CHAPTER 19

Emergency Core Cooling—Refilling

F. Mayinger

1 EMERGENCY CORE-COOLING SYSTEM

In spite of the shutdown of the reactor by scramming the core, heat still develops which is in the order of a few percent of the thermal power. In a nuclear reactor with an electric output of 1000 MW, this heat production in the first minutes after the scram will be in the order of 30/150 MW. Therefore, after the usually very short blowdown period, new cooling fluid has to be brought into the core as soon as possible.

This cooling fluid is made available by the emergency core-cooling systems. The design and the detailed apparatus of a core-cooling system for a pressurized water reactor is shown in Fig. 1. Simply stated, it consists of passive acting accumulators filled with borated water under a pressure of about 30 bars and of a series of pumps that have to be started to force water into the primary system. The accumulators are connected with the primary system by a selfopening valve, and they release their water into the core the moment the pressure in the primary system drops below the accumulator pressure. The long-time cooling then is managed by the pumps. In Fig. 1, we can see a pair of pumps for each of the four primary circuits; one of them is a high-pressure pump for small liquids and the other a low-pressure pump for high mass flow rates.

Qualitatively, the temperature behavior of the fuel rod cladding during the loss-of-coolant accident is shown in Fig. 2. Because of the flashing at the beginning of the blowdown in the first milliseconds, the heat transfer may even by improved until film boiling of dryout starts, which results in a steam temperature rise. In the meantime, the water will be accelerated in the core, which improves the heat-transfer behavior and so the cladding is cooled down again. Finally, the core loses its water content completely or almost completely, the remaining steam is not capable of cooling the fuel rods sufficiently, and the temperature rises again.

It goes far beyond the so-called Leidenfrost-temperature, which was

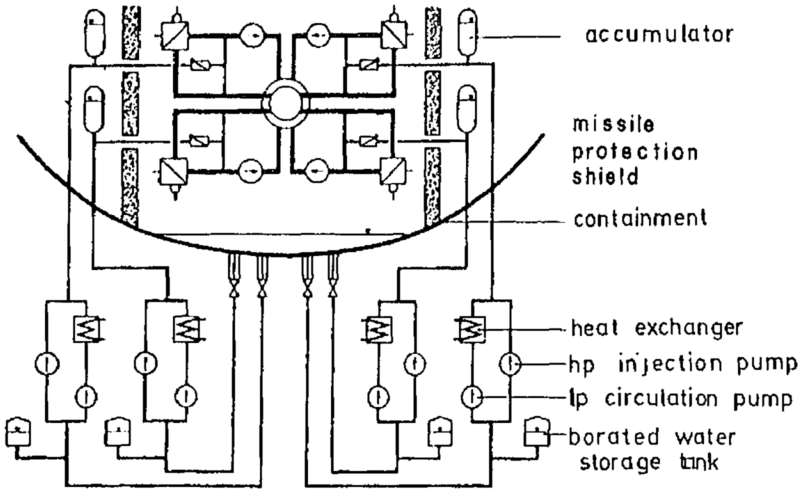


FIG. 1 Core-cooling system for a pressurized water reactor.

explained in Chap. 18 dealing with basic problems of burnout. That means that above this temperature water cannot wet the hot surface.

In the meantime, the emergency core-cooling system is supplying water to the primary system. The water is flowing through the unbroken pipelines to the lower plenum of the pressure vessel of the reactor and, because of the heat stored in the walls of the pressure vessel, there is evaporation. This vapor

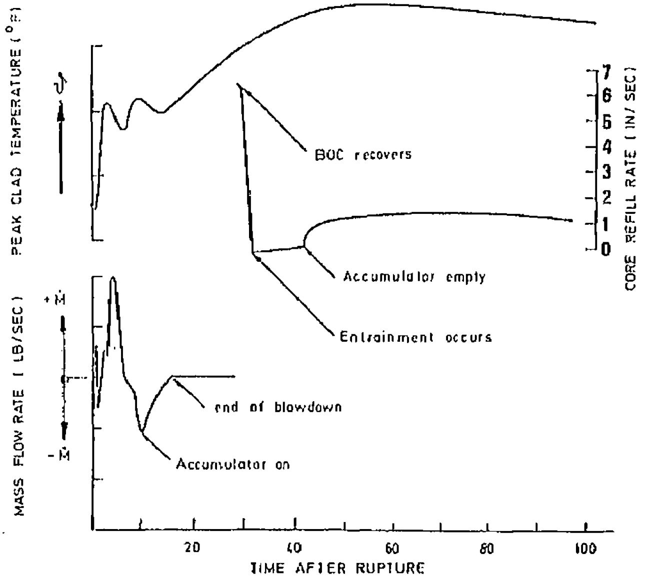


FIG. 2 Typical hot-rod temperature transient.

flows through the core upward and starts to cool the fuel rods by single-phase heat transfer. Finally, by adding more water, the water level reaches the lower grid plate of the core, which results in a very violent steam generation, and a mixture of steam with water droplets embedded is now flowing upward through the core. This mixture cools the core, which is still above the Leidenfrost-temperature, more intensively and the water level is rising in the core. Finally, starting from the bottom, the fuel rods will be wetted again, which means a sharp drop in the temperature—also called quenching—and then the heat is transferred to the liquid by nucleate boiling and by forced single-phase convection.

In addition, one has to be certain that the steam produced in the core can leave the upper plenum via the broken pipe without too high a pressure drop. A blockage of the steam in the upper plenum of the pressure vessel caused by two-phase pressure drop is called a steam binding; this would prevent new water entering the core from below. This means that we have to consider three phenomena during the refilling periods:

1 The rewetting or quenching of the hot rods
2 The heat transfer in the post-dryout region
3 Possible steam binding in the upper plenum

For the sake of completeness, one also should mention that the cooling of the core could be managed by spraying water into the core from above, which we also will discuss shortly. In safety considerations for nuclear power plants, usually it is assumed that the spray cooling is not very effective and, therefore, it is not given too much credit.

During the refilling period, there may be present several heat-transfer mechanisms along the fuel rods. The upper part of the rods, above the water level, will be cooled by the steam-water mixture produced in the lower part. This we call spray or fog cooling. Because of the high surface temperature, the rising water cannot wet the fuel rod cladding immediately. This means that even below the water level there is film boiling. The transition from film boiling to bubble boiling is accompanied by a very strong axial temperature gradient in the cladding, which is called rewetting or quenching. In the part of the rods below the quenching zone, the heat transfer is accomplished by liquid convection. Figure 3 shows these heat-transfer areas, including the surface and fluid temperatures.

2 QUENCHING

The quenching or rewetting mechanism is responsible not only for a strong temperature reduction, but it also produces the steam-vapor mixture to cool the upper unwetted parts of the core. As mentioned, we have to distinguish

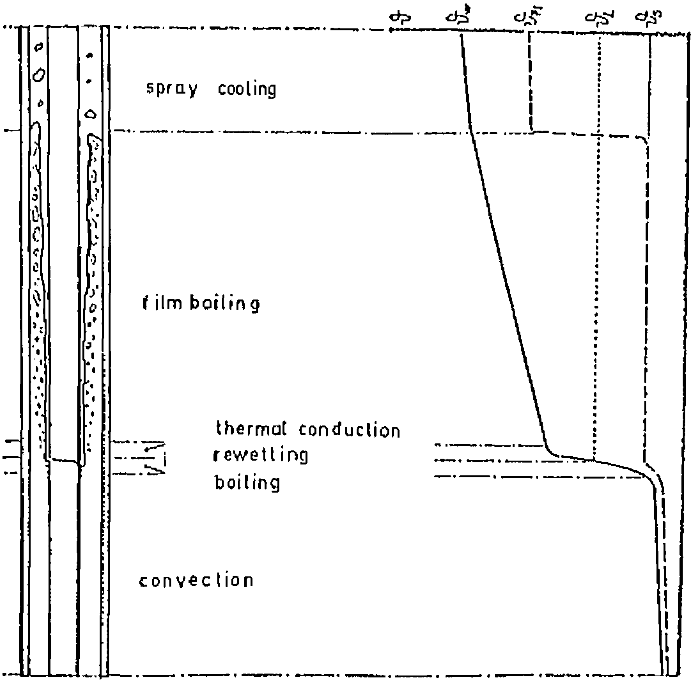


FIG. 3 Heat-transfer areas; surface and fluid temperatures.

between two cooling procedures: the spray cooling, which acts from above, and the real refilling of the core from below.

With spray cooling, in the very first moments only those parts of the upper core structure will be wetted that are below the Leidenfrost-temperature. These are, for example, the shrouds of the fuel elements. Therefore, the first cooling may start by thermal radiation between the fuel rod and the shroud. The efficiency of the spray cooling is dependent on the water distribution, the forming of water bridges between the rods, the so-called flooding, the evaporation, and the ballooning, or bending, of the rods. In addition, there may be a radiation heat transfer between the rods and the two-phase mixture.

Detailed research on the spray cooling and quenching mechanism was done by Yamanouchi (1968). Before presenting the theory of Yamanouchi we have to discuss qualitatively some hydrodynamic aspects of the quenching front. As mentioned, there may be formed water bridges, which influence the heat-transfer mechanism strongly. This mechanism may be compared with flooding, which happens if an upward-directed strong gas or vapor flow lifts a liquid flow and prevents it from coming downward. The mechanism is shown in Fig. 4. This phenomenon is well known in the two-phase literature, and it may occur in several types of apparatus for chemical engineering, such as distillation columns or bubble columns. The flooding is a function of the mass flow rate of the steam, the density ratio of liquid and water, and last but not least, it is influenced by the viscosity of the liquid and the surface tension. Because of the evaporation during flowing down the fuel rod, the liquid film becomes thinner and this may result finally in a dryout. This occurs mainly at low heat-flux densities and low steam quality. The thickness of the liquid film is not uniform and, therefore, dry patches may occur even before total evaporation of the film. Also, differences in surface tension and in the rewetting behavior of the surface may result in the forming of dry patches.

The usual conditions at the rewetting zone are shown in Fig. 5. The water film is strongly dispersed at the wetting front, which may be caused by the characteristics of film boiling. The droplets formed by this dispersion result in an indirect cooling of the unwetted zone.

We now shall discuss some details of Yamanouchi's theory. In a laminar

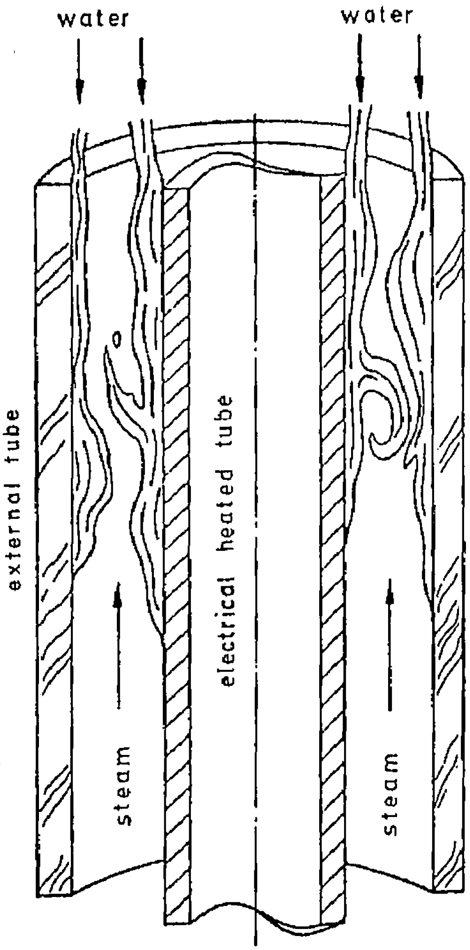


FIG. 4 Flooding.

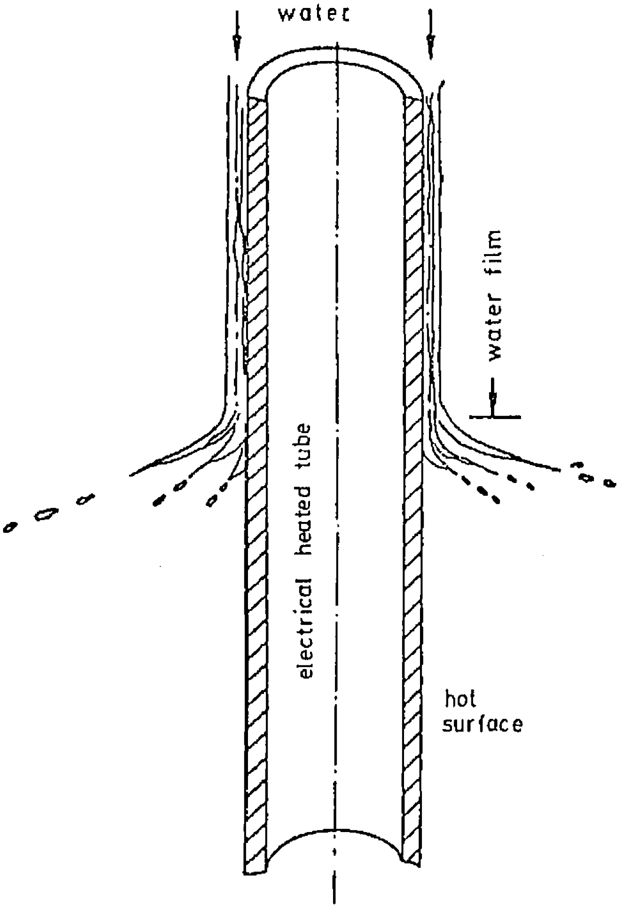


FIG. 5 Spraying.

falling film flow down a vertical surface without evaporation, the velocity of the liquid would be

$$u = \left(\frac{\rho_l}{3\eta_l}\right)^{1/3} \left(\frac{G_H}{\pi D \rho_l}\right)^{2/3} \qquad (1)$$

where ρ_l = density of liquid
η_l = viscosity
G_H = quantity of liquid flowing down the wall

The equation results from the simple conclusion that the gravity forces must be in equilibrium with the friction forces at the wall. If one assumes that this falling film velocity is equal to the moving velocity of the wetting front at a heated wall, with a temperature far above the Leidenfrost point, one would be far from reality, as measurements show. One reason is that the progress of the front is severely retarded by evaporation, which reduces the mass of the falling film.

Yamanouchi considers the cladding of a fuel element, assuming uniform temperature in the thin wall and neglecting heat production in the rod. He further assumes that the heat-transfer coefficient in the already wetted region is constant and that it is zero in the unwetted part. An energy balance then gives the equation

$$\lambda_s \delta \frac{d^2 T}{dz^2} + \rho_s C_s \delta u \frac{dT}{dz} - h(T - T_{\text{sat}}) = 0 \tag{2}$$

in which the first term is the axial heat conduction in the cladding, the second one the axial convective heat transport in the liquid film, and the third one the heat transfer from the wall in the wetted part. With the boundary conditions

$z = \infty \qquad T = T_\infty$

$z = -\infty \qquad T = T_{\text{sat}}$

$z = 0 \qquad T$: smoothly continuous

the solution of this equation is:

$$T_0 - T_{\text{sat}} = \frac{2(T_\infty - T_0)}{\sqrt{1 + \dfrac{4h_{\text{lg}}\lambda_s}{\delta \rho_s{}^2 C_s u^2}} - 1} \tag{3}$$

or, rearranged

$$u^{-1} = \frac{\rho_s C_s}{2} \sqrt{\frac{\delta}{h_{\text{lg}}\lambda_s}} \sqrt{\left[\frac{2(T_\infty - T_0)}{T_0 - T_{\text{sat}}} + 1\right]^2 - 1} \tag{4}$$

In this equation, T_0 is the temperature at the wet front, which acts as the limiting parameter at which the wall surface becomes wetted. From experiments in the literature, one can find that, at ambient pressure, this temperature is around 150°C. If the initial temperature of the rod is very high, for example, around 800°C, one can simplify Eq. (4):

$$u^{-1} = \rho_s C_s \sqrt{\frac{\delta}{h_{\text{lg}}\lambda_s}} \left(\frac{T_\infty - T_0}{T_0 - T_{\text{sat}}}\right) \tag{5}$$

So a simple model is given for calculating the speed of a wetting front if spray cooling is used.

With refilling from below, the rewetting procedure is different from the above-mentioned conditions. There will be film boiling in the unwetted region below the water level and a vapor film will be formed between the heater rod and the water, as shown in Fig. 6. If we assume that there is laminar flow in the vapor, we can describe the flowing conditions in the vapor film by the equation

$$\eta_d \frac{d^2 w}{dy^2} = \frac{dp}{dz} + \rho_d g \tag{6}$$

This equation gives the equilibrium between buoyancy forces, pressure drop, and wall friction. The pressure drop along the length of the rod, i.e., in the vertical direction, is governed purely by the weight of the water column above the wetting region, from which follows

$$\frac{dp}{dz} = -\rho_l g \tag{7}$$

and so we get

$$\eta_d \frac{d^2 w}{dy^2} = -(\rho_l - \rho_d) g \tag{8}$$

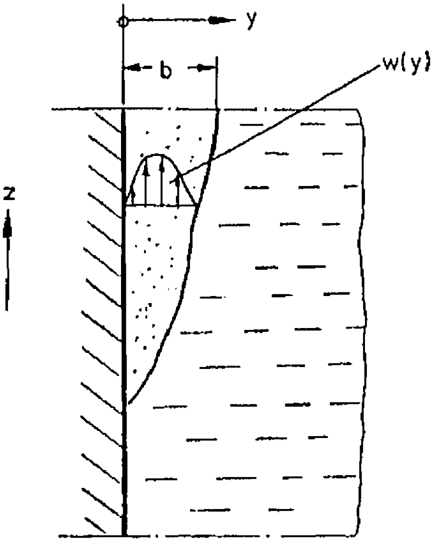


FIG. 6 Film boiling on an vertical wall.

and because of the fact that the density of the liquid is large compared with the density of the steam, we can write

$$\frac{d^2 w}{dy^2} + \frac{\rho_l g}{\eta_d} = 0 \tag{9}$$

The velocity of the vapor at the wall and at the vapor-liquid interphase must be zero and, by integrating with these boundary conditions, we get

$$w = \frac{\rho_l g}{\eta_d} \left(b \frac{y}{2} - \frac{y^2}{2} \right) \tag{10}$$

in which b is the thickness of the film, as shown in Fig. 6. The total steam mass flow rate finally can be calculated from

$$\dot{M} = \int_0^b \rho_d w \, dy = \frac{\rho_d \rho_l g b^3}{\eta_d 12} \tag{11}$$

Having calculated this vapor mass flow rate by using only hydrodynamic considerations, we now can use it in an energy balance in the unwetted region, assuming that there is a linear temperature profile in the vapor film:

$$\dot{q}_w \, dz = \frac{\lambda_d (T_w - T_{\text{sat}})}{b} \, dz = r_{fd} \frac{d\dot{M}}{dz} \, dz = \frac{r_{fd} \rho_d \rho_f g b^2}{\eta_d 4} \frac{db}{dz} \tag{12}$$

By rearranging this equation and with the definition of the heat-transfer coefficient, we get an expression for the heat-transfer coefficient

$$\alpha = \frac{\lambda_d}{b} = \left(\frac{\rho_d \rho_f g r_{fd} \lambda_d}{(T_w - T_{\text{sat}}) z \eta_d 16} \right)^{1/4} \tag{13}$$

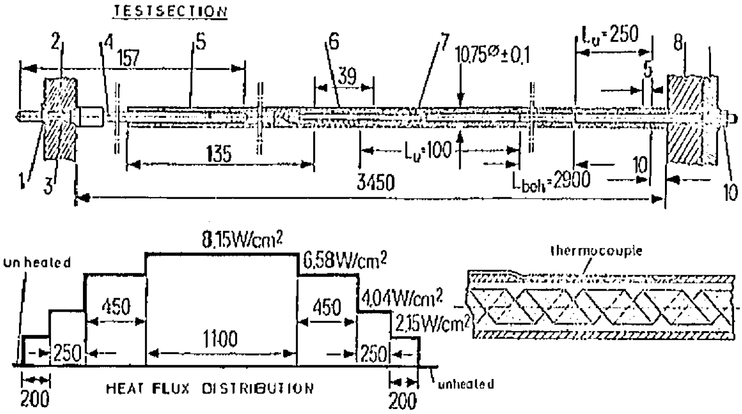
In reality, because of instabilities in the water column above the wetting point, we surely do not have a laminar flow in the vapor film at the wall. We soon shall observe turbulent flow and unsteady flow, which improves the heat transport from the wall. So, actually, we are forced to rely on experimental data for getting reliable predictions of the rewetting behavior of a fuel rod.

3 HEAT TRANSFER IN THE POSTDRYOUT REGION

There are several measurements reported in the literature dealing with heat-transfer coefficients during the refilling period after a loss-of-coolant accident. Most of them are done with inside cooled round tubes. Recently, there were published two test series done with big rod clusters, one of them carried out in the United States as the so-called FLECHT-tests (Blaisdell et al., 1973), and the other one done at KWU in Erlangen, with a core configuration of 340 rods (KWU Erlangen, 1973). While the FLECHT-tests are representative mainly for boiling-water reactors, the KWU experiments are carried out under pressurized-water conditions. The rods in the KWU test apparatus had the original dimensions of a fuel rod in a large power reactor, and their heat-flux distribution was similar to them. Figure 7 shows the design of such a rod, which is indirectly heated by electric power input.

As an example of the results gained in this test loop, Fig. 8 shows the temperature of the fuel-rod cladding versus time. The rising velocity of the water level in the core is used as a parameter. As we can see from this figure, all curves have a similar behavior. As long as the spray cooling is not sufficient to carry away all heat produced by electric heating in the rod, the temperature is still rising. At the temperature maximum—commonly called the turnaround point—the heat produced is just balanced by the cooling effect. With rising water level, the rod will become more and more quenched, which means that the vapor production is increased and the spray cooling improved. If the water level reaches a certain height, film boiling finally starts which, at the quenching front, changes to bubble boiling accompanied by a strong temperature deterioration. With decreasing water-level velocity, the heating period increases and the turnaround point as well as the quenching point is reached later. This means that for good cooling of the core, we have to refill with as much water as possible.

In Figs. 9 and 10, the influences of the system pressure and the initial cladding temperature on the temperature rise, turnaround time, and quench



SINGLE COMPONENTS

1 safety plate
2 fundamental plate
3 electric contact
4 plug
5 buching
6 current lead
7 cladding
8 contact plate
9 silverplate
10 female screw M 5

FIG. 7 Refilling experiments.

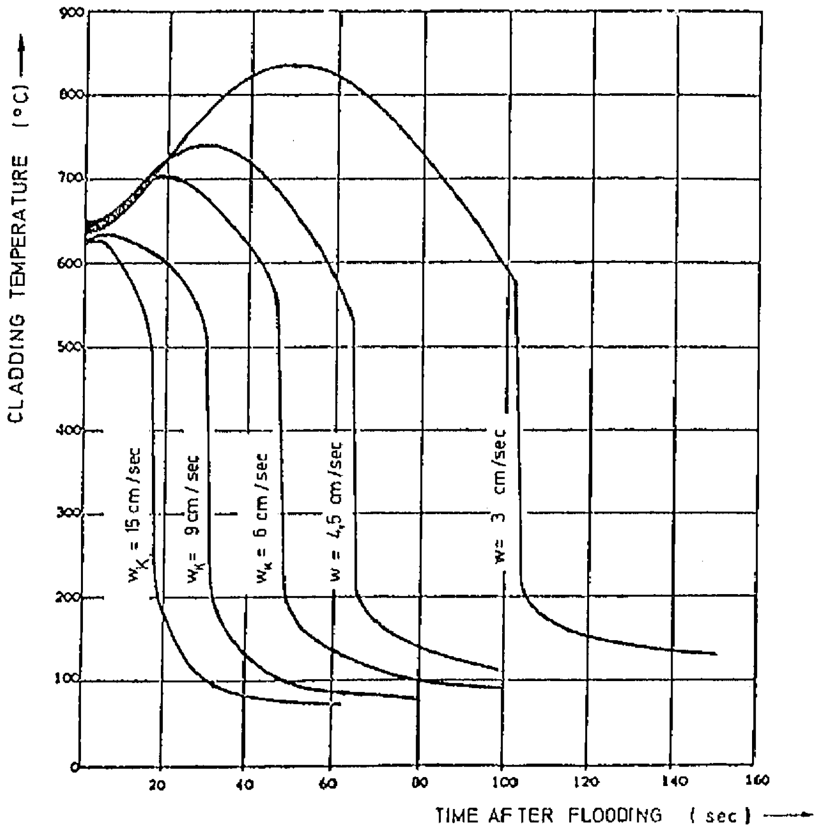


FIG. 8 Temperature of a fuel rod as a function of time.

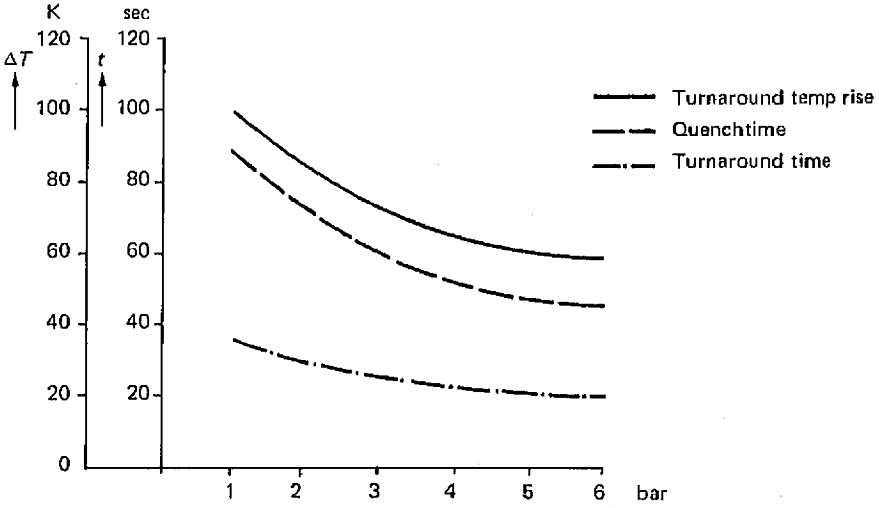


FIG. 9 Bundle flooding (bottom only); dependency on pressure. Run 42.57.56, $w_K = 6$ cm/s, $\delta_{H_2O} = 650°C$, $q_{max} = 8.2$ W/cm^2, $\delta_K = 25°C$. Bundle middle (pin 6, ax pos 4).

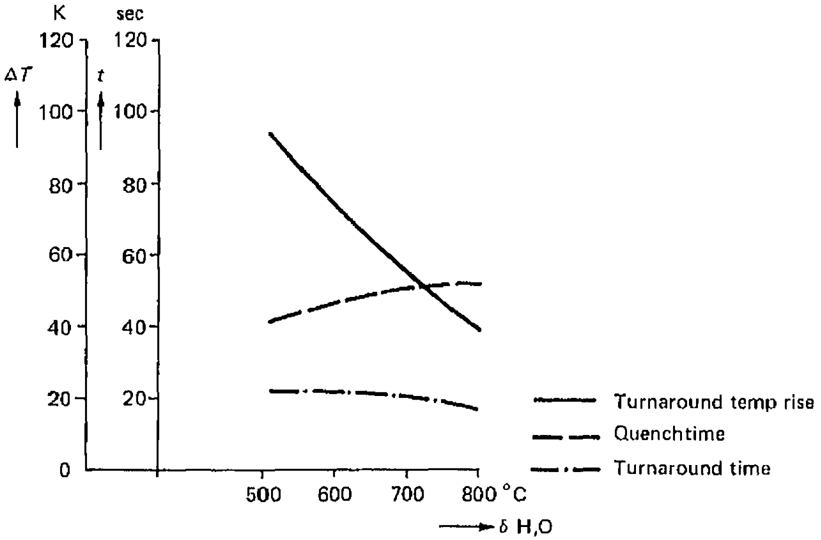


FIG. 10 Bundle flooding (bottom only); dependency on initial wall temperature. Run 47,57,65, $w_K = 6$ cm/s, $p = 4.5$ bar, $q_{max} = 8.2$ W/cm², $\delta_K = 25$°C. Bundle middle (pin 6, ax pos 4).

time are shown. The efficiency of the emergency core cooling is greatly improved with increasing system pressure. This is because of the lower specific volume of the vapor which is decreasing with pressure, and which produces the pressure drop in the upper plenum and so improves the water flow into the core. In addition, the heat-transfer coefficient is improved with higher vapor densities. With higher initial temperatures, there is a higher temperature gradient available for the heat transfer and, therefore, the temperature rise is greatly reduced. The turnaround and quench time are not influenced very much by the initial temperature, as seen on Fig. 10.

From the measured wall and fluid temperature, one can calculate the heat-transfer coefficient by using the differential equation for unsteady heat conduction in the heater rod. Figure 11 shows the dependency of the heat-transfer coefficient on the rising velocity of the water level. With lower water velocity, the vapor production becomes smaller and the spray cooling is deteriorated. Compared to this effect of the water velocity, there is only a small influence of the initial cladding temperature on the heat-transfer coefficient. Also, the influence of the heat flux is negligible. This gives the idea that the vapor is the dominant heat-transfer fluid, because in single-phase heat transfer there is no influence of the temperature and the heat-flux density on the heat-transfer coefficient, as is well known from the literature.

For the layout of an emergency core-cooling system and for core-safety considerations, the question arises as to how to predict the heat-transfer behavior in the refilling post-dryout period. We have to distinguish between three different regions with respect to heat transfer along the rod during refilling. The lowest part the rod is wetted and we have heat transfer by forced convection, perhaps caused by saturated or subcooled bubble boiling. In the immediate neighborhood above the wetting point there is film boiling, which was discussed briefly in Chap. 2, and which theoretically would reach up to the upper end of the water column. In reality, there is no quiet water level but a foam layer and a very dispersed liquid-vapor mixture. A certain distance above the water level, there is cooling by a vapor flow with droplets embedded. Because the surface temperature of the wall is above the Leidenfrost point, the droplets cannot wet the wall, but they are cooling the boundary layer, thus producing a steeper temperature gradient in the immediate neighborhood of the wall than there would be without droplet evaporation. There is a very detailed treatment of the thermodynamic and fluid dynamic conditions in this boundary layer given, for example, by Hewitt et al. (1967). We now shall discuss this theory, treating the problem in a purely empirical way.

As mentioned, the droplets cannot wet the wall and, therefore, the direct cooling of the wall is done by single-phase vapor flow. This suggests using the well known heat-transfer equations for single-phase flow as given, for example, by Collburn

$$\mathrm{Nu} = a\,\mathrm{Re}^{m}\mathrm{Pr}^{n} \tag{14}$$

and to add correction factors to this equation. This was done by several authors, and we have already discussed such equations in Chap. 5. There the equations given by Dougall and Rohsenow, and Groeneveld, were presented.

In practice, for safety and licensing calculations, very often simpler equations are used for predicting the heat-transfer behavior during refilling.

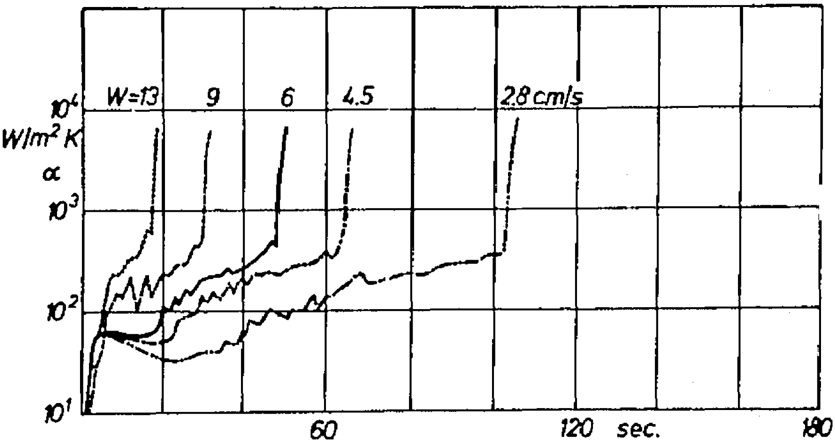


FIG. 11 Heat-transfer coefficient as a function of rising velocity of the water level.

The reason is that there are so many additional uncertainties in the calculations of the refilling process that a small error produced by a simpler equation, which can be handled more easily, is not too serious. Therefore, very often equations are used as given in appendix A, which sometimes merely take into account the single-phase heat transport.

4 STEAM BINDING, BALLOONING, AND COOLING-CHANNEL BLOCKAGE

The vapor produced during the refilling of the core will collect in the upper plenum above the core, and from there it has to flow through the primary piping to be distributed in the system. If there is too high a flow resistance, or if there is a water plug in the pipes, the vapor cannot escape and will build up to a higher pressure in the upper plenum. This results in a reduction of the water flow to the core, because the driving head for the water-flow rate to the core is only the difference in height between the water level in the core and the water level around the core in the downcomer of the pressure vessel.

This forming of a steam cushion is called steam binding, which may influence the heat transfer in the core very seriously and may even produce a fuel-rod failure. There are several possible ways to avoid or minimize steam binding. One is to make a bypass in the upper plenum between the hot side and the cold side–i.e., the downcomer–in the reactor pressure vessel, which can be done by selfopening valves, as is done in the Babcock reactors. Another possibility is the injection of cold water immediately into the upper plenum or through the pipelines of the so-called hot leg, i.e., the pipeline between the pressure vessel and the steam generator. This cold water condenses the steam produced in the core and blocked in the upper plenum. The reactors manufactured by the German company KWU are equipped with these hot-leg injectors, which are used mainly for avoiding steam binding by vapor condensation. Measurements done in a nuclear power plant before going into operation showed an efficiency of the hot-leg injection on this vapor condensation of between 60 and 80 percent. The cladding of the fuel rod is under internal pressure, which is a function of the burnup of the fuel. If the temperature of the cladding becomes too high because of this inside pressure, there may be a ductile or brittle failure of the cladding. The ductile failure of the cladding may result in a ballooning of the rod while with brittle failure, the rod may crack. The ballooning can have a strong influence on the heat-transfer behavior, if there is a large reduction in the flow area. Measurements have shown that, at the beginning of the ballooning, if the reduction of the flow area is small, there is even a slight improvement of the heat-transfer coefficient. But with reductions up to 60 and 80 percent, the flow can be blocked and the heat transfer in this area strongly reduced. There are only a few measurements available dealing with these problems so up to now, one cannot deduce clear results from them.

APPENDIX A

1 Forced convection heat transfer to vapor

Heinemann (1960):

$$h = 0.0157\ \frac{\lambda}{D}\ \mathrm{Re}^{0.84}\mathrm{Pr}^{0.33}\left(\frac{L}{D}\right)^{-0.04}$$

McEligot et al. (1966):

$$h = 0.021\ \frac{\lambda}{D}\ \mathrm{Re}^{0.8}\mathrm{Pr}^{0.4}\left(\frac{T_d}{T_f}\right)^{0.5}$$

thermophysical properties at $T_m = (T_d + T_w)/2$

2 Film boiling

Dougall and Rohsenow (1963):

$$h = 0.023\ \frac{\lambda_d}{D}\ \mathrm{Re}^{0.8}\mathrm{Pr}_d^{0.4}$$

$$\mathrm{Re} = \frac{DG}{\eta_d}\left[\frac{\rho_d}{\rho_f}(1-x)+x\right]$$

thermophysical properties at T_{sat}

REFERENCES

Blaisdell, Hochreiter, & Waring (1973). PWR Flecht-Set Phase A, Report *WCAP*-8238, Pittsburgh, Pa.

Dougall, R. S., and Rohsenow, W. M. (1963). Film Boiling on the Inside of Vertical Tubes with Upward Flow of the Fluid at Low Qualities, *MIT* 9079-26.

Heinemann, J. B. (1960). An Experimental Investigation of Heat Transfer to Superheated Steam in Round and Rectangular Channels, *ANL*-6213.

Hewitt, G. F., Bennett, A. W., Kearsey, H. A., and Keegs, R. K. F. (1967). Heat Transfer to Steam-Water Mixtures Flowing in Uniformly Heated Tubes in Which the Critical Heat Flux has been Exceeded, *UKAEA* Research Group Report *AERE-R* 5373.

KWU Erlangen (1973). Ergebnisse der Wiederauffüllversuche an einem 340-Stabbündel für den DWR, Bericht zu den DWR-Flutversuchen, *KWU RT* 34/*RT* 51.

McEligot, D. M., Ormand, L. W., and Perkins, H. C. (1966). Internal Low Reynolds-Number Turbulent and Transitional Gas Flow with Heat Transfer, *J. Heat Transfer*, vol. 88, pp. 239–245.

Yamanouchi, A. (1968). Effect of Core Spray Cooling in Transient State after Loss-of-Coolant Accident, *J. Nucl. Sci. and Technol.*, vol. 5, no. 11, pp. 547–558.