General approach to the description of boiling in a channelling situation; Subcooled Boiling region

In channels of large hydraulic diameters it may be expected that subcooled boiling will play an important role.

The subcooled boiling region extends from the boiling front (from the location of the Net Vapour Generation point (NVG) to the location of saturated boiling (also denominated extended boiling) which corresponds to the location at which the mean quality of the flow is equal to zero).
A two-phase flow layer develops nearby the heating surface as soon as the net vapour generation (NVG) conditions are exceeded. The location of NVG point is usually predicted with the SAHA and ZUBER correlation (SAHA and ZUBER [1974]). This correlation is only valid for channel flow under following conditions: Water and Freon, pressures from 1 to 14 MPa (10 to 140 bars), annular, tubular and rectangular geometries of small sizes (typically a few millimetres).

This correlation has to be checked for the conditions of interest here.

Depending on the hydraulic diameter of the channel, boiling may extend to the whole section of the channel (extended boiling). The quality and void fraction distribution between the location of NVG Point and extended boiling, (subcooled boiling), is also generally described with theories similar to those developed by ZUBER et Al. [1966] and ROUHANI and AXELSON [1969]. These theories are based on a 1D approach which is expected not to be sufficient for large channels.

A pressure drop may be calculated using a mean void fraction which may be derived from these theories. But the realism of such an approach needs to be tested. A mean void fraction may not have great significance if an important liquid layer exists on the opposite side of the channel with internal (to the channel) recirculations.

4.3.2 Extended (or quality) boiling region

Also, in the extended (or quality) boiling region, pressure drop calculations have to be validated for low pressure and high hydraulic diameter situations.

5. GENERAL APPROACH TO THE WATER RECIRCULATION PROBLEM AND FLOW INSTABILITIES:

Different types of instabilities may affect the recirculating mass flow rate [BOURE et Al., 1973]; two-phase flow instabilities are usually classified into two categories: static and dynamic instabilities.

Static instabilities concern the mean mass flow rate. The classical example is a flow redistribution between two parallel channels due, for instance, to the increase of inlet throttling on one of these channels. Under some conditions, a slight change of the inlet throttling initiates the development of a flow instability which may lead to very low mass flow rates and dry-out in the channel of concern.

Dynamic instabilities are periodic flow oscillations around a mean value of the mass flow rate (chugging, geysering,...). These oscillations may also lead to periodic dry-out and rewetting of some parts of the heating surface.

Static instabilities will first be analysed.
5.1 Static instabilities

In order to cope with this problem, one can make use of a well known and powerful approach based on the determination of the so-called External and Internal Characteristics (EC and IC).

This method is described in [HESTRONI, 1982] and has been extensively used for the analysis of boiling flows under forced convection in nuclear reactor safety problems. As will be shown below, this method is also applicable to natural convection flow problems.

First of all, the water recirculation flow must be divided into two arbitrary parts (figure 9) which will be considered as completely disconnected. The most physical choice would be to consider the hot leg on one side and the cold leg on the other. Two precise separation points must be considered. The first one may be the lower level of the structure containing the corium (point E) and the second is naturally the level of the surface of the water (point T) (or a submerged junction); this level is generally characterised by a constant pressure: in the case of a free water surface it is the containment pressure.

A "Characteristic" of a part of the circuit is defined as the variation of the pressure drop versus the mass flow rate flowing through the considered part of the circuit, for a given power level and a given cover (containment) pressure.

The term "Internal" will be attributed to the part of the circuit in which we are most interested in: the hot leg (from point E through the structure containing the corium and to the surface of the water). The term "External" will be attributed to the cold leg (from point E through the water return to the surface of the water).

The determination of the Internal and External Characteristics will provide:

- the recirculation mass flow rate and pressure drop at the intersection of both Characteristics (the Working Point);
- an analysis of the stability of the Working Point from the point of view of static and dynamic instabilities: a static instability (flow decrease) develops if the LEDINEGG criterion is not fulfilled:
  
  \[
  \text{Static stability criterion:} \quad (\text{DP/DQ})_{\text{int}} > (\text{DP/DQ})_{\text{ext}}
  \]

The dynamic instabilities are, to some extent, related to the slope differences of both Characteristics at the Working Point.

Thus this analysis permits to determine the effect of specific changes in the water circuit (introduction of pressure drops, ...) on the recirculating mass flow rate and flow stability.

In the following, examples and application to natural convection in reactor situations will be outlined:
Figure 9. Water recirculation in case of a core catcher below the reactor vessel. Cold leg and Hot leg.
5.1.1 The External Characteristic

The pressure drop in the cold leg is mainly related to the liquid height:

\[ DP = d \cdot g \cdot H \]

- \( d \): liquid density
- \( g \): gravity acceleration
- \( H \): height
- \( DP \): pressure drop

If some friction pressure drops exist in the part in which water returns to the structure, it has to be subtracted from the liquid height. The resulting shape of the External Characteristic is shown on figure 10.

5.1.2 The Internal Characteristic

The pressure drop over the hot leg is mainly related to the two phase flow which develops over the different parts of this hot leg and which depend on considerations such as:

- the geometry of the different parts,
- the two phase flow configurations (involving 2D or 3D effects).

As stated previously, the pressure drop over this part is clearly a very difficult thing to determine with actual knowledge (see also KYMÄLÄINEN, 1992-2) since all existing codes have been validated for normal core operation parameters ranges which are very far from the parameter ranges of interest here (low pressure, large hydraulic diameter) and since 2D and 3D effects are not easily handled and represented in 1 D approaches.

For low hydraulic diameter channels (a few millimetres) and forced convection the Internal Characteristic has a classical S shape as represented on figure 11. At onset of boiling, the friction pressure drop increases and this entrains generally an increase of the overall pressure drop. In this case, if the external Characteristic is a constant pressure drop corresponding to a natural convection liquid head as represented on figure 10, a stable Working Point will not exist; in this case the recirculation mass flow rate would be very limited leading to high qualities and low CHF.

Large hydraulic diameters and low mass flow rates may lead to subsequent modification of the shape of the Internal Characteristic as it is represented on figure 12 for LMFBR subassembly boiling under natural convection (RAMEAU et al., 1984). These measurements reveal an important pressure drop at the onset of boiling: this effect is related to sudden vaporisation in the outlet of the subassembly which was formed by a cylindrical tube of large diameter. The voiding of this tube decreased the gravity pressure drop which was not compensated by the increase of the friction pressure drop. The friction pressure drop only increased when the flow was further decreased and the quality increased. Application of the LEDINEGG stability criterion shows that under some conditions, natural convection boiling was possible. For instance, if inlet pressure drop was increased, the Working Point displaced from B to B'. At this point, if inlet pressure drop was further increased, the flow stability criterion was no more fulfilled and a flow excursion occurred which led to Working Point C' (stable) and high qualities (flow limitation and subsequent dry out). The same behaviour should be observed if outlet pressure drop was increased.
Figure 10 Typical "External Characteristic" for natural convection
Figure 11. Internal and external characteristic (classical shapes)
Figure 12. Pressure drop in a LMFBR (SPX) subassembly
5.1.3 Application to reactor conditions

In order to get a first idea of the shape the Internal Characteristic may have for a specific hot leg geometry, some calculations have been performed at CEA GRENOBLE.

Considered geometry:
- vertical, 4 meter long, heating structure,
- a 6 meter long vertical tube follows the heating structure,
- large hydraulic diameter (15 cm),
- low pressure conditions (1 bar) are considered.

The calculations are performed with the FLICA code, which is a 1D model not validated in the considered parameter range; thus following results must only be considered with care.

The calculated Internal Characteristics are shown on figure 13 for different power levels. It appears that these Characteristics show that the pressure drop decreases continuously with the decrease of the mass flow rate. This would mean that every Working Point is unconditionally stable. Furthermore the Working Point corresponding to liquid head of 10 meters (External Characteristic) would correspond to high mass flow rates (higher than 1000 kg/m2sec). The calculations also indicate that the slopes of Internal and External Characteristics are very close and near to horizontal at the Working Point which means that every pressure disturbance would lead to large flow oscillations (instabilities). Under these conditions, an increase of the pressure drops on the hot leg (at the inlet), see figure 13, would lead to a more stable flow but the recirculating mass flow rate is decreased.

These analyses show that the approach using Internal and External Characteristic methods are very useful and help to optimise overall design of the water circuit.

5.1.4 Limitations of application

Applications are limited to systems for which a clear water circuit may be identified.

Applications are not possible for the cases involving predominant 2D or 3D effects such as Boundary Layer Boiling.
Figure 13 Calculated internal characteristics with the FLICA code

Heating part: 4 meters long, gap = 15 cm
Prolongator tube: 6 meters long, diameter = 25 cm
Heat flux = 1 MW/m²
5.2 Dynamic instabilities

Many different types of dynamic instabilities exist.

Dynamic instabilities are quite complicated phenomena which depend on many parameters (among which: the whole flow path); they cannot be described with the preceding approach.

Low pressure conditions with large liquid to vapour density ratios combined with low heat fluxes are expected to favour the dynamic instabilities; the amplitude and period of flow oscillations may be very high.

Flow oscillations involve local boiling characteristics oscillations (quality and void fraction variations) which may lead to temporary dry-out.

Some studies concerning dynamic instabilities under natural convection boiling have been made during the past ten years; but none of the experiments available represents the main characteristics of the problem of concern here: large channel width, thick heating plates, inclined surfaces with two-phase boundary layers.

One parameter which may affect the dynamic instabilities and which is expected to concern the CHF is the thickness and the thermal characteristics of the heating wall. For a given heat flux and a given period of flow oscillations, the amplitude of the temperature variations will decrease with an increase of the thickness of the wall. If, at some moment during the oscillation period, CHF conditions are reached, the temperature of a thick wall will increase less then the temperature of the thin wall and thus rewetting of the thicker wall is expected to be easier then the rewetting of the thin wall when the liquid water comes back. As periodic dry-out and rewetting may be acceptable if the temperature does not increase too much (the problem must also be analysed from the point of view of structure mechanical behaviour), the thicker wall is expected to have higher heat flux removal capabilities than a thin wall.

However, it must be noted that the thickness of the wall is, by far, not the only parameter which may affect the dynamic instabilities. Outlet throttling, structure scale, pressure level (and other parameters) may have a great influence on the development of dynamic instabilities.

6. LARGE SCALE TESTS

As these results are very recent, they have intentionally not been included in the previous sections. The actual results need to be completed and analyzed in order to obtain reliable CHF conditions and a clear picture of the physics of boiling under conditions of interest.
6.1 CYBL tests at Sandia National Laboratory:

Full scale reactor lower head tests (CYBL) have been initiated by Sandia National Laboratories [CHU and Al., 1992, 1993, 1994]. In these tests a real size reactor lower head is heated internally by radiation (heat fluxes up to 0.4 MW/m² may be achieved for a total delivered power of 4.5 MW). The vessel has a thickness of about 1.4 cm. A 7 meters high cylindrical housing surrounds the test device and is filled with water (figure 14). The shape of the lower-head, the heat flux distribution, the water subcooling, and the flow pathes can be varied. The impact of vessel insulation can be analysed.

For heat flux levels limited to 0.4 MW/m², the ex-vessel boiling process is described as nucleate boiling. The boiling pattern is divided into two regions: a cyclic/pulsating bottom center region and an outer steady two-phase boundary layer region (see figure 15). Condensation takes place at the edge of both regions. the bulk of the water in the annular space between the reactor vessel and the cavity wall is single-phase liquid. Intense vaporisation takes place near the top surface of the water. The subcooling is mainly due to the gravity head of the water flooding the simulated reactor cavity.

The results of three CYBL tests series suggest that under prototypic heat loads and heat flux distributions, the AP-600 flooded cavity should be capable of cooling the reactor pressure vessel in the central region of the lower head that is addressed by these tests.

6.2 ULPU tests at University of California, Santa Barbara:

Several tests are performed at University of California, Santa Barbara in collaboration with IVO International Limited, Finland.

The tests began with a 60 cm long plate placed in a natural circulation water loop (ULPU). These tests are followed by the ULPU 2000 experiments which involve a slice of reactor bottom head (full scale in height).

ULPU test with vertical plate [KYMÄLÄINEN 2]:

A vertical heating plate is placed in a 15 cm square channel prolonged by a vertical circular tube with a variable pressure drop at the outlet representing the exit restriction of the natural convection path in the Lovisa reactor. The steel plate has a thickness of 1.4 cm. The vapor is condensed and returns through a cold leg. Only qualitative results are presented in [KYMÄLÄINEN 2]. It is indicated that the recirculating mass flow rate is high enough to authorize good cooling for heat fluxes up to 1 MW/m².

ULPU 2000 tests [THEOFANOUS et Al., 1994]:

The aim of these experiments was to investigate boiling and CHF behaviour on the external surface of a reactor lower head. The test arrangement represents a full scale (in height and width) slice of the lower head. The slice is 15 cm large. Three independant heater blocks (each covering, nominally, a 30° arc of a circle) can be arranged to obtain a full 90° angular sector. Both the power and the heater design were upgraded to allow a peak flux of 2 MW/m². Another important objective was to have a controled power shape over the whole extend of the heater surface. The heaters are instrumented with thermocouples.
Figure 14: Schematic of CYBL apparatus. The inner vessel is replaceable.
Figure 15: CYBL; schematic of Ex-Vessel Boiling Mechanisms
The authors propose a method to extrapolate the test results obtained on this slice test section to a reactor sector.

The test will be conducted with three different configurations (see figure 16):

Configuration I: is for studying saturated boiling in a 30° angle and especially in the region around the lower horizontal position of the reactor vessel.

Configuration II: is for simulating the complete geometry (a full one quarter circle) under both loop flow (including the effect of subcooling) or saturated conditions.

Configurations III: represents a channel geometry, as it might arise from particular thermal insulation designs with an inlet at the very bottom.

In the paper in reference only data from configuration I are presented.

The main results of the tests are presented on figure 17. It is concluded that 300 KW/m² may be considered as a conservative level of CHF on the very bottom of the lower head under saturation conditions. The CHF increases drastically with the angular position, reaches about 700 KW/m² at an angular position of 35° and 1000 KW/m² between 60° and 90°.

6.3 SULTAN tests at CEN Grenoble:

Analytical tests are conducted at CEA Grenoble (SULTAN experiments, J.M. BONNET et Al., 1994) with a 4 meter long (and 15 cm large) flat plate of variable inclination. The plate is direct current heated (plate thickness: 1.5 mm). The depth of the test section may be varied (3cm to 15 cm) so as the test pressure (1 to 8 bar) and inlet subcooling. The tests may be performed under forced convection conditions, (in order to determine the Internal Characteristics (pressure drops) and CHF conditions and validate calculation codes (void fraction profiles and temperature profiles measurements)), and under natural convection conditions. The maximum heat flux level will be 1 MW/m².

The test began with the plate in vertical position and a 3 cm channel depth.

An Internal Characteristic is qualitatively shown on figure 18.

The actual main trends of the results are the following:

- The measured pressure drop over the heated test section decreases continuously with a decrease of the mass flow rate (at constant power, cover pressure and inlet temperature); no "S" shape curve generally observed for boiling channels with low hydraulic diameters is obtained,

- The mass flow rate corresponding to natural circulation conditions (with a pressure head equivalent to a liquid water head corresponding to the heating length) is substantially greater than the mass flow rate for which CHF is obtained, even at heat fluxes as large as 1MW/m².

Many data concerning Pressure Drop curves and CHF conditions have been obtained.
Schematic of Configuration I in ULPU-2000. The heater blocks extend over the region $-30^\circ < \theta < 30^\circ$.

Schematic of Configurations II and III in ULPU-2000. The heater blocks extend over the region $0 < \theta < 90^\circ$.

Figure 16: Test configurations in ULPU 2000
Figure 17: ULPU 2000; Summary of all the CHF data obtained in Configuration I.
Solid symbols denote occurrence of Boiling Crisis; open circles denote persistence of nucleate boiling for 50 minutes; and crosses show persistence of nucleate boiling for 2 hours.
Figure 18: Qualitative aspects of Internal Characteristics (test section pressure drop versus mass flow rate) as measured on the SULTAN facility. Plate is in vertical position, channel depth = 3cm, 50°C subcooling at the inlet, 1 atmosphere over-pressure.
6.4 SBLB tests at Pennsylvania State University (intermediate scale):

Tests are performed at Pennsylvania State University under the sponsorship of USNRC. Following objectives have been set for these tests:

1) Perform heat transfer measurements of downward facing surfaces (hemispherical or toroidal shapes of various diameters)
2) Obtain a data base for CHF on downward-facing curved surface
3) Develop a comprehensive model for downward-facing boiling on a curved surface and validate the model
4) Establish a proper scaling law and develop a design correlation.

To carry out these objectives, an experimental test setup as shown in figure 19 is proposed (SBLB for Subscale Boundary Layer Boiling Experiments). This experimental setup consists of a water tank/condenser unit and a heated hemispherical or toroidal test section. The heated test section has five independently heated segments. Heating of the segments is provided by resistive heating using nichrome coils attached to the back of segments. Stainless steel and copper test sections (about 1.2 cm thick) with diameters ranging from 0.152 m to 0.381 m will be employed. The maximum heat flux level is 0.25 to 1 MW/m². The experimental pressure range is 1 bar to 2.5 bar.

The vessel may be preheated under dry conditions and then dropped into water. The variation of the temperature of the experimental vessel permit to determine the transient evolution of the heat exchange coefficient as a function of surface temperature of the vessel.
Schematic of the experimental apparatus for CHF testing on a downward-facing curved surface

Schematic of the curved heating surface and the test segments

Figure 19: SBLB Tests
7. HEAT EXCHANGE ENHANCEMENT TECHNIQUES

Heat exchanges may be enhanced by different techniques involving a modification of the heating surface. Massive fins or other structures may be emphasised. A review of such devices is given by [FARELL, 1991] and by [CELATA and CUMO, 1991]. Techniques like VAPOTRON and HYPER-VAPOTRON have been proposed by [BEURTHERET, 1970]. These kinds of devices are able to remove up to 10 MW/m². They have up to now been used only on small surfaces; the possibility of their adoption on large surfaces should also be considered with caution since scale effects (such as vapour accumulation effects) may significantly modify the performances of such techniques. It also seems very difficult to implement such devices on the external surface of a reactor lower head. Nevertheless, there may be an interest for application on core-catcher systems.

8. CONCLUSIONS

External cooling of reactor lower-head or core catcher devices by natural water circulation are considered as a reasonable objective. Considering the expected heat flux levels (between 0.2 to 1.5 MW/m²) film boiling should be avoided. This rises the question of the knowledge of the level of the critical heat flux for the considered geometries and flow paths. Only small scale experiments have been performed for the investigation of critical heat fluxes under natural convection. It appears from the analysis that geometry, scale and circuit effects (recirculating mass flow rate) strongly affect the critical heat flux level.

Recently (in fact since the beginning of 1994) new results are available from large scale experiments (CYBL, ULPU 2000, SULTAN). These results indicate that CHF larger than 1 MW/m² can be obtained under natural water circulation conditions.

In this report, emphasis is given to the pursuit of finding predictive models for the critical heat flux in large, naturally convective channels with thick walls. This theoretical understanding is important for the capability to extrapolate to different situations (various geometries, flow paths ...). The outcome of this research should be the ability to calculate Boundary Layer Boiling situations (2D), channelling boiling situations (1D) and related CHF conditions.

However, a more straightforward approach can be used for the analysis of specific designes.

Today there are already some CHF data available for hemispherical geometry and these data can be used before a mechanistic understanding is achieved.
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Nucleate boiling heat transfer has also been studied extensively on small inclined surfaces in pool boiling situations. As the heat transfer related to nucleate boiling is very high, the analysis of the heat transfer variations with angular orientation and other parameters has no great interest for present needs and will thus not be discussed here.
APPENDIX

List of Members of
PWG4's Task Group on Severe Accident Phenomena in the Containment (SAC)

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