REMI/HEAT COOL, a computer programme for calculation of core heat up with spray cooling

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REMI/HEAT COOL A COMPUTER PROGRAMME FOR CALCULATION OF CORE HEAT UP WITH SPRAY COOLING.

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Abstract

REMI/HEAT COOL is a computer programme for calculation of core heat up transients. The code determines the temperature transient of the fuel, and evaluates the influence of emergency core coolant, i.e. spray cooling. REMI/HEAT COOL is based on separate description of the steam and water phase in the primary system, and a detailed description of the radiative heat transfer between the fuel rods and the shroud. The latter does involve a determination of the absorption of thermal radiation in the two-phase flow. Furthermore the programme considers the decay heat, metal-water reaction, heat transfer due to conduction and convection, and the film flow on rods and shroud.

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CONTENTS.

1. INTRODUCTION.

1.1. Object of the Study.

The hydraulic and thermal safety analysis is an essential part of the whole complex of safety evaluations in nuclear power plants. It is vital to know the course of a possible accident in order to be able to predict its consequenses, and, what may be more important, to be able to design a safety system which effectively can reduce the consequenses of a possible accident.

The loss of coolant accident based on the assumption of a circumferential rupture with unobstructed discharge from both ends of the largest pipe is assumed to be the max. credible accident in a BWR or a PWR.

The main part of the coolant will be blown out of the reactor system in short time, leaving the core without cooling, if an emergency core cooling system (ECCS) is not brought into operation.

This report describes the computer program REMI/HEAT COOL, which is part of a set of programmes, aimed at the calculation of the reactor core response to a postulated loss of coolant accident.

REMI/HEAT COOL takes over the calculation of the core heat up, when the blow down is ceased, and the convective heat transfer is reduced so much, that the thermal radiation plays an essential role in the overall heat transfer.

Steam flow through a fuel element is calculated during the thermal radiation period considering the reactor core flow system as a closed loop consisting of core region, upper plenum,downcomer region, and lower plenum with possible remaining coolant water. The rupture may be chosen in the upper plenum corresponding to a steam line rupture or in the lower plenum corresponding to recirculation line rupture.

Pumps may be included by specification of the cross section in the downcomer region.

The energy production in the fuel is the decay heat, specified by the user, and the metal-water reaction, which may be limited either by the temperature (the parabolic law) or the steam concentration. Together with this and the heat transfer rate, convective and radiative, to the two-phase flow, the temperature distribution in the fuel rods is determined, using a finite difference approximation to the Fourier equation. A separate description of the steam and water phase is used in the two-phase flow, and combined with the equations for conservation of mass, momentum and energy, and the equation of state, the flow is determined. The film-flow on the fuel rods and the shroud

is calculated, using Yamanouchi's theory.

Multiple reflections are taken into account in the calculation of the radiative interchange. Total view factors, as derived by Hottel and Sarofim[10] are calculated from geometric view factors and emissivities of the solid surfaces. The transmissivity of the water droplets is taken into account, when ECC is in operation. The energy absorbed in the droplets is used to evaporation of the droplets.

1.2. Motivation.

The steam flow may be countercurrent or co-current to the spray coolant.

The direction of the steam flow and flow rate will affect the concentration and the sizes of droplets, which can advance down through the coolant channel. The concentration of droplets depends further of the supplied ECC - flow rate. For the same ECC - flow rate the concentration will increase with increasing countercurrent steam flow rate. The mean diameter of the advancing droplets will increase. If the concentration increase too much, there may be a risk for the droplets to combine and form bridges, which may result in instabilities and in the worst case obstruct the emergency cooling. An increasing mean diameter of the advancing dropelts will also mean an increasing transmissivity for the thermal radiation. The overall heat transfer will therefore also be affected.

The multiple reflection is the only possibility for the center rods to exchange energy with the non-heated and therefore easier wettable shroud. Due to the same reason a good knowledge of the real reflectivities of the solid surfaces is of importance.

2. THE THERMODYNAMIC - HYDRAULIC MODEL.

The thermodynamic - hydraulic model of REMI/HEAT COOL does include a detailed description of

1. The energy production arising from the fission product decay heat and the metal - water reaction.
2. The heat transfer in the fuel due to thermal conduction and the loss of energy from the fuel to the two-phase flow in the primary circuit due to convection and thermal radiation.
3. The two-phase flow in the primary circuit, based on a separate description of the two phases. The interchange of mass, momentum and energy between the two-phases are considered.

The geometry of the model, and the division of the primary circuit into regions are shown in figure 2.1. The number of regions and the number of fuel rods in the element may be chosen arbitrarily.

2.1. The Energy Production.

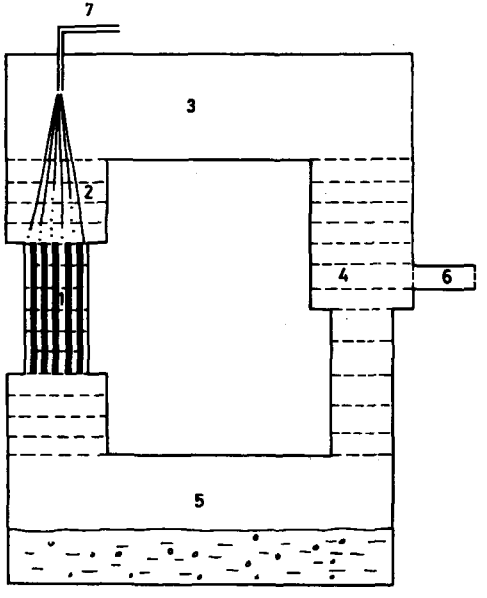
The energy production in the fuel element does arise from the decay of the fission products built up in the fuel, and from the chemical reaction between the cladding material, mostly zirconium, and the steam.

2.1.1. The Decay Heat.

The fission product decay heat are assumed everywhere to be proportional to the nuclear power in the fuel before the loss of coolant accident. The time dependence of the decay heat are calculated through interpolation in a tabel, describing a decay heat curve specified by the user.

2.1.2. Metal - water reaction.

At sufficiently high temperatures the cladding material, mostly zirconium, will react with the steam in the core.



1. Core
2. Riser
3. Upper plenum
4. Downcomer
5. Lower plenum
6. Leak
7. Emergency core spray system.

Fig.2.1. The primary circuit.

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 + Q$$

where $Q = 6.669 \cdot 10^6 - 0.257\ 10^3\ T_c$ J/kg Zr

and T_c is the temperature of the cladding, °C.

Provided sufficiently steam is available the reaction rate will be determined by the parabolic law [1]

$$\frac{ds}{dt} = -\frac{K}{s} \exp\left(\frac{-\Delta E}{R(T_c + 273)}\right) \text{ m/sec.} \qquad (2.1.1)$$

where s is the thickness of the ZrO_2 layer
$K = 0.3937 \cdot 10^{-4}$ m^2/sec.
$\Delta E = 1.905 \cdot 10^5$ J/mole
$R = 8.318$ J/mole °C, the gas constant.

In the case where sufficient steam is not available in order to maintain this reaction rate, the reaction rate is determined through diffusion of steam through a hydrogen film at the cladding surface. The mass transfer rate is given by [2]

$$\dot{M}_H = \varrho_g h_g \text{ kg/m}^2\text{sec.}$$

$$h_g = \frac{Nu\ D_g}{De} \qquad (2.1.2)$$

where ϱ_g is the density of the steam, kg/m^3
h_g a mass transfer coefficient, m/s
Nu the Nusselt number

$D_g = \frac{4.16 \cdot 10^{-4}}{P} (T_g + 273)^{1.75}$ m^2/s is the diffusivity of steam in hydrogen

De the hydraulic diameter, m
P the pressure, N/m^2
T_g the temperature of the steam, °C.

The type of process which gives the minimum reaction rate is then used in the calculation.

2.2. The Temperature Distribution in the Fuel.

The fuel element may be divided in an arbitrary number of groups of rods, assuming that the rods in a group have identical temperature distributions. For a rod representing each group the Fourier equation for thermal conduction is solved.

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q \qquad (2.2.1)$$

or in cylindrical coordinates, assuming rotational symmetry.

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} (rk \frac{\partial T}{\partial r}) + \frac{\partial}{\partial z} (k \frac{\partial T}{\partial z}) + Q \qquad (2.2.2)$$

where ρ is the density , kg/m^3
c the heat capacity , J/kg^oC
T the temperature , ^oC
t the time, sec.
r the radius , m
z the axial position , m
k the thermal conductivity , W/m^oC
Q the energi production , W/m^3

The boundary conditions are, a heat transfer coefficient for the gas gap, it may be specified by the user, and the heat flux at the surface of the fuel rods. For the ends of the fuel rods it is assumed that there is no heat transfer in the axial direction.

The Fourier equation for thermal conduction together with the boundary conditions, are solved using a finite difference method, together with a predictor-corrector integration technique.

The material properties used may be temperature dependent, the properties used in REMI/HEAT COOL are [2]

$\rho_{UO_2} = 10.2 \cdot 10^3 \ kg/m^3$

$\rho_{Zr} = 6.4 \cdot 10^3 \ kg/m^3$

$\rho_{ZrO_2} = 5.6 \cdot 10^3 \ kg/m^3$

$c_{UO_2} = 295 + 3.14 \cdot 10^{-2} \ T \ J/kg \ ^oC$

$c_{Zr} = 344 \ J/kg^oC$

$c_{ZrO_2} = 620 \ J/kg^oC$

$k_{UO_2} = 4.80 - 3.58 \cdot 10^{-3} \ T + 1.05 \cdot 10^{-6} \ T^2 \ W/m \ ^oC$

$k_{Zr} = 17.2 \ W/m^oC$

$k_{ZrO_2} = 26.0 \ W/m^oC$

The thermal conductivity used for the cladding are

$$k_c = \frac{k_{Zr} \ k_{ZrO_2}}{(1 - x) \ k_{ZrO_2} + x \ k_{Zr}} \qquad (2.2.3)$$

where x are the fraction of the cladding reacted with the steam.

2.3. The Two-Phase Flow in the Primary System.

The two phases in the flow are treated independently *), but coupled through the interchange of mass, momentum and energy. Furthermore, thermal equilibrium is not assumed to exist between the phases, and a heat transfer coefficient are specified.

The equations used for the calculation of the flow in the primary system, are the equation of state **) and the three equations for conservation of the mass, momentum and energy. The boundary conditions used, are the geometry of the model, as shown in fig. 2.1, the emergency core cooling spray system, and the heat transfer from the fuel to the two-phase flow.

2.4. The Steam Flow in the Primary System.

The determination of the steam flow in the primary system is based on a solution of the equation of state

$$T_g = T_g\,(\,Hg,\ P) \tag{2.4.1}$$

and the three equations for conservation of mass,

$$\frac{\partial \varrho_g}{\partial t} = -\frac{\partial}{\partial z}\,(\varrho_g V_g) + \dot{m} \tag{2.4.2}$$

* The normally used method, where the two phases are treated as one, and the quality and the slip ratio are specified, are of little value for this type of problems, because steam and water flow in opposite directions are likely to occur.

** In order to obtain solution to the equations without too large a consumption of computer time, a set of polynomials in two independent variables, describing the properties of steam and water, was developed. The polynominals are based on VDI[3], and within the parameter range of interest they fit the tabels to ± 5%.

conservation of momentum,

$$\varrho_g \frac{\partial V_g}{\partial t} = -\varrho_g V_g \frac{\partial V_g}{\partial z} - \frac{\partial p}{\partial z} - \varrho_g G - \frac{\partial F_g}{\partial z} + \dot{b} + \dot{m}\,(V'_g - V_g) \tag{2.4.3}$$

and conservation of energy

$$\frac{\partial}{\partial t}\left[\varrho_g\,(H_g - \frac{p}{\varrho_g} + \tfrac{1}{2}V_g^2 + zG)\right] = -\frac{\partial}{\partial z}\left[\varrho_g V_g (H_g + \tfrac{1}{2}V_g^2 + zG)\right] + Q_g \tag{2.4.4}$$

$$Q_g = q_g + \dot{m}\,(H'_g + \tfrac{1}{2}V'^2_g + z\,G)$$

where T_g is the temperature, °C

H_g the enthalpy, J/kg

P the pressure, N/m^2

ϱ_g the density, kg/m^3

V_g the velocity, m/sec

$\dot{m}$ the interchange of mass between the phases, kg/sec.

$G = 9.81$ m/sec^2 is the gravity

$\frac{\partial F_g}{\partial z}$ the friction to the channel wall, kg/m sec^2

$\dot{b}$ the momentum interchange between the phases

$$V'_g = \begin{cases} V_l & \text{for evaporation, } \dot{m} > o, \text{ m/sec.} \\ V_g & \text{for condensation, } \dot{m} < o, \text{ m/sec.} \end{cases}$$

Q_g the energy production, W/m^3

q_g the energy transfer from the boundary + the energy interchange with the water, W/m^3

$$H'_g = \begin{cases} H_{g,\,sat} & \text{for evaporation, } \dot{m} > o, \text{ J/kg} \\ H_g & \text{for condensation, } \dot{m} < o, \text{ J/kg} \end{cases}$$

and the subscripts g refer to the steam

l to the liquid

sat to the state of saturation.

A direct integration of these equation will normaly require large computer times. This is due to the fact that the solution will become instable if not [4]

$$\frac{\Delta t}{\Delta z}\,(|V_g| + c) < 1 \qquad (2.4.5)$$

where $c = \sqrt{\dfrac{\dfrac{p}{\rho_g^2} - \dfrac{\partial e_g}{\partial \rho_g}}{\dfrac{\partial e_g}{\partial P_g}}}$ is the velocity of sound

e_g is the internal energy of the steam

Δt is the time step used

Δz is the node length.

(2.4.5) will normally lead to

$$\Delta t < 1 \text{ m sec.}$$

However, for the core heatup and emergency core cooling transients, sonic phenomenas are of little importance and interest, and a suppression of these phenomenas [4] will normally allow an increase of the used time step with up to two orders of magnitude, with an equivalent reduction of the computation time. This is equivalent to the theory of an incompressible fluid. The stability requirement now becomes

$$\frac{\Delta t}{\Delta z}\,|V_g| < 1 \qquad (2.4.6)$$

Suppressing the sonic phenomenas the equation for conservation of momentum (2.4.3), and energy (2.4.4) will be reduced to

$$o = -\rho_g V_g \frac{\partial V_g}{\partial z} - \frac{\partial P}{\partial z} - \rho_g G - \frac{\partial F_g}{\partial z} + \dot{b} + \dot{m}\,(V_g' - V_g) \qquad (2.4.7)$$

$$\frac{\partial V_g}{\partial t} = o \qquad (2.4.8)$$

$$\frac{\partial \rho_g}{\partial t}\,(H_g + \tfrac{1}{2}V_g^2 + zG + \rho_g \frac{\partial H_g}{\partial \rho_g}\Big|_p) = \frac{\partial}{\partial z}\left[\rho_g V_g (H_g + \tfrac{1}{2}V_g^2 + zG)\right] + Q_g \qquad (2.4.9)$$

$$\frac{\partial P}{\partial t} = o \qquad (2.4.10)$$

$$\frac{\partial H_g}{\partial t} = \frac{\partial H_g}{\partial \rho_g}\Big|_p \frac{\partial \rho_g}{\partial t} \qquad (2.4.11)$$

Whereas the equation for conservation of mass (2.4.2) is unchanged.

2.5. The Behaviour of the Emergency Core Spray Water.

The spray water will be injected into the reactor through a set of nozzels placed in the upper plenum of the reactor tank. The liquid jet formed at nozzels will, due to the Raleigh instability and the interaction with the steam atmosphere, be unstable and after a short distance of travelling break up into an array of liquid droplets. Due to the high velocity and the thereby high Weber number of the droplets, the droplets will break up into smaller droplets on their way down to the core. Dependent on the size and velocity of the droplets, and on the velocity and density of the steamflow, only a fraction of the spraywater will reach the core, and provide a cooling. The rest of the spray water, mainly the small droplets will be swept away with the steam flow, and will not provide any cooling of the core.

Accordingly it is very important to calculate the break up of the jets, formed at the spray nozzels, into droplets and their subsequent break up into smaller droplets, in order to obtain a good estimate of

1. The amount of spray water, available for the cooling of the core.
2. The spectrum of the dropsize.

The last one is especially important, because the absorption of thermal radiation in the two-phase mixture in the core, is strongly dependent on the dropsize. And it should be notised that this absorption is the most important mechanism for cooling of the hot fuel during the core heat up transients.

2.5.1. The Break up of Liquid Jets.

A pertubation on a liquid jet will grow exponentially, and neglecting the viscosity it can be shown [5, 6] that the growth rate will be determined by

$$\omega^2 = \frac{\sigma}{2\rho_1 r_j^3}(kr_j)^2\left\{1 - (kr_j)^2 + kr_j\frac{We_j}{2}\right\} \qquad (2.5.1)$$

where σ is the surface tension, N/m.

r_j the radius of the jet, m.

k the wave number of the pertubation, m^{-1}.

$We_j = \frac{2r_j \rho_g u_j^2}{\sigma}$ is the Weber number of the jet.

u_j the velocity of the jet, m/sec.

The maximum growth rate occur for

$$kr_j = \frac{3}{16}We_j + \sqrt{\left(\frac{3}{16}We_j\right)^2 + \frac{1}{2}} \qquad (2.5.2)$$

Experiments shows that a jet will break up in accordance with (2.5.2), and then we obtain the dimension of the produced droplets.

$$d_o = 2r_o\left\{\frac{3\pi}{\frac{3}{8}We_j + \sqrt{\left(\frac{3}{8}We_j\right)^2 + 2}}\right\}^{\frac{1}{3}} \qquad (2.5.3)$$

Combining (2.5.2) and (2.5.1) the time until break up of the jet is obtained

$$t_j = \frac{\ln\left(\frac{r_o}{\Delta r}\right)}{\left(\frac{\sigma}{2\rho_1 r_o^3}\right)^{\frac{1}{2}}\left\{\frac{3}{16}We_j + \sqrt{\left(\frac{3}{16}We_j\right)^2 + \frac{1}{2}}\right\}\left\{\frac{1}{2} + \frac{3}{128}We_j^2 + \frac{We_j}{8}\sqrt{\left(\frac{3}{16}We_j\right)^2 + \frac{1}{2}}\right\}^{\frac{1}{2}}} \qquad (2.5.4)$$

The break up length of the jet is now easily obtained

$$L_j = u_j t_j$$

$$= r_o \ln\left(\frac{r_o}{\Delta r}\right)\sqrt{\frac{\rho_1}{\rho_g}}\frac{\sqrt{We_j}}{\left\{\frac{3}{16}We_j + \sqrt{\left(\frac{3}{16}We_j\right)^2 + \frac{1}{2}}\right\}\left\{\frac{1}{2} + \frac{3}{128}We_j^2 + \frac{We_j}{8}\sqrt{\left(\frac{3}{16}We_j\right)^2 + \frac{1}{2}}\right\}^{\frac{1}{2}}} \qquad (2.5.5)$$

where Δr is an initial pertubation to the surface of the jet. Comparison of equation (2.5.5) with experiments does indicate that Δr should be taken to the mean free path of the liquid molecules.

The break up length, as predicted by (2.5.5) must be regarded as an ideal maximum jet length, f. ex. violent turbulence will reduce the break up length. Another important fact is, that for high values of the Weber number, the viscosity of the liquid has to be considered. The influence of the viscosity will increase the break up length, i. e. the instability will be damped.

2.5.2. The Break Up of Droplets.

When a droplet is travelling through a gas with a velocity u_d, the droplet will be deformed due to the drag on the droplet. If the Weber number of the droplet is larger than 13 this deformation will cause a break up of the droplet into several smaller droplets.

Assuming no break up of the droplet, the drag will cause the droplet to oscillate about a certain critical deformation, determined as the deformation where the sum of the outside pressure and the pressure arising from the surface tension is constant over the droplet. If the droplet maintain the shape of an elipsoid during the deformation, the critical deformation is determined by

$$\alpha^{\frac{1}{2}} + \alpha^{-\frac{5}{2}} - \gamma^2 = C_D' We_d \qquad (2.5.6)$$

$$\alpha = \frac{d_x}{d_o}$$

where d_o is the initial diameter of the droplet

d_x the thickness of the droplet in the flow direction

$We_d = \frac{d_o \rho_g u_d^2}{\sigma}$ is the Weber number

ρ_g is the density of the gas

u_d the velocity of the droplet

σ the surface tension

$C_D' = \min(0.5, C_D)$

C_D is drag coefficient.

From various experiments it is known that if $We_d > 13$ the droplet will break up, and maintaining the surface energy it can be shown that the droplet will break up into n droplets *)

$$n = \left\{ \frac{1}{2\alpha} + \sqrt{\alpha} \frac{\ln\left(\alpha^{-\frac{3}{2}} + \sqrt{\alpha^{-3} - 1}\right)}{2\sqrt{\alpha^{-3} - 1}} \right\}^3 \qquad (2.5.7)$$

and with the diameter d_1,

$$d_1 = d_o \left\{ \frac{1}{2\alpha} + \sqrt{\alpha} \frac{\ln\left(\alpha^{-\frac{3}{2}} + \sqrt{\alpha^{-3} - 1}\right)}{2\sqrt{\alpha^{-3} - 1}} \right\}^{-1} \qquad (2.5.8)$$

---

*) A droplet can at least break up into two smaller droplets, and if this is the case it can easily from (2.5.7) and (2.5.6) be shown that $We_d = 13$, which is in accordance with the experiments.

The velocity of the droplet and thereby the Weber number at the moment of break up, can be obtained through an integration of

$$\frac{\partial^2 \alpha}{\partial t^2} = -\frac{9}{8} \left(\frac{u}{r_o}\right)^2 \frac{\rho_g}{\rho_l} \left\{ 2C_D' + \frac{2}{We_d} \left(2\alpha^2 - \sqrt{\alpha} - \alpha^{-\frac{5}{2}}\right) \right\} \sqrt{\alpha} \qquad (2.5.9)$$

$$\frac{4}{3} \pi r_o^3 \rho_l \frac{\partial u}{\partial t} = -\frac{1}{2} \rho_g u^2 \frac{\pi r_o^2}{\alpha} C_D \qquad (2.5.10)$$

where (2.5.9) determines the rate of deformation and (2.5.10) the decellaration.

If the Weber number of the produced droplets are greater than 13, they will break up too, and repeating the procedure, until a droplet with $We < 13$ is obtained, the final size, velocity and position of the droplets can be calculated.

It should be notised that the development of this model [5] is based, on a lot of assumptions, but if correlated against experiments it should provide a good tool for the prediction of the final dropsize.

2.5.3. The Drop Flow in the Core.

The droplets will have obtained their final size and velocity when they reaches the core, and that fraction of the droplets, which is not swept away by the steam flow, will be available for the cooling of the core. Due to the scattering of the droplets from the hot surface, the droplets can be treated as single droplets, and the drag coefficient is

$$C_D = \begin{cases} \frac{24}{Re} & \text{for } Re \leq 0.71 \\ 0.4 + 25.4\, Re^{-0.8} & \text{for } 0.71 < Re \end{cases} \qquad (2.5.11)$$

The concentration of the droplets can now be determined, and this together with the dropsize is the basis of the determination of the absorption of thermal radiation, as described in section 3.

2.5.4. Film Flow on Rods and Shroud.

The film flow on fuel rods and shroud is determined using the model of Yamanouchi [7,8]. The amount of spray water available per fuel rod for creation of water films is given by

$$G_r = \eta \frac{a_r}{A_e} G_e \qquad (2.5.12)$$

where a_r is the cross sectional area of fuel rod, m^2
A_e is the cross sectional area of the fuel element, m^2
G_e is the spray water per fuel element, kg/sec.
η is an experimentally determined distribution factor, and $\eta_{min} = 0.4$
G_r the water available for film flow.

The velocity of the film front is given by

$$u = \frac{1}{\rho_w c_w} \sqrt{\frac{h_{fg} k_w}{\delta_w}} \frac{T_o - T_s}{T_\infty - T_o} \quad \text{m/sec.} \qquad (2.5.13)$$

$$h_{fg} = 1.20 \cdot 10^6 \sqrt{\frac{G_r}{\pi d_r}} \quad W/m^2\,{}^\circ C \qquad (2.5.14)$$

where ρ_w is the density of the wall, kg/m^3
c_w the heat capacity of the wall, $J/kg\,^\circ C$
k_w the thermal conductivity of the wall, $W/m\,^\circ C$
T_o the Leidenfrost temperature, $^\circ C$
T_s the saturation temperature, $^\circ C$
T_∞ the temperature before the film front, $^\circ C$
h_{fg} the film heat transfer coefficient, $W/m^2\,^\circ C$
d_r the diameter of a fuel rod

2.6. Mass, Momentum and Energy Transfer between the Phases.

The evaporation of the remaining water in the lower plenum is calculated, using the Rohsenow correlation

$$\frac{c_l (T_w - T_s)}{H_{lg}} = 0.0013 \left\{ \frac{q}{\mu_l H_{lg}} \sqrt{\frac{\sigma}{G(\rho - \rho_g)}} \right\}^{0.33} Pr^{1.7} \qquad (2.6.1)$$

where c_l is the heat capacity of water, $J/kg\,^\circ C$
T_w the temperature of the wall, $^\circ C$
T_s the saturation temperature, $^\circ C$
H_{lg} the evaporation heat, J/kg
q the heat transfer, W/m^2
μ_l the viscosity of water, kg/m sec.
σ the surface tension, N/m
G = 9,81 m/sec^2 the gravity
ρ_l the density of water, kg/m^3
ρ_g the density of the steam, kg/m^3
Pr the Prandtl number.

The evaporation from the filmflow on rods and shroud is calculated using (2.5.14), and the evaporation/condensation from the droplets is calculated using [9]

$$Nu = 3.20 + 0.75\, Re^{0.5}\, Pr_g^{0.33} \qquad (2.6.2)$$

$$Re = \frac{d_d \rho_g (V_g - V_d)}{\mu_g}$$

where d_d is the dropletdiameter, m
V_g the velocity of the steam, m/sec.
V_d the velocity of the droplets, m/sec.
μ_g the viscosity of the gas, kg/m sec.

From the mass transfer rates the energy transfer is easily obtained. The momentum transfer between the droplets and the steam flow is obtained from the mass - transfer, and the drag coefficient (2.5.11).

2.7. Remarks.

The two-phase flow in the primary system is calculated using avarage parameters describing the water and the steam flow. This may, compared to the object of the model, turn out to be too rough a description, and if this is the case it is our intension, on a later stage of the programme development, to base the flow in the core region on a subchannel model.

3. THE THERMAL RADIATION MODEL.

3.1. Physical Model and Assumptions.

The system considered consists of several radiating surfaces, the fuel rod surfaces and the surface of the shroud.

The radiative interchange consists not only in the direct interchange between surfaces, which can "see" eachother directly, but the other surfaces contribute also to the transport of radiation due to the reflective characteristics of the surfaces (multiple reflection). Therefore a high reflectivity is of importance especially for the center rods of the fuel element, as the reflectivity in the system enable the center rods to exchange energy with the non-heated and therefore easier wettable shroud.

Fuel elements to BWR-reactors consist of up to 64 rods. The programme can handle this, but the fuel element may also be divided up in zones, where each zone contains more rods. This will of course mean reduced computer time, but at the expence of the detail of information attained.

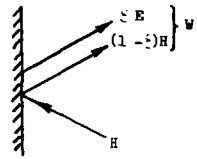
Emergency core cooling as droplet cooling (spray) is taken into account. The hydraulic part of the programme determines the concentration and mean diameter of droplets. The transmissivity in the coolant is calculated from these informations.

The analytical treatment of the thermal radiation is performed under following assumptions:

1. all surfaces are in thermal equilibrium during every time step,
2. all surfaces are grey and diffuse,
3. all surfaces interchange radiation uniformly,
4. the medium between the surfaces may be absorbing, but is non-scattering and non-radiating (cold medium assumption).

3.2. Analytical Model.

The absorption of the surfaces is equal to the emission. The sum of the reflectivity ρ and the emission is unity i.e. $\rho = 1 - \varepsilon$



The outgoing flux, W, the radiosity, is ref. to the sketch,

$$W = \varepsilon E + (1 - \varepsilon) H \quad \frac{\text{Watt}}{\text{m}^2} \qquad (3.2.1)$$

where E is the black body radiated flux and H is the incoming flux.

The netto flux, q''_{net}, is

$$q''_{net} = W - H, \quad \text{Watt/m}^2 \qquad (3.2.3)$$

positive as loss from the surface.

The incoming radiative energy to a surface k in the system consists of the outgoing radiative energy from the other surfaces, which can "see" the surfaces. The incoming flux may be reduced due to absorption in the medium between the surfaces, i.e.

$$A_k H_k = \sum_j \tau_{jk} W_j A_j F_{jk} \qquad (3.2.3)$$

where A is the area of the surface (m^2)

F_{jk} is the geometrical view factor from the surface j to the surface k (dim. less) [13]

τ_{jk} is the transmissivity of the medium between the surface j and the surface k (dim. less.)

The equation (3.2.3) may be rewritten, as

$$A_j F_{jk} = A_k F_{kj} = \varepsilon_k \varepsilon_j \qquad (3.2.4)$$

and

$$\tau_{jk} = \tau_{kj} \qquad (3.2.5)$$

i.e.

$$A_k H_k = \sum_{j \neq k} W_j \times \varepsilon_k \varepsilon_j \times \tau_{kj} \qquad (3.2.3a)$$

From equation (3.2.1)

$$H_k = \frac{W_k - \varepsilon_k E_k}{1 - \varepsilon_k} \qquad (3.2.1a)$$

and equation (3.2.2) and (3.2.1a)

$$Q_{net,k} = \frac{A_k \varepsilon_k}{1 - \varepsilon_k} (E_k - W_k) \qquad (3.2.6)$$

Combining (3.2.2) and (3.2.6) using the Kronecker delta gives

$$\sum_{j=1}^{N} W_j \left(\varepsilon_k \varepsilon_j \times \tau_{kj} - \frac{\delta_{kj} A_j}{1 - \varepsilon_j}\right) = -\frac{A_k \varepsilon_k}{1 - \varepsilon_k} E_k \qquad (3.2.7)$$

where N is the number of zones, and

$\delta_{kj} = 1$ for $k = j$

$\delta_{kj} = 0$ for $k \neq j$

A system of N linear equations are attained, when k goes from 1 to N. The outgoing flux W from each zone can then be calculated, when the geometrical view factors, the transmissivity and the temperatures in the system are known.

The netto interchanged energy between zone k and zone j can be written

$$Q_{k \rightleftarrows j} = Q_{k \rightarrow j} - Q_{k \leftarrow j} \qquad (3.2.8)$$

$Q_{k \rightarrow j}$ is that part of the total radiative energy, which arrives at and is absorbed by the zone j, after reflections from surfaces and absorption in the medium between the surfaces, from the zone k alone.

Therefore according to (3.2.6)

$$Q_{k \rightarrow j} = - Q_{net,j} = -\frac{A_j \varepsilon_j}{1 - \varepsilon_j} (E_j - {}_k W_j) \qquad (3.2.9)$$

where the index k before W_j just indicate, that the outgoing flux is originating in k alone.
This outgoing flux can be determined from the system of equations (3.2.7) when all E except E_k are set equal to zero.
Then

$$Q_{k \rightarrow j} = \frac{A_j \varepsilon_j}{1 - \varepsilon_j} \times {}_k W_j. \qquad (3.2.10)$$

In the case of k = j equations (3.2.2) and (3.2.9) give

$$- Q_{net,j} = - A_j \varepsilon_j E_j + Q_{j \rightarrow j} \qquad (3.2.11)$$

and

$$- Q_{net,j} = -\frac{A_j \varepsilon_j}{1 - \varepsilon_j} (E_j - {}_j W_j) \qquad (3.2.9)$$

or

$$Q_{j \rightarrow j} = \frac{A_j \varepsilon_j}{1 - \varepsilon_j} ({}_j W_j - \varepsilon_j E_j) \qquad (3.2.12)$$

Combining (3.2.10) and (3.2.12) using the Kronecker delta gives

$$Q_{k \rightarrow j} = \left[\frac{A_j \varepsilon_j}{1 - \varepsilon} \left(\frac{{}_k W_j}{E_k} - \delta_{kj} \varepsilon_k\right)\right] E_k \qquad (3.2.13)$$

The expression in the sharpedged parenthesis is the total view factor as derived by Hottel and Sarofim [10]. As the system of equations are linear, there are propertionality between ${}_k W_j$ and E_k, and the ratio is therefore independent of the temperature. The total view factor is therefore a constant so long as the transmissivity does not change.

$$S_k S_j = \frac{A_j \varepsilon_j}{1 - \varepsilon_j} \left(\frac{k^W_j}{E_k} - \delta_{kj} \varepsilon_k \right) \qquad (3.2.14)$$

$\delta_{kj} = 1$ for $k = j$

$\delta_{kj} = o$ for $k \neq j$.

3.3. Calculation Procedure.

The radiative interchange between a zone k and the zones in the system, when all zones are radiating can then be expressed by the total view factor as:

$$\sum_{j=1}^{N} Q_{k \neq j} = S_k S_1 (E_k - E_1) + S_k S_2 (E_k - E_2) + \ldots + S_k S_n (E_k - E_n) \qquad (3.3.1)$$

A further summation of equation (3.3.1) over all zones, k going from 1 to N, would give zero, if the transmissivity is unity corresponding to no absorbing medium between the surfaces in accordance with the assumption of thermal equilibrium.

However, when spray cooling is put on, a concentration of water droplets will arise as derived in the hydraulic part of this programme. Absorption of energy will take place, and the transmissivity will be lower than 1. The above mentioned summation will no longer give zero, but have a value according to the amount of energy absorbed in the water droplets.

The matrix-system of the linear equations (3.2.7) are solved by the Gauss-Seidels iterative method, as the matrix-system is sparse and the principal diagonal clear dominant.

The total view factors change, when the transmissivity changes. The transmissivity depends, as shown below, of the water droplet concentration, which again depends of the steam flow and its direction in relation to the droplets. In order to avoid the rather time consuming calculation of the total view factors each time the concentration changes the deviation between the concentrations is calculated. Only when the deviation has passed a preset value a new calculation of the total view factors is performed.

3.4. Transmissivity.

In accordance with the 4th assumption only absorption in the water droplets is taken into account.

The transmissivity may therefore be expressed as

$$\tau = I/I_o = \exp (-a \times RR) \qquad (3.4.1)$$

where I is the intensity of the radiation,
RR is the thickness of the layer of water droplets between the considered surfaces, and
a can be considered as the logarithmic decrement (macroscopic cross section) of the radiation.

The logarithmic decrement must depend of the number of droplets present between the surfaces and the surface of the droplets normal to the direction of the radiation, i.e. per unit volume

$$a \sim \sum_{1}^{N} \frac{\pi d_N}{4} \qquad (3.4.2)$$

if the droplets are assumed to be spheres.

The number of droplets per unit volume may be expressed by

$$N = \frac{1 - \alpha}{\pi/6 \times d^3} \qquad (3.4.3)$$

where α is the void and d is a mean droplet diameter.

The transmissivity can therefore be calculated from

$$\tau = \exp. \left(-\frac{3}{2} \times \xi \times \frac{(1 - \alpha)}{d} \times RR \right) \qquad (3.4.4)$$

4. CURRENT STATUS OF THE PROGRAMME AND FUTURE WORK.

The computer programme REMI/HEAT COOL is for the present moment in the development phase. In accordance to the plan the programme development, as described in this report, will be terminated and the programme thoroughly tested against experiments in the spring 1973.

The next step in the development of this model is to include several parallel fuel channels and a bypass channel in the model of the primary system, and it is the plan to include flowblockage due to swelling of the fuel rods. Furthermore, as already mentioned, it might be necessary to base the flow calculation in the core region on a subchannelanalysis.

In 1973 it is the plan to start up a new programme development, parallel to but based on REMI/HEAT COOL, in order to make a model able to take into account the use of flooding systems. This work should be terminated in 1974.

As a last step in the programme development is planned a combination of these two programmes, and the result should be an effective tool in the safety evaluation of a nuclear reactor.

5. RELATION TO OTHER COMPUTER PROGRAMMES AT RISØ.

A thorough hydraulic and thermal safety analysis results in very comprehensive calculations.

Even use of modern computers may limit the desirable detail in the analysis, system components and physical phenomena to be represented. It has, therefore, been found advantageous to devide the analysis up in three parts.

1. Analysis of the blow down limited to the calculation of the system decompression, system flows, discharge flows and influence of forces upon the inner core structure during the loss of coolant accident.
2. Analysis of the temperature transient in a single fuel rod during the blow down taking into account enthalpy increase, burn out and heat transfer to the coolant channel.
3. Analysis of the temperature transient in the fuel element after the blow down taking into account thermal radiation with multiple reflection, overall heat transfer to emergency core coolant and metal water reactions.

The last mentioned analysis is performed with the programme REMI/HEAT COOL described in the present report.

The blow down analysis has hitherto been performed with the programme BRUCH-S [11], which we through courtesy of "Institut für Mess- und Regelungstechnik" got at our disposal. BRUCH-S calculates the hydraulic behaviour of the primary coolant system in a boiling water reactor during various kinds of loss of coolant accidents. The programme is based on a nine node model of the system, without separate models for heat transfer between the fuel rods and the coolant. The model requires therefore information of heat transfer between coolant and core before a calculation can be performed.

The analysis of the temperature transient during the blow down is performed with the programme DINO [12], DINO is a two dimensional, transient heat conduction programme, which calculates the temperatures in a single fuel rod. The influence of the surrounding rods and shroud is taken into account as the outer wall of an annulus with equivalent amount of fuel and cladding as in the surrounding shroud and fuels. DINO uses relevant hydraulic data from the blow down programme to calculate the heat transfer to the coolant channel. It is, therefore, closely linked to a blow down programme through a data coupling technique, using an external computer storage device.

However, a new multirod thermo - hydraulic blow down programme DANBLOW is at the present under development.

The programme is intended to include subchannel analysis of the hydraulics, a temperature distribution in fuel and cladding, post burn out heat transfer coefficients, metal-water reaction, thermal radiation and simple neutron physics model together with an elementary description of the primary system.

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