Pressurized Thermal Shock-Mixing of a Direct Safety Injection Flow in a PWR Reactor Vessel Downcomer — Experimental and Analytical Results

M. Giot

Université de Louvain-la-Neuve, Département Thermodynamique et Turbomachines, place du Levant, B-1348 Louvain-la-Neuve, Belgium

P. Hernalsteen, E. Stubbe

Tractionel, Nuclear Department, 31 rue de la Science, B-1040 Bruxelles, Belgium

Abstract

For Pressurized Thermal Shock (PTS) studies, the unusual case of direct Safety Injection into the reactor vessel downcomer increases the importance of the cold water "mixing" with the warmer environment. To properly evaluate this effect, a twin approach was followed :

- development of a simple analytical mixing model, based on the fundamental conservation equations and semi-empirical "entrainment" correlations (TRAMIX program)
- design of a scale model test facility, in order to provide both a validation of the analytical tool and a direct insight of the phenomena.

1. INTRODUCTION.

In PWR nuclear power plants, the Pressurized Thermal Shock (PTS) is a transient condition whereby, during a depressurization accident, cold water from the Safety Injection (SI) system enters the reactor pressure vessel while the Reactor Coolant (RC) pressure is still significantly high.

If the vessel material is in a brittle condition (through irradiation and/or temperature), the PTS event may propagate preexisting cracks and challenge the integrity of the RC pressure boundary. Its severity is thus increased if there is imperfect mixing of the cold SI water with the warmer RC water.

Extensive studies, both analytical and experimental, have been conducted in the USA but were restricted to the usual case where the High Pressure SI (HPSI) nozzles are located on the RC cold legs. This results in extensive mixing before the SI flow reaches the reactor vessel downcomer.

Since for the Doel 1 and 2 Belgian units, there is a direct HPSI into the reactor vessel downcomer, it was not valid to extrapolate the favourable results obtained by the available generic studies. Therefore, additional analytical and experimental studies of the specific flow mixing conditions were undertaken

For the analytical approach, an original simple 2D model has been developed by TRACTIONEL from the fundamental conservation equations and the semi-empirical "entrainment" correlation used in other similar industrial conditions, such as atmospheric stack release. This led to the inexpensive computer program TRAMIX which was further validated against a wide range of experimental data, mainly limited to non nuclear discharges into infinite stagnant environment.

For the experimental approach, a half scale mixing test facility was designed and operated jointly by TRACTIONEL and the University of Louvain (UCL), with the dual purpose of validating the analytical tool under the specific geometry and of gaining direct insight of the mixing pnenomena under representative conditions.

2. THE TRAMIX PROGRAM.

Previous analytical studies of the PTS mixing phenomena are either extremely complex and correspondingly expensive (e.g. the COMMIX code developed by EPRI)or purely based on empirical correlations from low temperature, scale testing for typical configurations of

SI nozzles on RC cold legs (e.g. the CREARE tests).

An alternative approach has been followed by TRACTIONEL on the basis of available literature related to similar conditions from other industrial fields (atmospheric stack release, underwater effluent discharge,...). A theoretical model was thus developed from the fundamental conservation equations and the semi-empirical "entrainment" correlation originally proposed by MORTON [1] and further detailed by ELLISON & TURNER[2], HIRST[3] and SCHATZMAN[4].

Neglecting wall friction losses and heat transfer, the relevant conservation equations for a cold water jet injected downwards in an infinite stagnant hot water environment are :

- mass conservation :

$$\frac{dw}{dz} = E \rho_\infty u p \qquad \text{eq. (1)}$$

where w denotes the mass flow rate, E the entrainment constant, ρ_∞ the density of the environment fluid, u the axial jet velocity and p the jet perimeter. The entrainment constant is a function of the Froude number.

- momentum conservation :

$$\frac{dwu}{dz} = \rho^* ag \qquad \text{eq. (2)}$$

where $\rho^* = \rho - \rho_\infty$

is the origin of the buoyant force, a the jet cross section and g the gravity

- energy conservation :

$$\frac{dwh}{dz} = h_\infty \frac{dw}{dz} \qquad \text{eq. (3)}$$

where h denotes the jet fluid enthalpy per unit mass, and h_∞ the corresponding quantity for the environment.

- state equation :

$$\rho = \rho(h) \qquad \text{eq. (4)}$$

A fifth equation relates the mass flow w to its contributive terms u, ρ and a and varies in accordance with the assumed distribution of u and ρ across a.

For the so called "top hat" distribution (a rather unrealistic assumption of uniform values within the jet, yielding nevertheless some representative and even semi quantitative results) one has

$$w = \rho u a \qquad \text{eq. (5)}$$

For to so called "gaussian" profile, which matches closely the observed distributions

$$w = \int_0^\infty \left[\rho_\infty + \rho^* e^{-\left(\frac{r}{x}\right)^2}\right] u \; e^{-\left(\frac{r}{x}\right)^2} da \qquad \text{eq. (6)}$$

where x is the jet width taken at location where maximum velocity is reduced by a factor of e, and r the radial coordinate (across the jet)

Other quantities like wu and wh can also be similarly expressed.

While the model remains basically 1D ("top hat") or 2D ("gaussian"), it can describe :

- 2D flow geometries such as the flow between 2 parallel plane walls at a distance b with :
  $p = 2\,b$
  $da = 2\,b\,dr$ eq. (7)
- 3D axisymmetric flow geometries with :
  $p = 2\pi r$
  $da = 2\pi r\,dr$ eq. (8)

A more convenient common set of reduced equations can be obtained as follows :

- all quantities are normalized to the jet value at the injection point (upper case letters)
- velocity, specific mass and temperature refer to the maximum value on the jet axis
- enthalpy is replaced by temperature T (°C) and the relative water density is expressed as an approximative analytical function of T
- subscript ∞ refers to environment, and subscript o refers to jet at injection point.
- the axial coordinate is normalized to the mixing diameter at injection point.

$$D = 4 \frac{\text{jet cross section}}{\text{jet mixing perimeter}} \qquad \text{eq. (9)}$$

, the following set of equation is obtained :

$$\frac{dw}{dz} = 4\ E\ R_{\infty}\ U\ X^{m-1} \qquad \text{eq. (10)}$$

$$\frac{d}{dz}\ (W\ U) = \frac{2n}{F_o}\ \frac{R - R_{\infty}}{1 - R_{\infty}}\ X^{m} \qquad \text{eq. (11)}$$

$$\frac{d}{dz}\ [\,W\ (T - T_{\infty})\,] = 0 \qquad \text{eq. (12)}$$

$$W = n\ x^{m}\ U\ (\ R_{\infty} + R^{*}/1)/1 \qquad \text{eq. (13)}$$

$$R = \frac{1 + k\ To^{2}}{1 + k\ T^{2}} \qquad (k = 4{,}3\ 10^{-6}) \qquad \text{eq. (14)}$$

wherein : F_o is the FROUDE number $= \dfrac{Uo^{2}/2}{g\ D\ R_o^{*}}$ eq. (15)

$Ro^{*} = (\rho_o - \rho_{\infty})/\rho_o$

the parameters 1, m and n depend on the assumed distribution

as follows :

	1	m	n
TOP HAT model	1	1	1
GAUSSIAN 2D flow	$\sqrt{2}$	1	$\sqrt{\pi/2}$
GAUSSIAN 3D flow	2	2	2

The hereabove model has been further improved to include the effect of :

- constant coaxial velocity of the environmental fluid
- different density of mixing fluid
- confined environment
- recirculation of the entrained fluid
- heat transfer from walls
- wall friction
- transitional behaviour between injection point and established flow with gaussian distribution.

The various features have been incorporated in the simple inexpensive computer program TRAMIX.

Results from the TRAMIX code have been validated against experimental data from a wide range of references, including :

- data from non nuclear industrial fields, as reviewed by CHEN & RODI / 5 /
- data from PTS mixing tests performed on scale mock-ups in the USA (on behalf of EPRI)
- data from a specific single case study conducted by CHAO and al / 6 / with the COMMIX code.

Reasonable agreement was reached in all cases (as exemplified in figures 1 and 2). However most experimental data were related to stagnant, quasi-infinite environments. Moreover the simplicity of the code implies some geometric limitations ; in particular it cannot model true 3D configurations, resulting e.g. from the presence of a thermal shield in the vessel downcomer.

An experimental approach was thus further used to confirm the TRAMIX code validation and identify its possible extrapolation to the actual vessel geometry.

3. THE MIXING TEST RIG.

A mixing test facility was designed and operated jointly by TRACTIONEL and U.C.L./TERM.

FIG 1/2*

The test mock up is basically a 1/2 scale 180° model of the reactor vessel, on basis of the following simplifying assumptions (see fig. 3).

With reference to a vertical section of the actual vessel, up to the CL injection point, (fig.3-a), 7 control volumes are defined (fig.3-b) : it is considered that the significant parameters to be modeled in the test rig are :

- the control volumes 1 to 6
- the sectional configuration of the volumes 1 to 3 in the area of water injection, i.e. a 90° sector including a CL nozzle and a SI nozzle.

The actual sectional configuration (fig.3-c) can be further approximated by a rectangular layout (one half of an "equivalent" square vessel) where the thermal inertia (vessel wall and thermal shield) are maintained only in the central part (fig.3-d).

Based on this approximation of the actual vessel which seems to be sufficiently representative for the mixing phenomena, the test mock-up is now scaled down by a factor of 2 or a factor of 8 for the non homothetic control volumes. Also the entire semi-rectangular vessel mock-up is immersed in a cylindrical test vessel which acts only as a pressure boundary. (fig.4).

This results in a test mock-up which is easy to build and modify ; this flexibility can be used for parametric variations (water volumes, heat slabs, removable "thermal shield",...)

The PTS vessel is incorporated in a test loop (fig. 5) which provides the several functions required :

- filling and draining
- system heating and pressurizing
- cold water injection, with adjustable flow partition between CL and downcomer
- hot water discharge.

The system design pressure is 11 bar (eff) which allows a maximum operating temperature of 188°C (corresponding to a density ratio : $R^* = 0.14$).

The SI flow rate is adjustable between 6 and 36 m^3/h and can be maintained for up to one hour ; the vessel SI nozzle is fully scaled.

The test instrumentation includes temperature measurements (50 thermocouples) and velocity measurements (8 Pitot tubes and 8 turbine flow meters).

The instrumentation probes can be located in any combination of the 148 holes possitionned in the 2 plates defining the downcomer (fig.6). Each position can also accept 2 probes (of the thermocouple or Pitot type); when 2 opposite locations (plates A and B) are so equipped, a four point measurement of the radial distribution of a paremeter through the downcomer is available.

A sophisticated data acquisition system allows a flexible monitoring of the tests and a quick "user friendly" interpretation of the test results.

The 64 instrument signals and some auxiliary signals (pressure, flow meters,...) are digitalized and recorded by the 80 channels data acquisition system. Scanning requires only 30 μs/channel so that the acquisition rate can be adjusted as required during tests (from.1 s for the first seconds after injection up to a few seconds for the latter part of long term transients).

A matrix of about 30 tests has been defined in order to evidence the effet of several parametric variations and allow comparison with the corresponding predictions of the TRAMIX code.

For the simplest configuration, such as a single injection without "thermal shield" this is aimed at further validation of the code while for more complex configurations such as dual injections and or impact on the thermal shield discontinuity, it should be possible to define the empirical adjustments required to extrapolate the code use.

The test are also aimed at a phenomenological understanding of the mixing phenomena in the higher range of temperature. Previous insight of this kind has been limited to :

- low temperature phenomena in non nuclear applications
- atmospheric testing of reactor vessel configurations (Creare 1/5 scale plastic models)
- few tests (2 available) at higher temperature (NRC-EPRI 1/2 scale mock-up at 188°C; CL injection only).

The first 5 tests were conducted without thermal shield, at the maximum temperature and a direct injection flow rate variable between 10 and 36 m^3/h. This allowed shakedown of the installation and instrumentation check-up ; an unexpected dissymetry was observed with respect of the SI nozzle (lateral jet deviation and isolation of a "hot water pocket" on one side of the nozzle). Test results are illustrated by fig. 7.

Comparing the axial temperature profiles deduced from the TRAMIX data and from the model (fig. 8), generally good agreement is obtained with a tendancy of the analytical model to be conservative since the observed mixing was better than predicted.

In order to remove the uncertainties created by the asymmetric behaviour, the mock-up has been modified to center the SI nozzle. Tests will be duplicated in the modified geometry before the matrix program is resumed.

4. CONCLUSION :

The parallel development of the analytical and experimental approaches will allow the proper evaluation of the mixing effect when the safety injection is performed directly in the vessel downcomer. Present validations of the TRAMIX program give confidence in the physical significance of the analytical model and its reliable application to actual PTS conditions. It is expected that the code limitations (no 3D capability) will be overcome by proper correlations with the experimental results.

First results from the mixing test rig are encouraging but need to be confirmed before final conclusions can be reached.

Acknowledgment
The authors are endebted to Mr. L. Vanhoenacker and Mr. J. Franco for their efficient assistance in preparing this paper.

REFERENCES

/1/ MORTON B.R., TAYLOR A.G. & TURNER J.S. "Turbulent Gravitational Convection from Maintained and Instantaneous Sources", Proc. Royal Society, Serie A, vol. 234 1-23 (1956)

/2/ ELLISON T.H. & TURNER J.S. "Turbulent Entrainment in Stratified Flows", Journal of Fluid Mechanics, VOL6, 423-448 (1959)

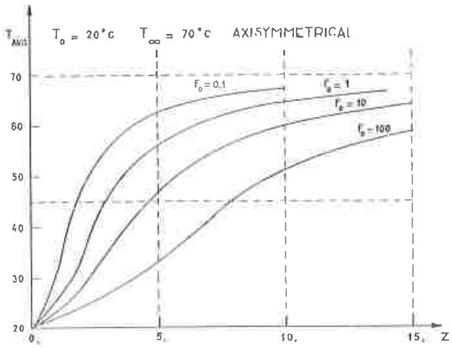
/3/ HIRST E.A. "Analysis of Round, Turbulent, Buoyant Jets Discharged to Flowing Stratified Ambients", report ORNL-4685 (1971).

/4/ SCHATZMANN M. "An Integral Model of Plume Rise" Atmospheric Environment, Vol 13, 721-731 (1979).

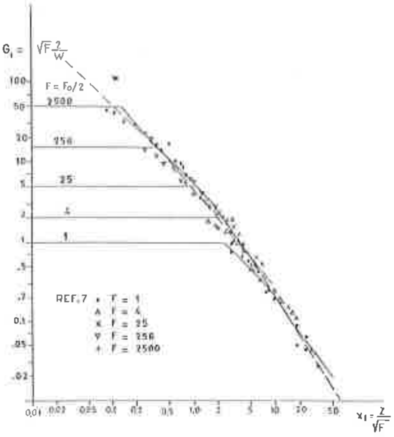
/5/ CHEN C.J. & RODI W. "Vertical Turbulent Buoyant Jets - A review of Experimental Data", Pergamon Press (1980)

/6/ CHAO J., LUNSFORD D., CHEXAL B. and LAYMAN W., "Analysis of Mixing with Direct Safety Injection into the Downcomer Region of a W Two-loop PWR", NSAC-63 (1984)

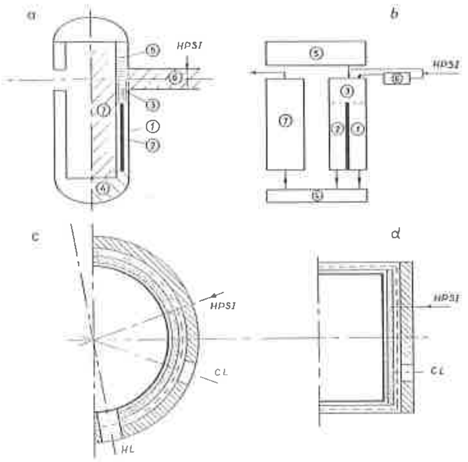
/7/ PRYPUTNIEWICZ J.R., BOWLEY W.W., "An experimental study of vertical Buoyant jets discharged into water of finite depth", Journal of heat transfer, 274-381 (1975).



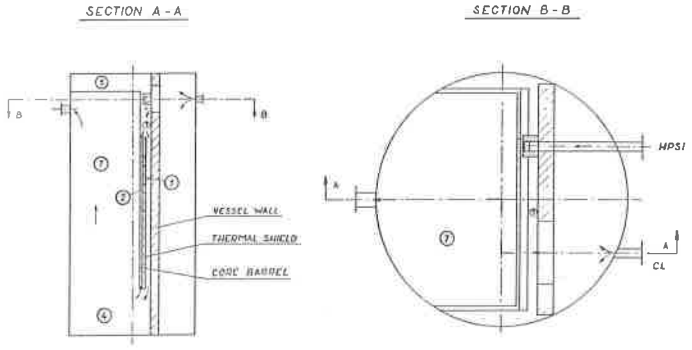
1 TRAMIX prediction of an an axisymetrical jet mean temperature (gaussian profile) as a function of the reduced axial distance, for several values of the Froude number. Temperature conditions are typical of the CREARE tests.



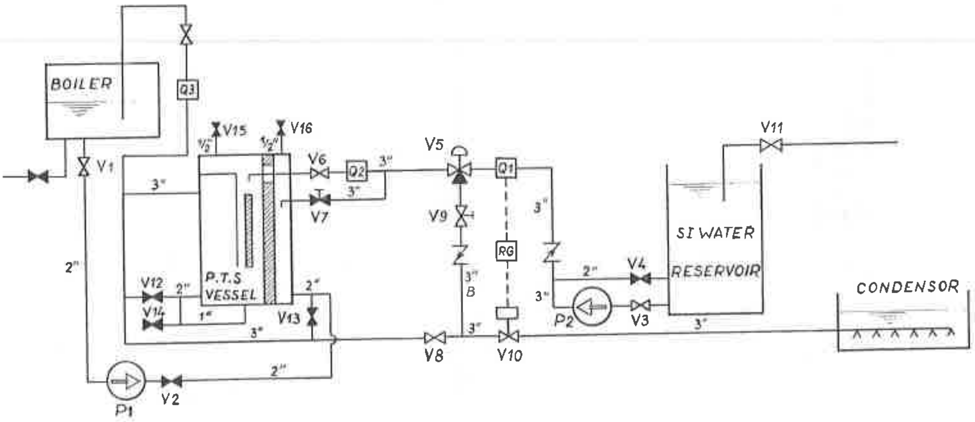
2 Comparison of the TRAMIX predictions (full lines) with an empirical correlation (dashed line) by CHEN & RODI. Only part of the test data is indicated.



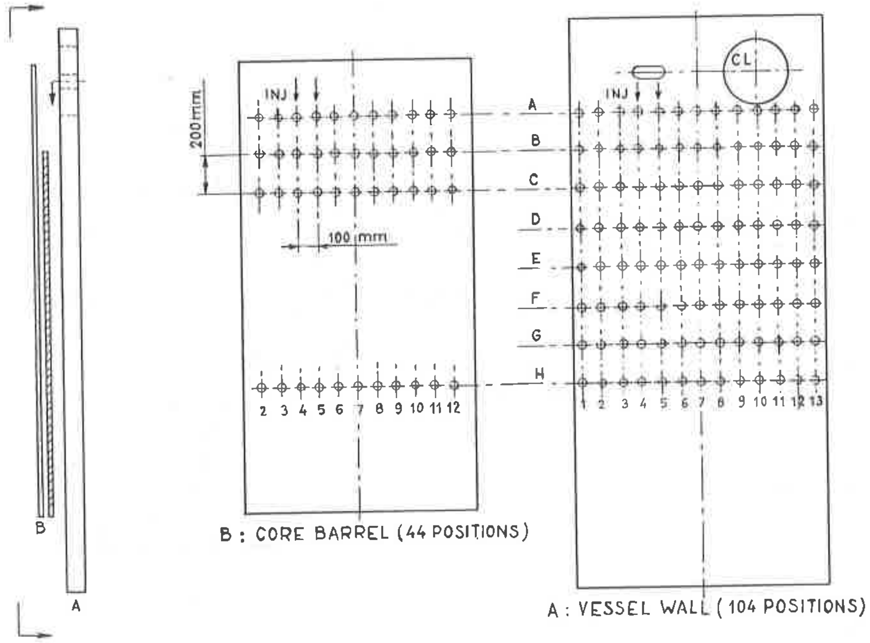
3 Reactor vessel modelization (not to scale)
(a) actual vertical section
(b) equivalent "control volumes"
(c) actual horizontal section (180°)
(d) equivalent rectangular layout



4 PTS test vessel



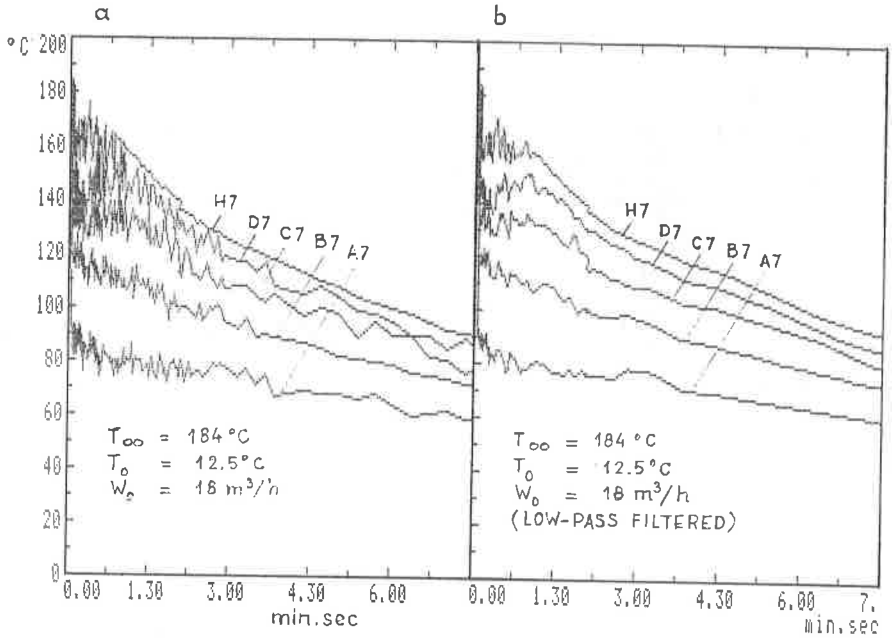
5 PTS test loop



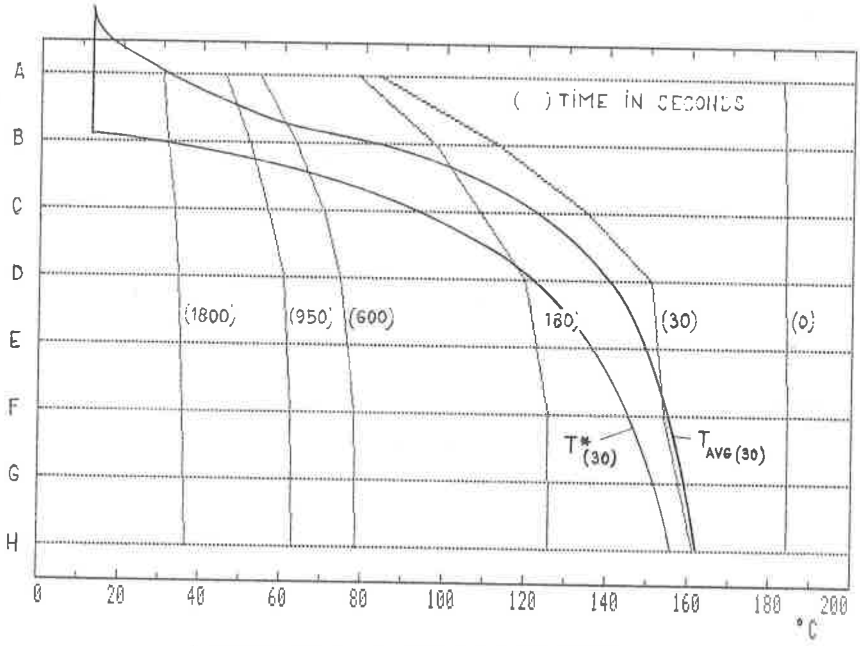
B : CORE BARREL (44 POSITIONS)

A : VESSEL WALL (104 POSITIONS)

6 PTS test instrumentation



7 PTS test results. Temperature measurements below a centered S.I. nozzle.
(a) recorded time history
(b) smoothed time history (numeric filter)



8 Comparison of test results (from fig 7) and TRAMIX predictions, (curves labeled T^*, T_{AVG}) for the temperature distribution below the SI nozzle.