CHAPTER 5

Enhancement of nuclear power plant safety by condensation-driven passive heat removal systems

K. Vierow
Department of Nuclear Engineering,
Texas A&M University, USA.

Abstract

In response to increasingly higher demands on nuclear power plant safety systems, the nuclear community is responding by developing “passive” safety systems that are inherently safe. Passive systems are those that do not rely on power supplies, moving parts or human intervention. Condensation heat transfer is a primary driving force for many of these systems. These passive condensation heat transfer systems are reliable and inherently safe because they rely on basic physical forces such as gravity and small pressure differences to transport energy and maintain the plant within design specifications. In recent years, due to advancements in our understanding of the phenomena and in analysis capabilities, designs for essential heat removal systems such as the containment long-term cooling systems have come to rely extensively on passive condensation heat exchangers. The development of innovative systems for future reactors promises to further increase the safety, reliability and economic competitiveness of nuclear power. While significant advancements have been made, challenges remain particularly with regard to accurate, detailed analytical evaluations of system performance. This chapter discusses the numerous ways in which passive condensation heat transfer enhances nuclear power plant safety in current and future nuclear power plants. The discussion focuses on U.S.-design light water reactors and U.S. reactor safety codes although there are many commonalities to reactors of other designs. The physical phenomena are described and the state-of-the art in analysis methods are presented. Challenges for improved analysis are summarized.
1 Passive systems with condensation heat transfer

1.1 Definition

Adoption of passive systems for heat removal during design basis and hypothetical accident scenarios is one of the strategies for achieving simplification and improving safety and reliability of future nuclear reactors. Passive systems are those that do not require any external input such as AC power sources or operator action to function. Compared with active systems, the passive designs are much simpler because they do not depend on the availability of large power supplies and they do not rely on safety-grade containment cooling systems, both of which add cost and complexity. Yadigaroglu [1] and Juhn et al. [2] provide reviews of the various passive designs.

The driving forces for these systems are relatively small forces such as natural circulation for cooling and gravity for condensate return. In particular, the heat transfer processes are driven by small pressure and temperature differences. Thus, to achieve the needed cooling rates, heat transfer with phase change is necessary. In one of the first passive concepts, General Electric designed the Simplified Boiling Water Reactor (SBWR) Passive Containment Cooling Systems (PCCS) with vertical heat exchangers that condense containment steam and transfer the heat to a pool outside the containment [3, 4]. The design has evolved [5] and become the basis for passive systems of several current plant designs in the U.S., Europe and Japan.

Another leading design takes advantage of the large heat transfer area on containment walls to condense steam on the inner surface and remove heat through the outer surface by natural circulation of air [6].

There is a strong move towards passive safety systems because the equipment is driven by failsafe forces or mechanisms such as gravity and natural circulation. Adoption of passive systems with efficient heat removal mechanisms will promote future installation of additional nuclear power plants that will increase both reliability and security to our energy supply.

1.2 Goals and requirements

Key goals of these condensation-driven passive heat removal systems include:

1. enhanced safety systems,
2. improved reliability, and
3. greater economic competitiveness via simplification.

Development of passive condensation heat removal mechanisms is particularly timely because the licensing of future nuclear reactors will require a stronger safety case than for previously licensed reactors. The requirements for these systems in U.S. reactors are specified in the U.S. Nuclear Regulatory Commission’s (NRC) Code of Federal Regulations (CFR). Appendix A of 10 CFR Part 50 defines several General Design Criteria such as GDC 35, “Emergency Core Cooling,” which stipulates that the emergency core cooling system (ECCS) be capable of...
heat removal to ensure the core maintains a coolable geometry [7]. For example, the Isolation Condenser System (ICS), a passive condenser in the ECCS of some BWR designs, must satisfy the criteria relevant to ECCS.

In addition, the Electric Power Research Institute (EPRI) led an industrial effort in the 1990s to define technical standards for advanced light water reactor designs that fulfill both the NRC criteria and utility requirements for operational and safety improvements [8, 9]. The Utility Requirements Document addressed both evolutionary and passive plant designs.

The designers may add additional requirements. For example, General Electric designed the Economic Simplified Boiling Water Reactor (ESBWR) ECCS to function successfully without any operator action for 72 hours following accident initiation [10].

1.3 Challenges

Skeptics of passive systems suggest that accident termination may be slower than for active systems. It will be shown in later sections that passive systems satisfy safety requirements, in part because of the extremely efficient phase change heat transfer that is possible with condensation. Additional margin is derived from the power densities of passive plants, which are generally lower than of plants with active systems.

System reliability has also been questioned in the past with regard to condenser heat removal initiation and performance over a wide range of conditions. A concern has been for system activation by small passive forces. Significant effort has been invested to demonstrate that noncondensable gases initially residing along condensation surfaces are quickly purged, enabling timely and efficient system startup. Regarding the range of operability, the performance of condenser in safety systems is confirmed experimentally and analytically prior to awarding the U.S. Design Certification.

Safety analyses of the AP600 and AP1000 indicate improved performance over active systems with respect to peak clad temperatures, peak pressures and Departure from Nucleate Boiling (DNB) margin [6]. ESBWR loss of coolant accident (LOCA) analyses of the ECCS performance using the ICS similarly show compliance with all of the applicable criteria [10].

A challenge remains to further clarify the details of the heat transfer phenomena. A more detailed understanding of the physics, including the condensate film behavior and noncondensable gas redistribution, will enable improved predictive capabilities and reduce the margins currently imposed to cover for analytical uncertainties.

2 Roles of passive condenser systems in nuclear power plants

The passive condensation heat transfer systems are divided into three classifications herein.
1. In-vessel decay heat removal during normal shutdown or refueling.
2. In-vessel decay removal under hypothetical accident conditions.
3. Containment heat removal under hypothetical accident conditions.

“In-vessel” refers to occurrence inside the reactor pressure vessel. “Containment” refers to occurrence in the containment atmosphere surrounding the reactor pressure vessel. Decay heat is the energy released by decay of radioactive fission products following reactor shutdown.

Current safety systems in U.S. Pressurized Water Reactors (PWR) and Boiling Water Reactors (BWR) and their possible passive condenser heat exchanger replacements are described below.

2.1 In-vessel decay heat removal during normal shutdown or refueling

The Residual Heat Removal (RHR) system, an active system, maintains the core in a safe condition during normal shutdown and refueling by pumping cooling water through the reactor core and removing core decay heat. Under hypothetical conditions, the RHR may be lost and alternative active cooling sources may not be available. The loss of RHR situation could lead to core boil-off, fuel rod heatup, and eventually core damage and has therefore been widely studied [11].

Steam condensation in the steam generator U-tubes can become one of the major heat removal mechanisms. As a passive mechanism, steam generated by coolant boil-off would enter the steam generator tube primary side via the hot leg, along with any noncondensable gases ingested during preparation for maintenance and/or refueling. Reflux condensation is the mode of phase change heat transfer occurring when a condensing gas and the liquid condensate flow in opposite directions. In the situation under investigation, steam flows vertically upward in steam generator U-tubes and water forms a condensate film that returns downward to the tube inlet plenum.

BWR safety systems in currently operating reactors rely on a Reactor Core Isolation Cooling system (RCIC) to maintain an adequate water supply in the reactor pressure vessel for core cooling and maintain the reactor in a standby condition. The RCIC also allows for complete shutdown under a loss of normal feedwater system [12]. The RCIC relies on active systems to carry out its functions [13].

In advanced BWRs such as the ESBWR, the ICS is the most comparable system to the RCIC [13]. Designed to passively remove reactor decay heat following reactor shutdown and isolation, the ICS can also prevent the initiation of other safety systems that could perform the RCIC functions. One of the design goals of ICS is to “achieve and maintain safe stable conditions” for 72 hours without operator action following a non-LOCA event. The ICS limits reactor pressure and maintains core cooling by condensation of steam in vertical tube bundles and return of condensate to the reactor pressure vessel. This passive heat removal proceeds independent of any active ICS initiation under reactor isolation events, loss of AC power, transients or hypothetical accidents.
2.2 In-vessel decay removal under postulated accident conditions

Active systems are present in current PWR and BWR that provide sufficient core cooling to prevent core damage and release of radioactive materials. An ECCS injects coolant flow into the primary piping to provide in-vessel decay heat removal during normal shutdown or refueling.

Condensation heat transfer is typically not a major decay heat removal mechanism in PWRs under postulated accident conditions. Reflux condensation in the steam generator tubes would be ineffective in meeting larger heat removal requirements because flooding would inhibit condensation at higher steam mass flow rates.

The active ECCS of the latest BWRs in commercial operation (BWR/6) consists of a high-pressure core spray, an automatic depressurization system, a low-pressure core spray and low-pressure core injection systems. The RCIC system and the RHR system may also be employed [14].

The ICS was designed for the ESBWR to passively remove sensible heat and decay heat following reactor shutdown and isolation by condensation heat transfer. It is part of the ECCS and acts in combination with other new passive features to replace the active components of current ECCS. It activates following sudden reactor isolation, station blackout (loss of all AC power), LOCAs and Anticipated Transient Without Scram (ATWS) [13]. By removing heat and returning condensate to the reactor pressure vessel, the ICS aims to avoid unnecessary reactor depressurization and actuation of other safety systems. The ICS is also considered the first line of defense against a severe accident [10].

2.3 Containment heat removal under postulated accident conditions

Containment systems are designed to contain the steam and radioactive materials released from the reactor pressure vessel following a postulated accident, assuming that the ECCS performs as designed.

PWR active systems include fan coolers and containment spray systems by which water is sprayed from the upper part of the containment. The falling drops condense steam to lower the pressure and cool the containment atmosphere. In the AP600 and AP1000 passive systems [6], steam condenses on a steel containment vessel and the heat is transferred outside containment. Air, circulating by natural convection along the outer surface of the steel vessel, removes the condensation heat. The steel containment vessel is a large heat transfer surface to provide sufficient heat removal even in the presence of noncondensable gases on the condensation side.

For containment heat removal under hypothetical accident conditions, BWRs suppress the pressure by forcing any released steam to flow through a large pool of water. The depressurization system that initiates flow is an active system. Some PWRs of Western design employ the vapor suppression concept by use of “ice condensers”. Conventional refrigeration equipment maintains ice in several large chests placed around the periphery of the containment. The chests are arranged
such that any steam released from a reactor system rupture must pass through the ice chests before flowing into the free volume of the containment. Both BWRs and PWRs employ active containment spray systems where water is pumped from a water source to spray nozzles at the top of the containment vessel.

The BWR pressure suppression system is completely passive in future reactor designs and does not require replenishment of water on the secondary side for a minimum of 72 hours. For the initial blowdown from full pressure, vertical vents direct steam from the drywell to a large pool in the wetwell where most of the vapor is condensed. Once the blowdown has progressed and the drywell-to-wetwell pressure difference is insufficient to clear the vents, the PCCS removes heat via condensation in vertical tube bundles. The PCCS loops are extensions of the containment pressure boundary. Each loop includes a condenser that sits in a pool of water and transfers the heat of condensing steam from the primary side to the coolant pool on the secondary side. The pools are vented to the atmosphere.

3 Description of scenarios and phenomena

3.1 General description of condensation heat transfer

The classical Nusselt analysis of condensation on an isothermal vertical plate in a stagnant steam environment serves as the starting point for describing other scenarios. Figure 1 shows the film condensation situation of the isothermal plate cooling the surrounding vapor, which condenses and creates a thin condensate film on the wall. The film is very thin for steam/water situations. A small natural convection current develops within the vapor region near the condensate film due to the downward flow of the film.

The phenomena occurring in the nuclear power plant safety systems at hand may be described by referring to the Nusselt condensation situation and superimposing complications relevant to the particular scenario. The condensation heat transfer scenarios that arise in passive condenser systems may be classified as:

1. “reflux condensation” in vertical tubes with steam/noncondensable gas inflow from the tube bottom end;
2. condensation in vertical tubes with steam/noncondensable gas inflow from the tube top end;
3. condensation in horizontal tubes with steam/noncondensable gas inflow at one end and condensate draining at the other end;
4. condensation in large water pools;
5. condensation on large vertical walls.

3.2 Reflux condensation in vertical tubes with steam/noncondensable gas inflow from the tube bottom end

During routine shutdown of a PWR for maintenance and refueling, the coolant system may be in a partially drained state known as “midloop operation”. In midloop
operation, the water level is above the core, but below the hot leg elevation. Various primary system closures such as the reactor vessel head may not be secured and air or nitrogen can be drawn into the system. Under hypothetical conditions, the RHR may be lost and alternative active cooling sources are not available.

Nitrogen injection from the accumulator into the reactor Coolant System (RCS) following a LOCA also corresponds to midloop operation with noncondensable gases present. If the accumulator valve were to fail following water injection, nitrogen would enter the RCS and degrade the heat transfer performance of the steam generator. Although the possibility of such a scenario occurring is highly unlikely, the consequences must be known.

Assuming loss of AC power, the possible alternative cooling sources are:

1. gravity drain from the Reactor Water Storage Tank,
2. core boil-off and steam venting, and
3. reflux condensation heat transfer in the steam generators.

Reflux steam condensation in the steam generator U-tubes with noncondensable gases present can become one of the major heat removal mechanisms. Some or all of the steam produced by coolant boil-off would condense inside the hot leg risers of the steam generator U-tubes and the condensate would drain to the hot leg and back to the core region. For reflux condensation to be an effective heat removal mechanism, the RCS must be closed and inventory must be maintained on the steam generator secondary side.

The reference situation is the classical Nusselt condensation of stagnant vapor on a vertical flat plate. Nusselt analysis provides a solution for the film thickness as a function of distance from the top of the plate and for the local heat transfer coefficient.
Compared to Nusselt condensation, the reflux case differs in that the steam has an upward velocity that exerts a shear force on the condensate film in the opposite direction of film draining. If the vapor shear on the liquid film is sufficient, condensate draining is prohibited. Liquid holdup or carryover upward by the vapor is known as “flooding”. Further, the tube flow is internal flow, which provides a constrained geometry that is susceptible to violent pressure oscillations upon flooding. The pressure oscillations would result in unacceptably unsteady performance of the U-tube steam generators.

Noncondensable gases inhibit condensation heat transfer by accumulating along the liquid film, thereby preventing steam from reaching the heat transfer surface. The situation in PWR U-tubes is shown in Fig. 2. Specifically, with noncondensable gases accumulating along the condensate film, steam must diffuse through the gas layer to reach the heat transfer surface. If the gases are not removed, the gas layer adjacent to the liquid film will be steam-starved and the condensation rate will be severely degraded. The steam partial pressure at the condensate surface will be significantly lower than the steam partial pressure in the bulk of the steam/gas mixture and most of the steam will pass through the condenser tube riser without condensing.

With regard to flooding, at a given distance from the condenser tube inlet, a vapor/gas mixture will have more upward momentum than a pure vapor flow. Thus, the condensate film will experience a greater shear upward. Conversely, since less vapor condenses when noncondensable gases are present, there will be less condensate and the effects of flooding on stable operation may therefore be less. Additional investigations are necessary to clarify the effects of noncondensable gases on flooding.

Figure 2: Reflux condensation.
Reflux condensation does not occur on the downflow side of PWR U-tubes because the steam/gas mixture and the condensate liquid are flowing in the same direction.

3.3 Condensation in vertical tubes with steam/noncondensable gas inflow from the tube top end

3.3.1 Condensation in IC tubes under normal shutdown and isolation conditions

The ICS consists of multiple loops, each with an isolation condenser unit that condenses steam on the primary side and transfers heat through the tube wall to the secondary side water pool. Condensed steam drains from the tubes back to the reactor pressure vessel to maintain core cooling. Each ICS loop has noncondensable gas vent lines from the top and bottom headers that can purge noncondensable gas from the unit and assure good heat transfer performance. The ICS is expected to have an inflow of essential pure steam under most operating conditions. During a severe accident, hydrogen from a core coolant interaction may enter the tubes. Noncondensable gases from the containment can enter the ICS units after the reactor pressure vessel depressurization.

The inlet to the ICS condenser tubes is open during normal reactor operation while the exit is valved shut. Thus, the condenser tubes are filled with condensate water and the noncondensable gas vent lines are shut. The condensate return valves open upon LOCA initiation, providing a source of coolant inventory to the core. During refueling, the ICS loops are isolated from the reactor, with all steam supply, condensate return and vent line valves closed [13].

The physical situation inside a vertical tube, such as an IC tube, is shown in Fig. 3. A steam–noncondensable gas mixture enters the condenser and vapor begins to condense at the inlet. As steam is drawn to the cooling surface, the gas experiences a force similar to suction through a permeable wall. The noncondensable gas concentration at the film interface becomes higher than that in the central core and a gas–vapor boundary layer develops adjacent to the liquid boundary layer. Between the annular gas boundary layer and tube centerline, the steam concentration is constant. However, the cross-section average of noncondensable gas concentration increases with distance along the tube axis as the boundary layer thickens. At some axial location, the boundary layer bridges the tube so that there is no longer a central core of inlet composition.

With steam continuing to condense, but at diminishing rates, a fully developed condition may not be achieved in the gas phase. Downstream from the point of nearly complete condensation, the gaseous mixture contains steam in equilibrium with the condensate and noncondensable gas, with a partial pressure that maintains tube total pressure at nearly the system pressure level.

A distinguishing feature of forced convection condensation inside tubes from the Nusselt flat plate case and reflux condensation is the effect of interfacial shear. The gas phase has a higher velocity than the condensate film, producing
interfacial shear and increasing condensate film turbulence. With the gas and liquid film both flowing downward, turbulence thins the film and reduces film resistance to heat transfer. Additionally, the increased interfacial shear promotes turbulence and mixing in the gas core. The resistance of the noncondensable gas boundary layer to condensation heat transfer is reduced. A second distinction concerns the axial variation of the cross-section average temperature and species concentration for the internal flow case. In contrast to the stagnant atmosphere case, the temperature decreases with distance along the condenser tube and the noncondensable gas concentration increases. Axial variations of the conditions driving heat and mass transfer arise, but they do not occur in the stagnant gas, vertical flat plate situation.

Sparrow and Lin’s work [15] show similarity in the boundary layers and a uniform interface temperature. For a constant, free stream gas mass fraction, Denny, et al. [16] note nonsimilarity in the three-phase problem. With a variable centerline gas mass fraction, the problem becomes even more nonsimilar in character. An exact
analytical solution would require solving radially and axially dependent boundary layer conservation equations that could not be reduced to ordinary differential equations.

### 3.3.2 Condensation in IC and PCC tubes under hypothetical accident conditions

During a postulated accident in which there is a large energy release from the primary system, steam and flashing water can cause a significant containment pressure rise. For the passive plants, new systems for removal the energy sources to outside of the containment without releasing radioactive materials are needed. A condensation heat transfer mechanism of long-term decay heat removal, the PCCS has been incorporated into the design of the ESBWR[5].

The PCCS is a post-LOCA, low pressure, decay heat removal system designed for the SBWR [3, 4] and upgraded for the larger power rating ESBWR [10]. The function of the PCCS is to remove heat from the reactor containment system (drywell and suppression chamber) and maintain pressure below the design value by passive means. The primary components of the PCCS are several condensation heat exchanger units. Located in a large pool of water outside of the containment, the PCCS units consist of an upper steam plenum, condenser tubes, and a lower condensate plenum (Fig. 4).

On the primary side of the PCCS units, noncondensable gases and decay heat steam enter from the drywell. Steam condenses inside the tubes and condensate drains to the GDCS pools. These pools are elevated relative to the reactor and serve to maintain reactor water inventory following an emergency depressurization of the primary system. These pools drain to the reactor pressure vessel when the sum of drywell pressure plus water head in the drain lines is greater than the sum of the reactor vessel pressure plus vessel water head above the drain line inlet nozzles. As the condensation proceeds, gases and a small amount of steam exiting the condenser tubes are vented to the suppression pool. The steam, drain, and vent flows are driven by natural circulation and the pressure difference between the drywell and suppression chamber.

On the secondary side of the PCCS units, heat is carried away from the condenser tubes by water in the surrounding natural circulation pools. Pool water inventory is maintained sufficient to prevent tube uncovering for at least 72 hours. The pool initially is subcooled at atmospheric pressure, and rises to saturation temperature at just above one atmosphere after a few hours of decay heat removal.

The distribution of noncondensable gases throughout the containment system is a key factor in determining the post-LOCA conditions and behavior of the PCCS units. During normal reactor operation, the SBWR containment is inerted with nitrogen, and operates at just above atmospheric pressure. The containment gas mixture is composed primarily of nitrogen and steam. The low oxygen content prevents buildup of a potentially combustible gas mixture. However, the noncondensable gas inventory has the potential to degrade the performance of the heat exchangers.
Early in the blowdown transient, most of the drywell gas is transferred to the suppression chamber gas space, along with the blowdown steam, via the main drywell-to-suppression chamber vent system. The PCCS was designed for long-term heat removal and does not have the capacity to remove all of the blowdown heat. In the longer term, steam produced by decay heat is released by the reactor pressure vessel into the drywell for intake by the PCCS. Residual noncondensable gas in the drywell is vented to the suppression pool via the PCCS units and, in the process, degrades heat removal performance by inhibiting steam condensation.
within the tubes. The ICS ingests steam produced by decay heat and any noncondensable gases that have entered the reactor pressure vessel. The phenomena inside the tubes are the same as described for the ICS in the previous section.

3.3.3 Condensation in horizontal tubes with steam/noncondensable gas inflow at one end and condensate draining at the other end

As one of the most widely used types of heat exchangers, horizontal condensation heat exchangers have traditionally found many industrial applications, including in the process industry, the air conditioning and refrigeration industry, and for condensation of mixed vapors for distillation of hydrocarbons [17].

In the nuclear industry, horizontal heat exchangers are also widely used. Recently, a horizontal heat exchanger design has been proposed for a PCCS of future light water reactors [18]. Tujikura et al. [19] and Ueno et al. [20] also consider the participation of horizontal steam generators as condensers in PWRs in the event of postulated accidents. Current PCCS designs typically employ a vertical condenser [5]. The horizontal design is proposed because horizontal heat exchangers have a potentially higher heat removal capability than vertical heat exchangers [21] and higher seismic resistance.

The details of condensation heat transfer in the presence of a noncondensable gas in horizontal condenser tubes are not well understood. Compared to the well-studied case of in-tube condensation for vertical downflow [22, 23], the complication of this phenomenon mainly comes from several factors. The first is the non-symmetrical two-phase phase distribution in the tube cross section (Fig. 5). Also, within the gas phase, when the velocity is low, the asymmetrical noncondensable gas concentration caused by the density difference between the noncondensable gas and vapor could affect the heat transfer [24]. For flow regimes with low gas-phase superficial velocity, the heat transfer characteristics at the top and bottom of the tube are quite different, and thus the heat transfer coefficients are also different. Second, the interfacial phenomena including film surface instabilities and droplet entrainment/deposition may play a larger and different role than in vertical tubes. Under low gas velocity conditions, condensate droplets may detach from the condensate film due to gravity, interacting with the gas core and exposing a cooler condensate film surface to the vapor. The third factor is the mode of condensate drainage. In a horizontal tube, condensate must be carried out by its own momentum or by shear from the vapor/gas mixture whereas gravity draining occurs in a vertical tube.

Gravitational and interfacial shear forces determine the local flow regime. The flow regimes are commonly classified into three categories, as reviewed by Wu [25]:

- annular and annular-mist flow, which are driven primarily by shear forces.
- stratified flow, wavy flow and slug/plug flow, which are gravity driven.
- wavy-annular flow, which have strong contributions from both the gravity and shear forces.
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For shear-driven flows, the heat transfer mode across the condensate film is forced convection heat transfer. For gravity-driven flows, the condensate film experiences largely conduction at the top of the tube and a combination of forced convection and conduction at the bottom of the tube.

3.4 Condensation in large water pools

Condensation in large water pools differs from the other condensation modes discussed herein because the condensation surface is not a liquid film. Rather, vapor undergoes direct contact condensation on the surrounding subcooled water in a complicated variety of interfacial configurations and thermal hydraulic interactions. The vapor phase may be discontinuous (bubbly flow) or discrete (jet flow) depending on whether the vapor transport is due to blowdown of the drywell into the suppression chamber or venting from the PCCS heat exchangers.

During the initial blowdown of a BWR, the drywell steam/gas mixture is discharged into a large, annular water volume termed the suppression pool. The hydrodynamic phenomena associated with the steam/gas jets are rapid and violent due to the large driving pressure difference between volumes. Pressure waves against the outer wall of the suppression pool are expected along with a high degree of turbulence due to condensation chugging and mixing of the entire suppression pool.

In the longer-term containment cooling by the PCCS, the PCCS condensers purge a vapor/noncondensable gas mixture into the suppression pool via a vent line with relatively shallow submergence at the exit. Internal circulation of the noncondensable gas within the vapor bubbles affects the condensation rate. The vent line is submerged shallow enough to vent, yet deep enough for vapor bubble condensation below the water surface.

A detailed description of the phenomena, with emphasis on the noncondensable gas effect, is provided by Xu [26].
3.5 Condensation on large vertical walls

The PCCS provides one method for passively removing energy from the containment to the atmosphere, thereby avoiding a potential threat to the structural integrity of the containment. A second method for containment heat removal relies on thermodynamics principles. During a hypothetical LOCA, the flashing coolant released from the primary side break will condense on the containment walls if the surface temperature is below the dew point. Because the wall heat transfer area is large, condensation on structures can be an important heat removal mechanism.

Heat removal by condensation on large vertical containment walls is an AP-1000 and AP-600 passive safety feature. A secondary side air circulation system has been incorporated into the design to take advantage of the wall heat transfer. Other systems without the secondary side may take smaller credit for this heat removal mechanism. Dropwise condensation will occur on the upper regions of the condensation surfaces. Most of the surface is expected to be covered with a condensate film.

Departures from the Nusselt analysis scenario include the presence of noncondensable gases and the effect of the liquid–gas interface on the heat transfer rates. A wavy interface on the film increases transport of heat, mass and momentum by increasing the turbulence intensity, decreasing the gas viscous sublayer thickness and by reducing the laminar film thickness.

4 State-of-the-art analysis methods

4.1 Basic approaches

Rigorous safety analysis is needed to design and license a nuclear power plant. The basic approach for analysis of new systems is to apply the techniques used for standard plants to the passive plant systems, modifying the analyses as experimental data becomes available.

Many empirical formulations apply correction factors to the local heat transfer coefficient or Nusselt number obtained from the Nusselt analysis. For pure vapor condensation on a vertical plate, the vapor boundary layer and the film are typically thin enough for the boundary layer assumptions to be valid. Other assumptions in the Nusselt analysis are listed below. These are reflected in the velocity and temperature profiles of Fig. 1.

1. Stagnant, pure vapor at $T_{sat}$ (no noncondensable gases).
3. Laminar flow and constant properties in the condensate film.
4. Condensate film heat transfer by conduction only, no momentum or energy transfer by advection in the condensate.

Nusselt solved the momentum equation for the condensate film to obtain the film thickness as a function of distance from the top of the plate. The film thickness was converted to a thermal resistance, from which local and plate-averaged heat transfer coefficients were formulated.
\[ h(z) = \frac{k_l}{\delta(z)} \]  

(1)

where the local film thickness is:

\[ \delta(z) = \left[ \frac{4k_l\mu_l (T_{sat} - T_{surf}) z}{g \rho_l (\rho_l - \rho_v) h_{tg}} \right]^{1/4} \]

The original work of Nusselt has been extended by Rohsenow [27] to account for the thermal advection contribution by adding a term to the latent heat of vaporization. The local film heat transfer coefficient is expressed as:

\[ h(z) = \left[ \frac{g \rho_l (\rho_l - \rho_v) k_l h_{tg}}{4 \mu_l (T_{sat} - T_{surf}) z} \right]^{1/4} \]  

(2)

Theoretical models are preferable because they better reflect the physical phenomena and are not restricted to ranges of conditions of particular experimental facilities. Current modeling techniques for relevant condensation heat transfer scenarios are discussed below.

4.2 Reflux condensation in vertical tubes with steam/noncondensable gas inflow from the tube bottom end

Reflux condensation in nuclear engineering applications is generally evaluated as part of a reactor system analysis using a reactor safety code. The heat transfer models that the codes call upon for reflux condensation analysis were developed for condensation of vapor/condensate co-current downward flow on flat plates, in tubes or for other situations and were shown to have deficiencies in predicting reflux condensation heat transfer. The capabilities of reactor safety codes such as RELAP5 [28, 29] and TRACE [30] have been recently evaluated to predict reflux condensation. Moon and Park noted these deficiencies in RELAP5, while Queral presented a system evaluation without details on the reflux condensation model or results.

Some of these evaluations have used the correlations of the codes inappropriately. For example, Park et al. [29] used correlations in RELAP5 developed for downward steam flow in a reflux condensation analysis. The gas mixture Reynolds number is the highest where the condensate film is thickest, which renders correlations developed for other in-tube situations inapplicable for reflux condensation analysis.

Several recent experimental programs have provided new data on reflux condensation heat transfer rates for development of empirical correlations [28, 31–35]. These correlations are generally a function of Reynolds number of the gas mixture.
and/or condensate, noncondensable gas concentration, and dimensionless property quantities such as the Prandtl number and Jacob number. They are simple and formulated to be compatible with reactor safety code implementation. The correlations have been implemented in reactor safety codes such as RELAP5/SCDAPSIM/MOD3.2 [33] and verified against independent data sets.

Moon et al. [28] correlated a degradation factor to account for degradation by noncondensable gases and enhancement by vapor shear. The local Nusselt heat transfer coefficient, when multiplied by this factor, provides a local heat transfer coefficient for reflux condensation.

\[ F(z) = \frac{h_{\text{exp}}(z)}{h_{l}(z)} = 2.58 \times 10^{-4} Re_{v}^{0.200} Re_{l}^{0.502} W_{\text{air}}^{-0.244} Ja^{-0.642} \]  

where \( W_{\text{air}} \) is the local air mass fraction. The stated range of validity is \( 6,110 < Re_{v} < 66,586, 1.2 < Re_{l} < 166.6 \) and \( 0.140 < W_{\text{air}} < 0.972 \).

Nagae et al. [33] derived a local Nusselt number for the interfacial heat transfer coefficient, \( h_{i} \), using the data of Vierow et al. [32].

\[ N_{ui} = \frac{h_{i} d_{ui}}{k_{v}} = 120 \left( \frac{P_{T}}{P_{\text{air}}} \right)^{0.75} \max \left(1.0, a Re_{l}^{b} \right) \]  

where \( Re_{v} = j_{v} d_{ui} / v_{l} \leq 5,000 \), \( a = 0.0012 \) and \( b = 1.0 \). This correlation is valid for steam–air mixtures under laminar flow conditions.

Most recently, Lee et al. [35] correlated a local heat transfer coefficient correction factor as:

\[ F(z) = \frac{h_{\text{exp}}(z)}{h_{l}(z)} = 4.88 \times 10^{-4} Re_{l}^{0.59} W_{\text{air}}^{-0.29} Ja^{-0.89} \]  

where \( 1.5 < Re_{l} < 246, 0.02 < W_{\text{air}} < 0.96 \) and \( 0.014 < Ja < 0.123 \).

The lack of mechanistic models for reflux condensation may be traced to insufficient understanding of factors not present in the classic Nusselt situation. First, the vapor velocity and vapor-condensate film interactions must be considered. Interfacial waves induce film turbulence and Nusselt’s assumption of a linear film temperature distribution becomes invalid. The local heat transfer coefficient may be a strong function of the vapor velocity [36] Second, noncondensable gases are generally present in nuclear power plant applications. Third and unique to reflux condensation, flooding limits the range of conditions under which reflux condensation is stable.

Gross and Philipp [36] provide a summary of the development of mechanistic models for reflux condensation heat transfer starting from the Nusselt analysis. They noted that the theoretical Nusselt model had been extended to include vapor flow effects such as drag coefficients.

The Gross and Philipp study of the shear stress effect on the local Nusselt number provides insight for new mechanistic model development. Under pure vapor
conditions, the shear stress was shown to decrease the Nusselt number for low film Reynolds numbers and to enhance heat transfer at high film Reynolds number. A semi-empirical model was presented for local Reynolds numbers of very thin films, eqns (6) and (7). For thicker films, the effect of shear stress on Nusselt number was successfully correlated, eqn. (8). Increased understanding of the film behavior at the film-gas interface and the noncondensable gas flow is needed for further mechanistic model development.

\[
\delta^* = 0.59 \tau^* + \left( 3^{1/3} - 0.0086 \tau^* \right) \left( Re_l + 0.28 \tau^* \right)^{1/3}
\]  

where \( \delta^* \) is a dimensionless film thickness and \( \tau^* \) is a dimensionless shear stress at the vapor–liquid interface.

\[
Nu = \left[ 0.59 \tau^* + \left( 3^{1/3} - 0.0086 \tau^* \right) \left( Re_l + 0.28 \tau^* \right)^{1/3} \right]^{-1}
\]  

\[
Nu_{corr} = Nu_{\tau\rightarrow0} \left[ 1 + \left( 0.18 \tau^* + \tau^*^{2.2} \right) \left( -0.25 + 0.016 Pr_l^{1.08} \right) \right]
\]  

4.3 Condensation in vertical tubes with steam/noncondensable gas inflow from the tube top end

For PCCS analysis, empirical correlations have been developed from the early 1990s [22, 37]. Multiplication factors were obtained for the local Nusselt heat transfer coefficient to account for shear enhancement and noncondensable gas degradation. These enabled efficient analysis with reactor safety codes.

Several researchers have extended the Nusselt analysis for pure vapor condensation on a vertical plate in a stagnant gas atmosphere, providing valuable insights into the phenomena occurring in vertical tube geometries such as the Isolation Condenser and PCCS heat exchangers.

The first series of analyses were for condensation with noncondensables on a flat plat with a laminar condensate film. Sparrow and Eckert [38] performed a boundary layer analysis which showed the large degrading effect of a noncondensable gas on heat transfer rates for a laminar condensate film. Comparing the results with experimental data, they noted that free convection to/from the condensation surface plays an important role when noncondensable gases are present although this effect was not included in their analysis. Also using boundary layer analysis, Koh et al. [39] considered the shear forces at the liquid–vapor interface due to induced motions of the vapor. The shear effect on heat transfer rates was small for Prandtl numbers of one or greater but large for Prandtl numbers in the range of liquid metals. Sparrow and Lin [15] derived rigorous sets of conservation equations for the liquid and vapor boundary layers that considered the liquid shear forces on the vapor and free convection. Minkowycz and Sparrow [40] investigated the interfacial resistance phenomena in greater detail and found that
formulation of the case with interfacial shear does not yield a similarity solution. This analysis considered the roles of temperature in the diffusion equation and variable properties in the boundary layers. Rose [41] provided an algebraic relation between the heat and mass transfer properties and obtained good agreement with the boundary layer analyses and experimental data.

Several of the free convection boundary layer analyses underpredicted experimentally measured heat transfer coefficients. The validity of the boundary layer analyses was demonstrated by Al-Diwany and Rose [42] who performed experiments with particular care to avoid unintentional forced convection flows and obtained good agreement between analysis and experiment.

Sparrow et al. [43] solved the boundary layer equations for the vapor/noncondensable gas condensation with forced convection and a laminar condensate film. The vapor energy equation was not considered due to relatively small energy flow in the vapor and a numerical procedure was employed to solve the equations. The heat transfer rate in a forced convective flow was shown to be less sensitive to the noncondensable gas concentration than in a free convection situation. Denny et al. [16] observed nonsimilarity of the situation and solved the equations with a finite difference technique.

While the boundary layer approach has been solved for laminar flow conditions and great insight into the phenomena was obtained, incorporation of the boundary layer equations into reactor safety analysis is not practical. A method based on the heat and mass transfer analogy allows for simpler formulations while retaining good accuracy.

Colburn and Hougen [44] first applied the heat and mass transfer analogy to vapor condensation using the stagnant film model for vapor–air mixtures. The overall heat transfer conductance between the condenser tube wall and vapor–air mixture is the sum of the conductance of the condensate film and the vapor/noncondensable gas boundary layer. The heat transfer through the gas boundary layer includes sensible and latent heat transfer. The latent heat transfer is evaluated by using the stagnant film model combined with the heat and mass transfer analogy.

Peterson’s diffusion theory [45] significantly improved modeling capabilities by providing a theoretical analysis method compatible with reactor safety codes. Peterson introduced the concept of a “condensation thermal conductivity” in developing the diffusion layer model, wherein the overall gas-side conductivity is formulated as a combination of the condensation thermal conductivity for latent heat transfer and the standard thermal conductivity for sensible heat transfer. Treating the gas film as a diffusion layer, Peterson [45, 24] derived a condensation thermal conductivity in the diffusion layer model on a molar basis:

\[
k_c^p = \frac{1}{\phi} \frac{h'_q h_q PDM_q^2}{R^2 T^3}
\]

where

\[
\phi = \frac{\ln[(1 - x_{gb})(1 - x_{gb})]}{\ln(x_{gb}/x_{gb})}
\]

\[
(9)
\]
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$k^p$ is the condensation thermal conductivity, $P$ is pressure, $D$ is the diffusion coefficient, $M$ is the molecular weight and $x$ is molar fraction. The total heat transfer coefficient is conveniently given by combining the parallel gas-side latent heat transfer and sensible heat transfer coefficients in series with the liquid-side heat transfer coefficient:

$$\frac{1}{h_l} = \frac{1}{h_{\text{c}}} + \frac{1}{h_{\text{k}}} = \frac{L}{Sh \cdot k^p_{\text{c}} + Nu \cdot k_{\text{k}}} + \delta_l$$  \hspace{1cm} (11)

Peterson’s diffusion theory has been incorporated into several reactor safety codes such as TRACE and CONTAIN. The model is successful in predicting condensation heat transfer rates in vertical tube experiments prototypic of the PCCS and other vertical tube heat exchangers with a trend to slightly underpredict the data. Since the underprediction is not extreme and in the conservative direction, the results are generally acceptable. There have been, however, several attempts to modify the theory formulation.

The diffusion layer model for condensation heat transfer of vapor with noncondensable gases was originally derived on a molar basis. Developed from an approximate formulation of mass diffusion, the effect of variable vapor–gas mixture molecular weights across the diffusion layer on mass diffusion was neglected. This is valid for a gas with a molecular weight close to that of the vapor or for low vapor mass transfer rates, however a large error may be incurred if a steep gradient in the gas concentration exists across the diffusion layer. Liao and Vierow [46] show from the kinetic theory of gases that Fick’s law of diffusion should be expressed on a mass basis rather than on a molar basis. A generalized diffusion layer model was derived on a mass basis with an exact formulation of mass diffusion. The generalized model considers the effect of variable mixture molecular weights across the diffusion layer on mass diffusion and fog formation effects on sensible heat. Under certain limiting conditions, the generalized model reduces to that developed by Peterson.

The condensation thermal conductivity derived on the mass basis was recast to a form comparable to that derived on a molar basis by using the Clausius–Clapeyron equation and the ideal gas law.

$$k_c = \frac{\phi_2' h_k' h_k P D M \phi_1' M_g}{R^2 \bar{T}^3}$$  \hspace{1cm} (12)

where

$$\phi_1 = \frac{\ln[(1-m_{gb})(1-m_{gi})]}{\ln(m_{gi}/m_{gb})}$$  \hspace{1cm} (13)

and

$$\phi_2 = \frac{\bar{M}_m^2}{M_{mb} M_{mi}}$$  \hspace{1cm} (14)
\( \phi \), in eqn. (13) is analogous to \( \phi \) in eqn. (10) and takes into account the effects of noncondensable gas and suction on vapor condensation. \( \phi_2 \) in eqn. (14) is a new factor, which takes into account the effects of variable mixture molecular weights on vapor diffusion resulting from large concentration differences through the diffusion layer. Comparisons with a variety of experimental data show that the generalized diffusion layer model were shown to better predict the data than molar-based diffusion layer models. The generalized diffusion layer model is currently being implemented and tested in reactor safety codes.

4.4 Condensation in horizontal tubes with steam/noncondensable gas inflow at one end and condensate draining at the other end

Similar to condensation in a vertical tube, condensation in a horizontal tube is of the film condensation mode except very close to the steam inlet where the droplet mode may be observed. The tube orientation, however, introduces complications that render analysis of horizontal tube condensation far more than a mere extension of vertical tube analysis. First, while annular flow occurs in vertical tubes, the flow regime in horizontal tubes depends on the vapor–film shear and the peripheral and axial location. Therefore a methodology for flow regime determination must be added. Second, because the condensate film thickness varies with peripheral location, the fluid and heat transfer phenomena are highly three-dimensional. The conservation equations for the boundary layer analysis should be expanded to include the peripheral coordinate. Third, the interfacial phenomena including film surface instabilities and droplet entrainment may play a larger and different role than in vertical tubes. Models should be added for these phenomena.

The method for flow regime determination is discussed first because selection of the heat transfer models depends on the local flow regime. Wu and Vierow [47] and Thome et al. [48] provide recent reviews of methods for flow regime determination in horizontal tubes with condensation. In addition to investigations for nuclear safety systems, Thome et al. are conducting experimental and theoretical work to better understand refrigeration and other industrial systems. Thome et al. [48] presented a flow regime mapping based on estimations of the “logarithmic mean void fraction”, which lead to liquid and vapor mass velocities and a flow regime determination. A validated heat transfer model for condensation inside horizontal plain tubes was developed using this flow regime mapping [49].

Gravitational and interfacial shear forces determine the local flow regime. The flow regimes are commonly classified into three categories, as reviewed by Wu [25]:

- annular and annular-mist flow, which are driven primarily by shear forces;
- stratified flow, wavy flow and slug/plug flow, which are gravity driven;
- wavy-annular flow, which have strong contributions from both the gravity and shear forces.
Wu [25] adopted flow regime criteria from Jaster and Kosky [50] and Soliman [51–53] for theoretical modeling of steam in larger diameter tubes representing the PCCS tubes. Both criteria were developed for condensation inside tubes and apply to larger tube sizes than those used by Thome. Jaster and Kosky expressed flow regime criteria for annular flow-to-transition flow and transition flow-to-stratified flow as a ratio of the axial shear force to the gravitational force. Soliman predicted the mist-to-annular flow transition based on a modified Weber number that represents a balance between forces inhibiting liquid entrainment and vapor inertia enhancing mist formation. For the annular-to-wavy flow transition, Soliman [51] adopted a modified Froude number, which is a balance between inertial and gravitational forces on the liquid film.

Following flow regime identification, the local heat transfer calculation may be formulated. The pure vapor formulations and vapor/noncondensable gas formulations are presented below.

Chato [54] proposed a Nusselt number formulation for condensation of pure vapor in low-velocity stratified flow. The Nusselt number has the same functional dependencies as Nusselt’s formula for condensation on flat plates but with a lower coefficient. For higher velocities in stratified flow, Rosson and Meyers [55] showed that the Nusselt number at the top of the tube has the same functional dependencies with a \( Re^n \) multiplier to account for vapor shear effects. The Nusselt number at the bottom of the tube depends on the \( Re, Pr \) and the Lockhart–Martinelli parameter \( X \).

For shear-driven, pure-vapor, annular flow situations, Cavallini and Zecchin [56], Shah [57] and Dobson and Chato [58] obtained Nusselt number correlations in the form of the Dittus–Boelter correlation times a two-phase multiplier. These are the most widely used correlations for reactor safety analysis, although approaches based on evaluation of shear on the laminar sublayer and interfacial surface have also been developed. Levich [59] adopted a boundary layer approach based on a laminar sublayer at the wall and a second viscous sublayer near the liquid–gas interface in which surface tension arising from turbulent deformation damps the turbulent interfacial fragmentation.

Thome et al. [49] present a heat transfer calculation method for pure vapor condensation that covers all of the flow regimes expected in reactor applications and is in a format compatible with reactor safety codes.

To account for the noncondensable gas effect on reducing heat transfer efficiency, several reactor safety codes employ Peterson’s [45] diffusion theory. The boundary layer work presented in earlier sections was formulated for flat surfaces and the available empirical correlations are restricted to the ranges tested.

In summary, numerous models and correlations exist for various aspects of the problem; however the call remains for a robust and verified model applicable to nuclear safety system scenarios.

### 4.5 Condensation in large water pools

The phenomena associated with vapor bubble condensation in large water pools have been studied most recently by Xu [26]. Xu presents an experimental investigation...
of the direct condensation of bubbles in a subcooled water pool, with and without noncondensable gas. Although these phenomena are important for evaluation of containment pressures, the discussion of analysis techniques herein is limited to condensation in the film mode.

4.6 Condensation on large vertical walls

The heat and mass transfer analogy is widely employed by reactor safety codes for evaluation of condensation heat transfer rates on containment walls. To evaluate the heat transfer rates, correlations are implemented for natural convection, forced convection and mixed convection. Invoking the heat and mass transfer analogy, the Sherwood number is assumed equal to the Nusselt number for the mass transfer rate calculation. The degrading effect of noncondensable gases on the condensation heat transfer rate is accounted for by incorporating diffusion theory to provide the appropriate log mean pressure in the mass transfer equations. Peterson [60] demonstrated the improvement of this diffusion theory representation over earlier methods that employed correlations based on the Uchida data.

To complete the models, CONTAIN [61], MELCOR [62] and COMMIX [57] have adopted the same film tracking model to calculate the condensate film thickness on containment walls. Summarized by Sha [57], the film tracking model assumes filmwise condensation and computes the film thickness, film temperature and velocity. Because the film is generally <1 mm in thickness, laminar flow predominates and the classic Nusselt analysis is the basis for the formulation of the boundary layer equations.

5 Analysis challenges

Remaining challenges for analysis of passive systems driven by condensation heat transfer arise from incomplete understanding of phenomena, uncertainty in boundary conditions and numerical issues. These issues impact analysis at the fundamental heat transfer level and at the reactor system level.

Major challenges include:

1. Better understanding of condensate film behavior in reflux and horizontal condensers, including both film sublayers and the film surface interactions. Boundary layer analysis may be a useful tool for this purpose.
2. Peripheral characteristics of condensate film behavior in horizontal and inclined tubes. Additional experimental study with film visualizations would be beneficial.
3. Mixing in large volumes to predict noncondensable gas concentrations at condenser tube inlets.
4. Accurate calculations over a long duration.
5. Accounting for the tighter coupling of the primary loop pressure with the containment pressure in passive plants than in active plants.
6 Summary

Passive systems driven by condensation heat transfer represent a return to simplicity while achieving significant strides in reactor safety. These passive condensation heat transfer systems are reliable and inherently safe because they rely on basic physical forces such as gravity and small pressure differences to transport energy and maintain the plant within design specifications. While significant advancements have been made, challenges remain particularly with regard to accurate, detailed evaluations of heat transfer rates.

The numerous roles for passive condensation heat transfer systems have been summarized in this chapter with a focus on U.S.-designed light water reactors and U.S. reactor safety codes.

The state-of-the-art in analysis methods was presented along with analysis challenges at the phenomenological level and system level. Suggestions with respect to advancement of the condensation modeling were provided. In particular, boundary layer analysis was shown to have provided great insight into the details of the phenomena, particularly for laminar condensate films. Extension of the boundary layer analysis for turbulent flows under additional boundary conditions and geometries is desirable. Secondly, condensate film behavior in inclined and horizontal tubes is not well understood under nuclear safety system conditions. Additional experimental studies could clarify the phenomena and provide a theoretical basis for modeling.

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Nomenclature

Symbols

\[ D \] diffusion coefficient
\[ d \] diameter
\[ F \] multiplication factor
\[ g \] gravity vector
\[ h \] local heat transfer coefficient
\[ h_c \] condensation heat transfer coefficient
\[ h_{\text{exp}} \] experimentally measured heat transfer coefficient
\[ h_t \] Nusselt heat transfer coefficient, film heat transfer coefficient
\[ h_{lg} \] latent heat of vaporization
\[ h_s \] sensible heat transfer coefficient
\[ j \] superficial velocity
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$Ja$ Jacob number
$k$ thermal conductivity
$L$ characteristic length
$M$ molecular weight
$m$ mass fraction
$Ma$ noncondensable gas mass fraction
$Nu$ Nusselt number
$P$ pressure
$Pr$ Prandtl number
$R$ universal gas constant
$r$ radial coordinate
$Re$ Reynolds number
$Sh$ Sherwood number
$T$ temperature
$u$ velocity
$W$ noncondensable gas mass fraction
$x$ mole fraction
$y$ coordinate normal to the condensation surface
$z$ coordinate parallel to the condensation surface

Greek symbols

$\delta$ condensate film thickness
$\theta$ circumferential coordinate
$\mu$ dynamic viscosity
$\nu$ kinematic viscosity
$\rho$ mass density
$\tau$ shear stress

Subscripts

$\text{air}$ air
$\text{corr}$ correlation
$g$ gas
$gb$ gas in the bulk
$gi$ gas at the interface
$i$ interface
$l$ liquid
$max$ maximum
$\text{sat}$ saturation
$surf$ surface
$v$ vapor
$\text{wall}$ wall
References


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