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TEST PREDICTION FOR THE GERMAN PKL TEST K5A USING RELAP4/MOD6

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I. INTRODUCTION

RELAP4[1] is a computer code developed specifically to predict the transient thermal-hydraulic behavior of a PWR and related experimental reactor systems during postulated LOCA conditions. RELAP4/MOD6[2] is an extension of RELAP4/MOD5[3]. Several new analytical models have been added to the MOD5 version to extend the analysis capability for PWR reflood calculation.

This study was undertaken for the purpose of assessing RELAP4/MOD6 calculation capability during reflood. Results from West German PKL Test K5A were used for data comparisons. The heater rod temperature and the core mixture level are discussed.

The major new features in RELAP4/MOD6[a] include models for moving mesh core heat transfer, local entrainment, and core vapor superheat. In addition, the heat transfer logic has been modularized to facilitate changing boiling curves as may be dictated by a particular reactor system or transient. A new set of heat transfer correlations is available for PWR-BWR blowdown, as well as PWR reflood.

The core heat transfer model enables the user to finely partition, over a specified length, the input coarse heat slab conductors, thereby obtaining a more accurate description of heat transfer. The fine mesh partitioning will follow the quench front movement. Moving meshes can be used simultaneously in separate core channels (that is, for cold, average, or hot channels).

[a] RELAP4/MOD6 User's Manual can be obtained from the National Energy Software Center, 9700 South Cass Avenue, Argonne, Illinois 60439, U.S.A.

II. CORE SUPERHEAT MODEL

To improve the calculation of the surface heat transfer coefficient for both the moving mesh and coarse heat slab conductors, the local fluid properties can be calculated using the core superheat model. The superheat calculation begins by assigning a pseudovolume to each moving mesh or coarse heat slab. A steady state heat and mass balance is performed for each pseudovolume in the core region above the collapsed liquid level with a local fluid quality, a local vapor temperature, and a local mass flux computed for each slab. Liquid is assumed to be at saturation conditions throughout the core. However, vapor superheating is calculated and reflected in the convection term in the energy equation.

The core superheat model is based on the following:

(1) The mass flow rate above the collapsed liquid level is uniform during each time step

(2) Potential and kinetic energy terms in the energy equation are neglectable

(3) Energy partitioning function is internally generated to specify the fraction of stored energy being transferred from the heat slab to each phase

(4) The entrainment model calculates the entrained liquid drops and vapor mass flow rates at the interface between the collapsed liquid and steam dome.

The calculated local vapor and liquid mass flow rates at the point of entrainment are

$$W_g = \frac{\int_0^{Z_m} q dZ - W_{in} (h_{\ell_{sat}} - h_{in})}{h_{\ell_g}} \tag{1}$$

and

$$W_{\ell_{ent}} = EN (W_{in}) \tag{2}$$

where

Z = vertical distance from core inlet (m)

W_g = local vapor mass flow rate (kg/s)

q = local heat flux (W/m-s)

$W_{\ell_{ent}}$ = local entrained liquid mass flow rate (kg/s)

Z_m = height in core at which entrainment is initiated

W_{in} = liquid mass flow rate at core inlet (kg/s)

h_{ℓ_g} = latent heat vaporization (W/kg)

$h_{\ell_{sat}}$ = saturated liquid enthalpy (W)

h_{in} = enthalpy of liquid entering core (J/kg)

EN = entrainment fraction specified.

For each pseudovolume assigned to a heat slab above the mixture level, the mass balance is

$$W_{\ell_{out}} = W_{\ell_{in}} - \frac{\lambda Q}{h_{\ell_g}} \quad . \tag{3}$$

$$W_{g_{out}} = W_{g_{in}} + \frac{\lambda Q}{h_{\ell_g}} \tag{4}$$

where

λ = energy partition function = fraction of total heat flux, Q, going into liquid phase

Q = heat transfer rate (W/s)

$W_{\ell_{out}}$ = outlet liquid mass flow rate (kg/s)

$W_{\ell_{in}}$ = inlet liquid mass flow rate (kg/s)

$W_{g_{out}}$ = outlet vapor mass flow rate (kg/s)

$W_{g_{in}}$ = inlet vapor mass flow rate (kg/s).

The overall energy balance is

$$W_{\ell_{in}} h_{\ell_{sat}} + W_{g_{in}} h_{g_{in}} + Q = W_{g_{out}} h_{g_{out}} + W_{\ell_{out}} h_{\ell_{sat}} \quad . \tag{5}$$

Equation (5) yields

$$h_{g_{out}} = \frac{Q + (W_{\ell_{in}} - W_{\ell_{out}})\, h_{\ell_{sat}} + W_{g_{in}}\, h_{g_{in}}}{W_{g_{out}}} \quad . \qquad (6)$$

The result may be equated to

$$h_{g_{out}} = h_{g_{sat}} + C_p(T)\, [T_{out} - T_{sat}] \qquad (7)$$

yielding the outlet vapor temperature T_{out}, where

$h_{g_{out}}$	=	outlet vapor enthalpy (J/kg)
$h_{g_{in}}$	=	inlet vapor enthalpy (J/kg)
T_{out}	=	outlet vapor temperature (K)
T_{sat}	=	outlet saturation temperature (K)
T	=	temperature (K)
$C_p(T)$	=	vapor specific heat (J/kg-K)
$h_{g_{sat}}$	=	saturated vapor enthalpy (J/kg).

III. ENTRAINMENT MODELS

Entrainment phenomena during reflood can be analyzed using a number of options in MOD6. Presently the modified Steen-Wallis[4] model is the recommended model. This model is based on an annular flow droplet entrainment correlation that was developed for fully developed turbulent flow. The critical superficial vapor velocity for the onset of entrainment is defined by

$$j_{g_{crit}} = HC2 \left(\frac{\rho_\ell}{\rho_g}\right)^{1/2} \left(\frac{\sigma}{Ug}\right) \qquad (8)$$

where

ρ_ℓ	=	liquid density (kg/m^3)
ρ_g	=	vapor density (kg/m^3)
σ	=	surface tension (N/m)

Ug = vapor viscosity (N-s/m)

HC2 = user-input constant.

Entrainment commences when the volumetric flux of vapor generation due to the heat transferred to the collapsed liquid exceeds the critical vapor velocity. Once entrainment is initiated the fraction of core inlet liquid flow being entrained is given by

$$EN = EN2 \left[1 - e^{-HC1 \left(V_g^* - HC2\right)}\right] \tag{9}$$

where

EN2 = user-input maximum entrainment fraction

HC1 = user-input constant

$V_g^* = \frac{j_g \mu_g}{\sigma} \left(\frac{\rho_g}{\rho_\ell}\right)^{1/2}$ = dimensionless vapor velocity

j_g = volumetric flux of vapor based on core area (m/s).

IV. REFLOOD HEAT TRANSFER CORRELATIONS

Figure 1 details the RELPA4/MOD6 reflood heat transfer correlations and their regions of application.

A nonequilibrium state of superheated vapor and saturated liquid is allowed to exist in the core during reflood. The method used to represent this nonequilibrium state is similar to that used by Kirchner[5]. Heat transfer correlations representing different heat transfer mechanisms are combined to obtain the heat flux into each phase component. This partitioning is then available for use in the nonequilibrium core model.

V. RELAP4/MOD6 PREDICTION FOR THE GERMAN PKL TEST K5A

The present study was undertaken for the purpose of evaluating the predictive capability of RELAP4/MOD6. The concept of a "blind" test prediction was utilized in which the investigator has no prior exposure to the specific experimental data he is attempting to predict. One of the presently available data sources for reflood study is the cold-leg break reflood Test K5A at the Kraftwerk Union (KWU) PRIMAR KREISLAUF (PKL) experimental facility[6,7] in Erlangen, West Germany.

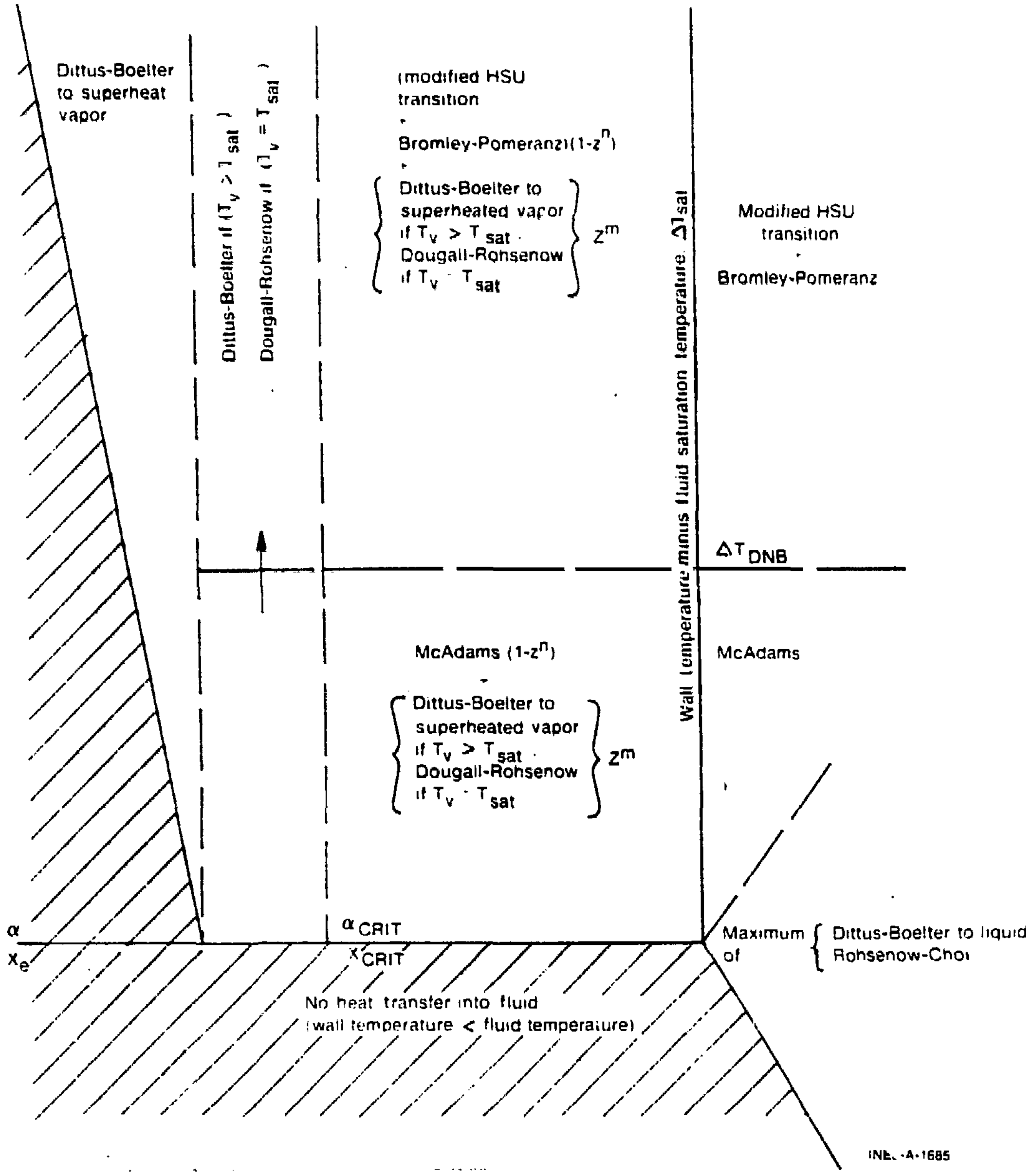

Fig. 1 RELAP4/MOD6 reflood heat transfer correlations and their regions of application.

1. FACILITY DESCRIPTION AND TEST CONDITIONS

The PKL facility is a three-loop simulation of a West German pressurized water reactor, fabricated in a reduced scale that maintains prototype volume-to-power ratio. It was designed specifically for system experiments simulating the reflood phase of hypothetical LOCA accidents. The full length electrically heated 340-rod core is divided into hot, average, and cool channels and has an overall power capacity of 1.45 MW and a peak power of 1.5 kW/m. Test K5A was a 200% cold-leg break experiment with an initial system pressure of 0.42 MPa. The emergency core coolant was injected into the intact loop, cold legs, and into the upper annulus. The coolant was at 100 K subcooling. The average injection rate for the first 35 seconds was about 15.5 kg/s: Thereafter, the rate was suddenly reduced to between 10.5 and 6.8 kg/s. The initial cladding temperature at the 2-m elevation was 833 K. The secondary side of the steam generators were initialized at 544 K with a saturated liquid level at 7.5 m.

2. RELAP MODEL OF THE SYSTEM

To model the PKL facility for Test K5A, RELAP4/MOD6 standard modeling procedures and guidelines for input parametric values were employed. The RELAP4 PKL model consists of 37 control volumes, 40 nodes, and 50 heat conductors as shown in Figure 2. Thirty-six heat conductors were used in the core volume to simulate the experimental electrical heater rods. Fourteen heat conductors were also used to model steam generators, the upper annulus, and downcomer walls. One volume, representing the containment system with its suppression tank and phase separators, was assigned pressure time dependency. One junction was assigned as a fill junction for injection of ECC water.

Calculation of system behavior was initiated with the experimental system filled with saturated steam and representative rods in each of the three electrically isolated core sections at prescribed surface temperatures. ECC injection was initiated in this environment at time equals zero seconds.

The system model has three loops, one broken and two intact (one of which is of double size), to represent a four-loop PWR. Three steam generators and three simulated pump volumes are used. The break was modeled in the cold leg, between the simulated pump and the upper annulus vessel. The downcomer and upper annulus were represented by a U-tube concept incorporating a steam bypass pipe between the lower plenum and the upper annulus. The new MOD6 models for liquid entrainment, vapor superheating, reflood heat transfer, and the moving heat conduction mesh model for tracking the quench front (moving mesh) were implemented in the three core channels for calculating reflood phenomena.

3. DATA COMPARISONS

The RELPA4/MOD6 predicted results of the PKL K5A reflood test compared well with the experimental thermal and hydraulic system data. Comparisons included heater rod surface temperature, system pressure, mass flow rates, and core mixture level. Figure 3 shows the heater rod temperature at the hot spot elevations and the 1.26-m elevation in the hot core channel. At the 1.26-m elevation, RELAP4/MOD6 overpredicted the maximum temperature rise by about 30 K. At the hottest spot, both the test data and RELAP4/MOD6

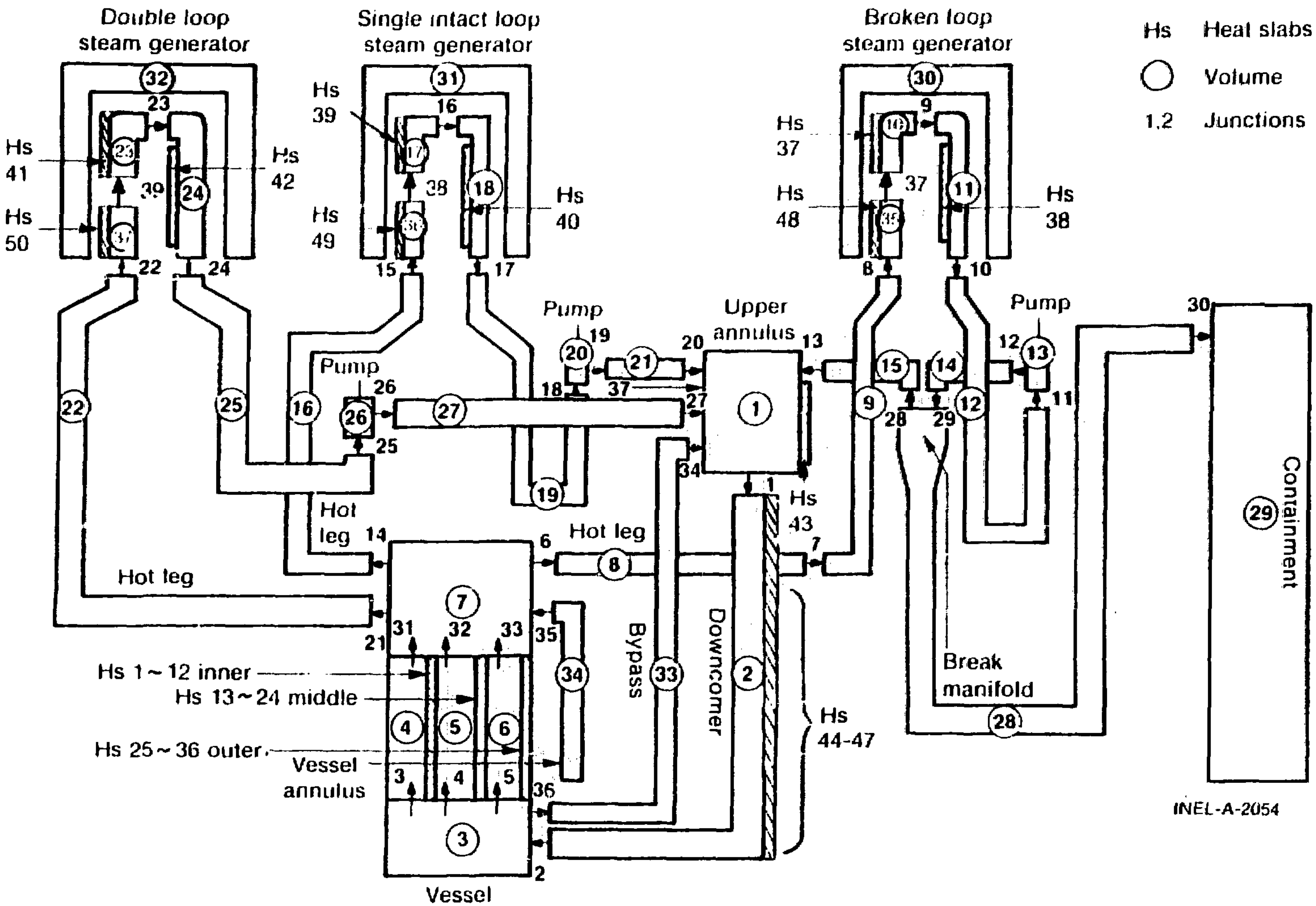

Fig. 2 PKL three-loop RELAP4/MOD6 nodalization.

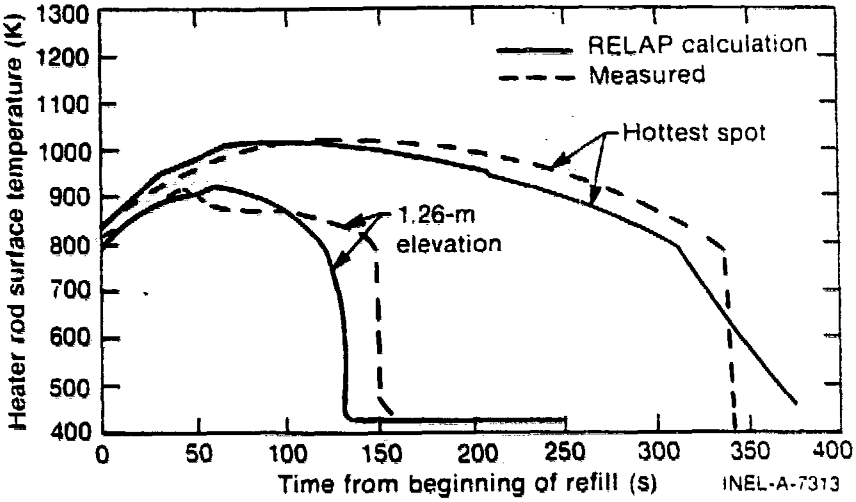

Fig. 3 Comparison of calculated and measured heater rod surface temperature for PKL reflood Test K5A.

calculations give the same maximum rod surface temperature of 1020 K. Figure 3 also indicates that RELAP4/MOD6 underpredicted the quench time by only 25 seconds when compared with the test data. Figure 4 shows that the predicted average core mixture level is in good agreement with the test data; the predicted value at the transient time of 100 and 300 seconds is, respectively, about 10% and 25% higher than the experimental values.

4. CONCLUSIONS

RELAP4/MOD6 is a computer code developed specifically to predict the transient thermal-hydraulic behavior of a PWR and related experimental reactor systems during

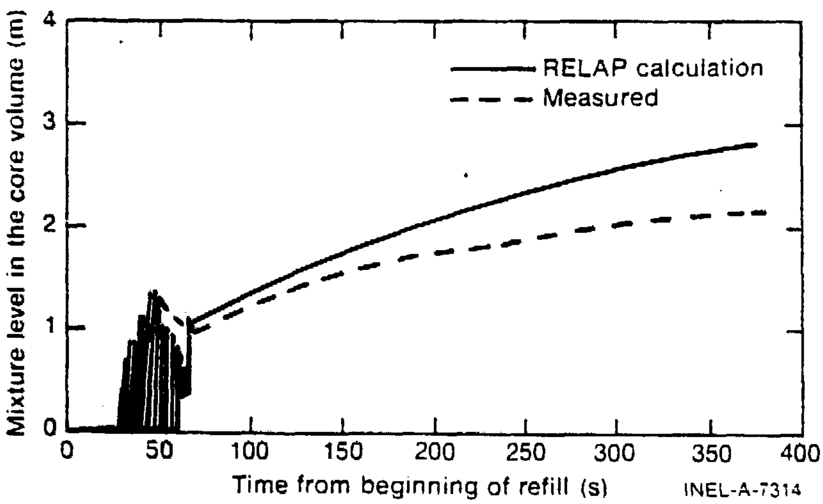

Fig. 4 Comparison of calculated and measured core mixture level for PKL reflood Test K5A.

reflood phase of postulated LOCA conditions. A "blind" test prediction for the German PKL reflood Test K5A was conducted using RELAP4/MOD6. The results of the prediction were in good agreement with experimental data indicating that RELAP4/MOD6 is capable of predicting transient reflood phenomena in the 200% cold-leg break test configuration of the PKL reflood facility.

VI. REFERENCES

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