PASSIVE RESIDUAL HEAT REMOVAL SYSTEMS
FOR CURRENT AND FUTURE LIGHT WATER REACTORS

A Thesis

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PASSIVE RESIDUAL HEAT REMOVAL SYSTEMS
FOR CURRENT AND FUTURE LIGHT WATER REACTORS

A Thesis

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Department of Mechanical Engineering
Abstract

of

PASSIVE RESIDUAL HEAT REMOVAL SYSTEMS
FOR CURRENT AND FUTURE LIGHT WATER REACTORS

by

Ian James Treleaven

The main problem with nuclear power during a shutdown is that decay heat is still present and needs to be removed to prevent a number of problems. The traditional method of removing heat is through forced circulation via pumps. This setup works well unless the pumps are damaged or lose electricity. Therefore, there has been plenty of research conducted on Passive Residual Heat Removal Systems (PRHRS). These types of systems use multiple natural convection paths to dissipate the residual heat from both the reactor vessel and the containment structure before it can cause major problems.

The purpose of this thesis is to investigate the PRHRS for the Pressurized Water Reactor and the Boiling Water Reactor, and show where they stand in terms of future reactor design and possible retrofits for existing reactors.

Research showed that many nations are already implementing PRHRS in future designs. However, it is recommended that they retrofit existing reactors to prevent a similar Fukushima disaster and to fully utilize the lifespan of their investment.

Previously proposed retrofits involve levees and hydrogen ventilation. Newly proposed retrofits introduced in this investigation pertain to using the PRHRS and fuel
rod bundle geometry. Both technologies have been used on reactors before, but they have never been considered for use as a retrofit. They both offer specific benefits to engineers in designing retrofits, as detailed in the study.

_______________________, Committee Chair
Dr. Dongmei Zhou

_______________________
Date
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Ian Treleaven
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Chapter 1

INTRODUCTION

1.1 PROBLEM WITH NUCLEAR POWER

One major problem with nuclear power is that the heat generated from the nuclear fuel is inherently unstable. The heat generated in a nuclear reactor naturally accelerates unless the chain reaction is controlled. Although the self-sustaining chain reaction in nuclear fuel can be stopped in the event of a shutdown, decay heat is still present and must be dealt with to prevent a meltdown of the nuclear rods or a breach in the containment structure.

Because of the inherently unstable nature of nuclear power, there is plenty of ongoing research on passive safety designs. Although there are many degrees of passive safety designs, they typically rely less, or not at all, on electricity, mechanical parts, human input, working fluids, and/or automated sensors. Passive safety designs rely on physical phenomena such as pressure differentials, gravity, natural convection, material response, and phase change, to regulate a process [1]. These designs are a major part of a safe nuclear energy future, with less risk of disastrous meltdowns.

One of the most promising passive safety designs is the Passive Residual Heat Removal System (PRHRS). This system uses natural convection to dissipate residual decay heat from the nuclear fuel rods in the event of a reactor shutdown and thus addresses the issue of overheating.
1.2 CONSEQUENCES OF DROPPING NUCLEAR ENERGY

In addition to the inherent problem with nuclear energy, the recent Fukushima Daiichi disaster has caused many more countries to rethink their nuclear energy strategy. Some nations have decided they want to either phase-out existing nuclear power plants and/or put a hold on constructing new plants, while other nations are still actively seeking new construction, but incorporating lessons learned from Fukushima [2]. A brief summary of many nations’ nuclear policy post-Fukushima is listed below in Table 1.1.

Table 1.1 Summary of nation’s nuclear policy post-Fukushima [2].

<table>
<thead>
<tr>
<th>Policy responses to the Fukushima Daiichi accident.</th>
<th>Nuclear phase out — no new build</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>Plants under construction suspended; Fukushima 1–4 to be decommissioned; remaining 50 plants successively shut down by 5 May 2012. Two restarts in July 2012. Future use of nuclear power contested. Subsequently, phase out intentions by late 2030s announced.</td>
</tr>
<tr>
<td>China</td>
<td>The award of new construction licences was suspended but lifted again in October 2012.</td>
</tr>
<tr>
<td>Belarus, Turkey, UAE</td>
<td>First plant ordered.</td>
</tr>
<tr>
<td>Chile, Indonesia, Malaysia, Morocco, Saudi Arabia</td>
<td>Active preparation with final decision delayed or no final decision.</td>
</tr>
<tr>
<td>Thailand, Jordan</td>
<td>Continue preparing infrastructure.</td>
</tr>
<tr>
<td>Bangladesh, Vietnam, Egypt, Nigeria, Poland</td>
<td>Plans to introduce nuclear power cancelled.</td>
</tr>
</tbody>
</table>

Phasing out nuclear power should be done very carefully as there are many negative consequences. For example, Japan plans to phase out all of its nuclear energy production by 2040, while it is the third largest nuclear power producer in the world. If not done properly, this will have a negative effect on the economy, as close to 27% of its energy came from nuclear prior to the Fukushima accident [3]. Shutting down the
reactors will also bring increased energy prices and energy dependence, as Japan needs to import nearly all its fossil fuels [3]. An increase in fossil fuels usage also means an increase in CO2 and particulate matter expelled into the air. In addition, switching to purely renewable energy sources will also increase energy prices placing an extra burden on Japan’s economy [3]. A purely renewable energy portfolio is not currently viable since many of these options are either not currently economically feasible and/or are intermittent in their power output.

Other nations that plan a nuclear free future may also be missing the safety of nuclear energy. Replacing nuclear energy with other sources will increase human deaths [4]. Table 1.2 below lists deaths per TWh produced for a year for various energy industries. Factoring in all hazards pertaining to an energy source, nuclear is by far the safest form on energy production [4]. No energy source walks away with a clean record, as there will always be hazards.

**Table 1.2 Deaths per TWh for various energy sources [4].**

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Death Rate Deaths per TWh</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal (elect, heat, cook - world avg)</td>
<td>100 (26% of world energy, 50% of electricity)</td>
<td></td>
</tr>
<tr>
<td>Coal electricity - world avg</td>
<td>60 (26% of world energy, 50% of electricity)</td>
<td></td>
</tr>
<tr>
<td>Coal (elect, heat, cook) - China</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>Coal electricity - China</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Coal - USA</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td>36 (36% of world energy)</td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>4 (21% of world energy)</td>
<td></td>
</tr>
<tr>
<td>Biofuel/Biomass</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Peat</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Solar (rooftop)</td>
<td>0.44 (0.2% of world energy for all solar)</td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td>0.15 (1.6% of world energy)</td>
<td></td>
</tr>
<tr>
<td>Hydro</td>
<td>0.10 (Europe death rate, 2.2% of world energy)</td>
<td></td>
</tr>
<tr>
<td>Hydro - world including Banglai</td>
<td>1.4 (about 2500 TWh/yr and 171,000 Banglai dead)</td>
<td></td>
</tr>
<tr>
<td>Nuclear</td>
<td>0.04 (5.9% of world energy)</td>
<td></td>
</tr>
</tbody>
</table>
Furthermore, nations that choose to forgo nuclear energy will miss all the benefits the future may hold for this industry. These nations will be behind with the technology should they choose to restart a nuclear energy program, although they can lease the technology at a price. This is unfortunate since the future of nuclear energy has so much potential.

Two technologies currently have the potential to make fissionable material last for tens of thousands of years each: fast breeder reactors and fissionable material extraction from seawater [5]. Fast breeder reactors have the ability to create more fissionable material than it consumes [6]. In addition, the future of nuclear energy looks strong as safety improves and the cost decreases due to future modular designs and economies of scale [6]. Nuclear energy’s high temperature output is also ideal for water desalination and separating hydrogen from oxygen in water (electrolysis). This is a definite selling point if fresh water is in shortage or if the hydrogen economy ever takes off [6].

1.3 POTENTIAL SOLUTION FOR A SAFE NUCLEAR ENERGY FUTURE

No one can force all nations to give up their nuclear energy production, as it is an important part of a nation’s energy portfolio. In fact, a majority of countries with nuclear power have plans to expand nuclear power while incorporating the lessons learned from the Fukushima accident. In addition, the interest of countries considering introducing nuclear power remains high, while a few countries have a “wait-and-see” approach. The Fukushima accident, globally, is expected to slow down and delay growth of nuclear power but not reverse it [2].
Although nuclear energy has come a long way since its infancy, there is always a chance of a nuclear meltdown since the energy creating process is inherently unstable. Just like any new technology in its early years, there is a steep learning curve. Nuclear energy is not immune to this.

Nuclear energy will remain a major player in the generation of usable energy and is expected to increase in the future as fossil fuels become scarcer and the nuclear industry becomes more advanced. Advancements such as passive safety designs, nuclear fuel recycling, and possibly even fusion means nuclear energy is here to stay [6]. However, the recent earthquake/tsunami disaster in Japan that sparked a meltdown at Fukushima Daiichi plant has set nuclear energy back years in positive public relations it once had.

Although we do learn from our failures, this is not something we want to do with nuclear power. Since nuclear power is not going away any time soon, this is where Passive Safety Designs (PSD) come into play. The PSD that is the most promising is the Passive Heat Removal System (PHRS) since it is the system in charge of removing heat from the source: the reactor core. This will prevent the nuclear fuel rods from overheating and possibly melting. PHRS’s are necessary for the future of nuclear energy because they are inherently safer and can win the public and lawmakers over in favor of safe nuclear energy. Most nations will not just instantly walk away from a newly built reactor because they need to recoup the massive investment they just made. Those nations that plan to phase out nuclear energy can benefit from a PHRS because of the possibility of retrofits to existing reactors.
1.4 THESIS OBJECTIVE

Since the Fukushima disaster, nuclear power is at a turning point for many nations. It would be wise for all nations to consider all the possibilities for their energy strategy. Therefore, the objective of this thesis is to investigate the PRHRS for two types of light water reactors and show where they stand in terms of future reactor design and possible retrofits for existing reactors. The two types of light water reactors investigated are the Pressurized Water Reactor (PWR) and the Boiling Water Reactor (BWR), because they represent over 80% of the reactors worldwide currently in use today [6].

This thesis will first cover background information on light water reactors and natural convection phenomena before getting into specific PRHRS for the PWR and BWR. Next, it will analyze the Fukushima disaster and potential retrofits for existing LWR’s to prevent such a disaster. Finally, the conclusion will be presented followed by suggested future work.
Chapter 2
LIGHT WATER REACTORS

2.1 INTRODUCTION

A basic understanding of nuclear reactors is necessary to understand the remaining sections of this thesis. However, it is beyond the scope of this paper to explain every detail of a nuclear reactor. Therefore, only two types of reactors used in this investigation are covered. Namely, the PWR and the BWR, since they comprise a vast majority of reactors currently in use worldwide [6].

2.2 NUCLEAR POWER PLANT BASICS

The main purpose of a commercial reactor is to generate heat. This heat is typically used for electricity generation or heat for manufacturing. Figure 2.1 and Figure 2.2 below show basic schematics for the BWR and the PWR, respectively. Electricity generation in most power plants is done similarly, in that water turns into steam to turn a turbine/generator. The steam is then condensed back into liquid water and repeats the cycle. The origin of heat from most power plants comes from burning of fossil fuels, whereas the heat from a nuclear reactor comes from nuclear fission.
The chain reaction of nuclear fission is regulated by control rods, which absorb neutrons, thus slowing down and controlling the rate of fission. The control rods can be adjusted to control the rate of fission, thus allowing the power plant to adjust the rate of power supplied to the grid to meet changing demand [8].
If any kind of accident occurs, such as a Loss of Coolant Accident (LOCA) or a Loss of Flow Accident (LOFA), the reactor may enter SCRAM mode, where the control rods are fully inserted and the self-sustaining chain reaction is stopped. This is usually synonymous with a shutdown [8].

Although the chain reaction of fission has ceased, decay heat is still present and must be dealt with. Decay heat is initially about 7% of the steady-state power before shutdown, and will continue to decrease as time progresses [9]. Although a small percentage, this decay heat will continue to heat the water unless it is removed. If not, the cladding on the nuclear rods may melt and contact the water, creating explosive gases. Further, the nuclear rods may fully melt and have the potential to breach the reactor vessel and maybe even the containment vessel as well.

This decay heat is usually removed with water powered by pumps, just like in the usual operation of the power plant. A problem begins when the pumps fail. Thus is why PRHRS have such a promising future in the design of new reactors and as potential retrofits in present reactors.

2.3 LIGHT WATER REACTORS

Light Water Reactors (LWR) represent a class of nuclear reactors that use ordinary water, H₂O, as the coolant and moderator. This represents a vast majority of commercial reactors in use today. The other class of reactors is the Heavy Water Reactor (HWR), which use deuterium oxide, D₂O, as the coolant moderator. Both reactors have their place, although LWR’s are the most frequently used commercial reactor today [9].
2.3.1 BOILING WATER REACTORS

Within the class of LWR’s, there are Boiling Water Reactors (BWR), Pressurized Water Reactors (PWR), and Supercritical Water Reactors (SCWR). As stated before, only PRHRS of the BWR’s and the PWR’s will be analyzed.

A simplified schematic of the BWR can be seen above in Figure 2.1. The main circulatory loop in the BWR touches the fuel rods directly and is thus radioactive. This loop is also two-phase, in that water can be in the liquid or vapor state depending on where it is in the loop.

2.3.2 PRESSURIZED WATER REACTORS

The PWR can be seen above in Figure 2.2. The main difference to look for is that there are two circulatory loops. The water in the primary loop remains in the liquid phase because it is under extremely high pressure, upwards of 15 MPa [10]. The heat from this loop is exchanged with the secondary loop, which is in two-phase. One main benefit of this design is that the water in the secondary loop contacting the turbine, condenser, and pump, is not radioactive.

Although there are many advantages and disadvantages to either design, comparing them serves no purpose for this paper. However, this paper will analyze the PRHRS for each type of LWR.
Chapter 3
NATURAL CONVECTION PHENOMENA

3.1 INTRODUCTION

Natural convection will occur if a heat source (hot side) is placed below a heat sink (cold side). The fluid will begin to circulate because of the thermally induced buoyancy forces created from the density difference in the fluid [11]. This configuration with the heat source below the heat sink is unstable because the fluid will want to circulate. This is the ideal situation for heat transfer. The opposite situation, with the heat sink below the heat source is stable because the density difference will only create thermal stratification and not any buoyancy force. This situation is inefficient for heat transfer.

Natural convection can occur in a single-phase or two-phase. In single-phase natural convection, the working fluid will stay a liquid or a gas the entire time. Two-phase natural convection will alternate between liquid and gas as in a boiling/condensing loop. The working principle in a boiling/condensing natural convection is the same as the single-phase. It is caused from a thermally induced buoyancy force created from a density difference. However, the difference in density is substantial, compared to single-phase, since one side of the loop is gas and the other liquid. Boiling/condensing loops also have the advantage of transferring heat at a constant temperature since the heat transferred is latent heat, unlike a single-phase loop, which is sensible heat.

A basic understanding of natural convection is necessary to understand the remaining sections of this thesis. Therefore, this chapter covers the types of natural
convection followed by governing equations for a single-phase natural circulation loop in steady state.

3.2 TYPES OF NATURAL CONVECTION

The terms natural convection and natural circulation are sometimes used interchangeably, although there are slight differences. The difference is whether the system is open or closed. In this paper, a Natural Convection System (NCS) will imply an open system as seen below in Figure 3.1. In this situation, the hot air rising through the top of this solar chimney mixes with the air above it in an infinite reservoir and is not forced to recirculate through the bottom once it is cooled. Therefore, the system is open and is considered an NCS.

![Figure 3.1 A solar chimney demonstrating an NCS [12].](image)

Natural convection in a closed system will be defined as a Natural Circulation Loop (NCL) because the same mass of fluid is recirculated. An NCL can be further refined into whether or not it is constrained to follow a particular path. For example, in Figure 3.2 below, the water is not constrained to follow a particular path and will create
its own path naturally. On the other hand, in **Figure 3.3** below, the water is constrained to follow the pipe’s path. This specific type of NCL is typically called a thermosyphon.

![Figure 3.2 A natural circulation loop [13].](image)

**Figure 3.2** A natural circulation loop [13].

![Figure 3.3 A natural circulation loop (thermosyphon) [11].](image)

**Figure 3.3** A natural circulation loop (thermosyphon) [11].

Various PRHRS in nuclear reactors make use of NCL’s and NCS’s, in both single and two-phase, to properly remove residual heat. Experimental correlations are available
for many natural convection situations. For brevity, only steady state single-phase NCL’s will be examined.

3.3 STEADY STATE BEHAVIOR OF SINGLE-PHASE NCL’S

Designing a working PRHRS is a complicated task because it requires heat to transfer between many different mediums and loops to reach the atmosphere. Heat must first be removed from the reactor vessel and then from the containment structure. Although designing every natural convection loop in a PRHRS is complicated, the most sensitive loop is the natural circulation loop to remove heat from the reactor vessel. Therefore, only the steady state behavior of the single-phase natural circulation loop in the reactor vessel will be briefly analyzed on how they operate. Similar equations exist for two-phase flow.

Steady state flow in the natural circulation loop in the reactor vessel is attained when the driving buoyancy force is balanced by the retarding frictional force [14]. The balancing of the two forces is expressed as:

$$-g \rho dz = \frac{R W^2}{2\rho}$$  \hspace{1cm} (3.1)

where:

- \(g\) = gravitational acceleration
- \(\rho\) = density of the fluid
- \(z\) = vertical direction
- \(R\) = resistance
- \(W\) = volumetric flow rate
The values for resistance and density can be calculated from the equations below:

\[ R = \sum_{i=1}^{N} \left( \frac{fL}{D} + K \right)_i \left( \frac{1}{A^2}_i \right) \]  

\[ \rho = \rho_0 \left[ 1 - \beta \left( T - T_0 \right) \right] \]  

where:

- \( N \) = nth item that causes resistance
- \( f \) = Darcy-Weisbach friction coefficient
- \( L \) = length
- \( D \) = hydraulic diameter
- \( K \) = local pressure loss coefficient
- \( A \) = flow area
- \( \rho_0 \) = reference density
- \( \beta \) = thermal expansion coefficient
- \( T \) = temperature
- \( T_0 \) = reference temperature

Since the driving force in a natural circulation loop is low, it is very important to determine the pressure loss of all components in the loop accurately. The retarding force is the sum of the skin friction, form friction, and acceleration of the fluid. Skin friction is caused by the shear stress at the wall of pipes. Form friction is caused from the geometry of various components such as valves, elbows, and tees. There is also a head loss from the acceleration of the fluid due to a change in flow area or density. A change in flow area derives from expansions and contractions, while a change in density comes while the
fluid passes through the heated/cooled sections. There are hundreds of experimental correlations available to find the exact values of “f” and “K” in the above equations for both single and two-phase flow for various situations [15].

A useful experimental correlation that helps engineers estimate the flow rate of the fluid in the natural circulation loop is given as:

$$W = \left[ \frac{2\rho_0^2 \beta g Q_h \Delta Z_c}{RC_p} \right]^{\frac{1}{3}}$$

(3.4)

where:

\(Q_h\) = total heat input rate

\(\Delta Z_c\) = center line elevation difference between the heater and cooler

\(C_p\) = specific heat

Note the parameters of importance for engineers of water based NCL’s are the resistance and the centerline height between the heated/cooled sections. To maximize flow rate, one must increase the centerline height, while decreasing the flow resistance. This is hard to do since resistance is dependent on pipe length, so increasing the centerline height also increases resistance. Experiments are needed alongside parametric studies to find out what size is optimal for the given situation [14].
Chapter 4
PASSIVE RESIDUAL HEAT REMOVAL SYSTEMS

4.1 INTRODUCTION

Although there are many PRHRS designs, only two designs are reviewed here to show how they operate. One applies to the PWR and the other to the BWR. These PRHRS’s will be used in new reactors expected to come online over the next couple of years [16]. PRHRS designs for both the PWR and the BWR have the same goal in mind: remove heat from the core and put it in the atmosphere. However, we must first determine how a PRHRS stands in the International Atomic Energy Agency (IAEA) degree of passive safety scale. The PRHRS for the PWR and BWR will be followed by the advantages and challenges of a PRHRS. Finally, this chapter will end on reliability.

4.2 CLASSIFICATION OF PASSIVE SAFETY DESIGNS

As previously stated, passive safety designs typically rely less, or not at all, on electricity, mechanical parts, human input, working fluids, and/or automated sensors. Passive safety designs rely on physical phenomena such as pressure differentials, gravity, natural convection, material response, and phase change, to regulate a process [1].

Because there are so many ways to create a passive safety design for nuclear reactors, the IAEA has created a way to compare the degree of passive safety for various designs, as summarized below in Table 4.1. Using none or as few of these is considered ideal. Note, that natural circulation and natural convection, as used in the PRHRS, only uses item number one.
Table 4.1 IAEA degrees of passive safety [1].

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>No moving working fluid</td>
</tr>
<tr>
<td>2.</td>
<td>No moving mechanical part</td>
</tr>
<tr>
<td>3.</td>
<td>No signal inputs of ‘intelligence’</td>
</tr>
<tr>
<td>4.</td>
<td>No external power input or forces</td>
</tr>
</tbody>
</table>

The IAEA does warn, however, that passivity is not synonymous with reliability. Passive safety describes the strategy used in maintaining a degree of safety, and is not a level of safety itself. Deeming whether a reactor is safe still depends on the criteria used to evaluate the safety level [1].

4.3 PRHRS for the PWR

The PRHRS highlighted for the PWR applies to Westinghouse’s AP600 and AP1000 reactors. The PRHRS for this application consists of three natural convection paths, one path to remove heat from the reactor vessel, and two paths to remove heat from the containment structure.

The first path removes heat directly from the core/reactor vessel as shown below in Figure 4.1. Note the heat source, the core, is physically below the heat sink, the heat exchanger. This set-up is a single-phase liquid-water natural circulation loop. In the case of Loss of Flow Accident (LOFA), the water will naturally circulate around the loop, transferring heat to the In-containment Refueling Water Storage Tank (IRWST) via the u-tube heat exchanger.
Figure 4.1 PWR reactor vessel heat removal process [17].

The water in the IRWST will soon begin boiling off. The water vapor then leaves the IRWST through vents and begins to fill the containment structure. This additional heat needs to be removed out of the containment vessel. This is done with a two-phase boiling/condensing natural circulation loop as seen below in Figure 4.2. Latent heat from the water vapor is transferred to the steel containment dome as it condenses into liquid to return to the IRWST to recirculate once again.

As the containment dome heats up, its heat transfers to the outside air coming through ducts in the concrete structure. This air natural convection system is augmented with the evaporation of water over the top of the steel containment dome from the gravity drain tank resting above it.
4.4 PRHRS for the BWR

The PRHRS highlighted for the BWR applies to the Westinghouse’s SWR-1000 reactor. It consists of four natural convection paths, one to remove heat from the reactor vessel and three to remove heat from the containment structure.

The primary core cooling loop for the BWR is a two-phase boiling/condensing natural circulation loop as shown below in Figure 4.3. The main components consist of a feed line, a back line, and a flooding pool. The right side of the figure shows what happens during an accident while the left side shows normal operation. In the result of an
accident, the water in the reactor vessel will begin to boil, creating water vapor. This causes the liquid water level to lower, while the vapor rises, just enough so the water level is below the emergency condensers (heat exchangers). These heat exchangers are located just above the floor of the Geodatic Flooding Pool in Figure 4.3 below. The vapor will then condense inside the emergency condensers and proceed back to the bottom of the reactor vessel to recirculate. This loop will proceed in a clockwise manner for the accident side of the figure. This will not happen during normal operation, as the water level in the reactor vessel is a passive way of triggering when the core cooling should occur.

![Figure 4.3 BWR reactor vessel heat removal process](image)

*Figure 4.3 BWR reactor vessel heat removal process [17].*
The heat exchanged from the emergency condenser to the core flooding pool is done through boiling as seen below in *Figure 4.4*. This water vapor will then travel to a containment cooling condenser in another two-phase boiling/condensing NCL. The mixture condenses on the condenser and drips back down to the flooding pool to recirculate.

The heat gained in the containment cooling condenser creates a single-phase water NCL with the dryer-separator storage pool on top. This is the third path.

In the fourth and final path, the storage pool evaporates to the surrounding air in an evaporative type of NCS.
4.5 COMPARE AND CONTRAST

Although both PRHRS remove heat from the core in different manners, they are strikingly similar in the overall process. Both PRHRS first transfer heat from the reactor vessel to the containment structure, and then to the atmosphere. The primary loop for both systems transfers heat from the reactor vessel to an in-containment pool via an NCL.
However, the manner in which they do this has to be different because the BWR is two-phase flow, while the PWR remains in single phase.

In the second loop, the in-containment pool boils and sends heat and moisture up to either a heat exchanger, like in the BWR, or the containment dome, which acts like a giant heat exchanger as in the PWR.

The biggest difference is in the third path. The third path for the BWR transfers heat from the in-containment heat exchanger to a pool outside the containment structure. The pool then evaporates to the atmosphere in a natural convection system, the fourth path. In contrast, the third and final path for the PWR transfers heat from the containment dome to the outside air via natural convection and evaporation over the dome.

4.6 ADVANTAGES

4.6.1 SIMPLICITY AND SAFETY

One of the main advantages of a PRHRS is that the natural circulation loop is a much simpler method of removing heat compared to an active system [11]. It also eliminates the safety issue associated with the failure of circulating pumps since natural circulation is based on physical phenomena and will always perform if designed correctly [11]. In addition, since the driving force of NCL’s is so weak, engineers try to minimize hydraulic losses by reducing the numbers of bends, elbows, transitions, etc., which results in a simpler and cheaper design [11]. This is seen below in Figure 4.5, which compares
the Westinghouse AP1000 to previous generation designs of similar power output. Fewer components and an overall simpler design mean a more reliable system.

Figure 4.5 AP1000 - simplification of design [16].

4.6.2 BETTER FLOW DISTRIBUTION IN PARALLEL CHANNELS

Natural circulation loops in PRHRS show better flow distribution throughout the parallel channels in the reactor core compared to forced circulation [11]. Forced circulation in parallel channels usually causes a maldistribution of pressure, leading to a maldistribution of flow, which can cause localized boiling or hot spots on the nuclear fuel cladding. Since the driving force of natural circulation is weak compared to forced
circulation, the problem of maldistribution of flow is significantly decreased by an order of magnitude less [11].

### 4.6.3 INCREASE FLOW WITH POWER

The flow in the natural circulation loop in a PRHRS increases with heat input rate [11]. This is an important aspect since an increase in heat input rate means more heat needs to be dissipated, which can be accomplished with an increased in flow rate.

### 4.6.4 LARGE THERMAL INERTIA

Large volume pools are used in PRHRS as a method to transfer heat passively from one location to another. The safety of a nuclear power plant benefits from this during a SCRAM because it provides a large thermal inertia that enables engineers to have more time to troubleshoot before anything catastrophic happens [17].

### 4.7 CHALLENGES

#### 4.7.1 WEAK DRIVING FORCE

The main disadvantage of natural circulation is that it has a weak driving force [11]. The easiest way to increase the driving force, and thus flow rate, is to increase the loop height as can be seen in Equation 3.1. The drawback of this, besides increased cost, is that a taller loop may raise seismic concerns as well as increase the loop’s hydraulic resistance. Thus, the height of most natural circulation loop is usually less than ten meters [11].
4.7.2 LOW FLOW RATE

With a weak driving force, engineers aim to reduce hydraulic resistance. One way to achieve this is to not only eliminate components like valves and tees, but also increase the diameter of the pipes. The main drawback to this is that large volume natural circulation loops can result in zonal control problems and unstable flow (instability) [11].

4.7.3 INSTABILITY EFFECTS

Instability effects are present in both forced and natural circulation, although the effect is much less in forced circulation. This is attributed to the nonlinear nature of the natural circulation phenomenon, where a change in driving force affects the flow, which, in turn, affects the driving force [11]. This back and forth effect leads to an oscillatory behavior called instability. Forced circulation can attenuate this problem by adding additional pumps at the inlet orifice. However, pumps are not an option in a fully passive residual heat removal system. Instability effects must be analyzed carefully to prevent localized boiling or hot spots. In addition, engineers much also specify a proper start-up procedure to avoid the potential damage from instability effect [11].

4.7.4 LOW CRITICAL HEAT FLUX

In general, Critical Heat Flux (CHF) describes the thermal limit where a phase change occurs in such a manner that causes a decrease in heat transfer and can cause localized hot spots [18]. For example, imagine a hot metal rod submerged in water at a
temperature a few degrees below saturation temperature, as not to cause boiling. The heat from the rod will transfer to the water via convection only and with relatively low heat flux. Now imagine the metal rod at a temperature a few degrees above saturation temperature. Vapor bubbles will begin to grow on the surface of the rod and begin to release. The heat transfer at this point is a combination of convection to the water and phase change to vapor. The overall convection increases because the bubbles will naturally rise due to density, increasing flow. This also increases the overall heat flux. If the temperature is further increased, the vapor bubbles will release together in a sort of jet or column, again increasing heat flux. There comes a point where if the temperature of the rod is further increased, the overall heat flux will decrease, and this point is called the Critical Heat Flux. This happens because the boiling is happening so fast that a film of vapor surrounds the rod. This film blankets the rod and inhibits thermal conductivity because the thermal conductivity of gas is less than a liquid. After this point, the temperature of the rod may increase, but the overall heat flux decreases, meaning the rod will retain more of its heat and potentially melt.

The CHF in the natural circulation of PRHRS is lower than forced circulation systems [11]. However, it is less of a problem in PWR’s than BWR’s because they operate at a much high pressure, preventing boiling from occurring in the primary loop. Since flow in natural circulation loops is low, the CHF can be a challenge to overcome for BWR’s. Fortunately, parameters such as pressure, flow, exit quality, and heat flux distribution are varied to overcome this potential problem of low CHF [11].
4.7.5 THERMAL STRATIFICATION

Thermal stratification denotes the formation of horizontal layers of fluid of varying temperatures with the warmer layer above the cooler ones [15]. This will eventually occur in every pool of water used in a PRHRS as heat is transferred into the pool from the heat exchangers. Thermal stratification presents a problem because it decreases the heat transfer efficiency as the temperature of the water increases close to that of the heat exchanger. Engineers can combat this by exciting natural circulation in the pool by using a long vertical tube-type heat exchanger. Another way to combat this problem is to increase the surface area of the pool and get air to pass over the pool to enhance evaporation if possible [15].

4.8 IAEA TABLE OF ADVANTAGES AND DISADVANTAGES OF NCS

The IAEA has provided a nice summary of some advantages and disadvantages to using natural circulation systems as seen below in Table 4.2.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced Cost through Simplicity</td>
<td>Low Driving Head</td>
</tr>
<tr>
<td>Pumps Eliminated</td>
<td>Lower Maximum Power per Channel</td>
</tr>
<tr>
<td>Possibility of Improved Core Flow Distribution</td>
<td>Potential Instabilities</td>
</tr>
<tr>
<td>Better Two-Phase Characteristics as a Function of Power</td>
<td>Low Critical Heat Flux</td>
</tr>
<tr>
<td>Large Thermal Inertia</td>
<td>Specific Start up Procedures Required</td>
</tr>
</tbody>
</table>

Table 4.2 IAEA summary of advantages and disadvantages of NCS [17].
4.9 RELIABILITY

Although nuclear power is the safest form of energy generation, in terms of number of deaths per TWh, the public and lawmakers remain very skeptical about nuclear power safety despite the statistics. This may be due to the fear factor of radiation and other fears the word “nuclear” brings about. Therefore, the reliability of nuclear power is more important now than ever before for the future of nuclear power.

4.9.1 PROBABILISTIC RISK ASSESSMENT

Probabilistic Risk Assessment (PRA) is a methodology used to evaluate risks associated with complex engineering systems such as nuclear power plants [16]. PRA gives engineers a way to compare like systems. The exact method used to evaluate nuclear power plants is extremely complicated and is not be described in this paper. Instead, the PRA of the Westinghouse AP1000 PWR will be highlighted.

4.9.2 PRA FOR THE WESTINGHOUSE AP 1000 PWR

The PRA methodology was used interactively in the design process of the AP1000 [16]. This gave engineers the chance to make design and operational changes from the results. Because of the PRHRS and other passive safety systems on the AP1000, it has achieved a very low core-melt and large-release frequencies that are well below current operating plants and well below the Nuclear Regulatory Commission (NRC) upper limit [16]. Core Melt Frequency (CMF) and Large Release Frequency (LRF) are two main measures of the PRA of nuclear power plants and are sought to be
minimized. These two values are frequencies given in units of occurrences per year as shown below in Table 4.3. These frequencies include shutdown events and external events. The middle column shows the NRC’s standards, while the right column shows the frequency for the AP1000. It can be seen that the frequency of the AP1000 is several orders of magnitude lower than the NRC’s standards for both the CMF and the LRF, meaning accident occurrences are extremely minimized.

Table 4.3 AP1000 CMF and LRF to the NRC’s standards [16].

<table>
<thead>
<tr>
<th></th>
<th>Nuclear Regulatory Commission (NRC)</th>
<th>Westinghouse AP1000 PWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Melt Frequency (CMF)</td>
<td>1 E-4 (occurrences per year)</td>
<td>4.2 E-7 (occurrences per year)</td>
</tr>
<tr>
<td>Large Release Frequency (LRF)</td>
<td>1 E-6 (occurrences per year)</td>
<td>3.7 E-8 (occurrences per year)</td>
</tr>
</tbody>
</table>
Chapter 5
FUKUSHIMA DAIICHI DISASTER

5.1 INTRODUCTION

The Fukushima Daiichi nuclear power plant disaster will go down in history as one of the worst alongside Chernobyl and Three Mile Island. It is unfortunate that this happened to an older Gen. 2 BWR design because the reactor was nearing the end of its life cycle and was due soon for a decommission [19]. This happened as the world is transitioning to Gen 3+ PWR/BWR designs that utilize PRHRS [19]. The newer designs presently being constructed could have potentially fared much better in the same earthquake/tsunami scenario. There is still much to learn from this disaster.

This Fukushima disaster is very important to analyze because it will provide useful insight into how we can prevent this from happening again. This chapter will cover how the disaster began and where nations will go from here.

5.2 HOW IT HAPPENED

It was a chain of events that led to the Fukushima plant disaster. The disaster unfolded on March 11th, 2011, when a major earthquake shook off the coast of Japan. The reactor itself performed properly, fully inserting its control rods, and ceased to produce electricity. This is typically fine for most SCRAM situations since the circulating pumps can still get electricity from the grid. However, the power grid was unstable and shut down. The next line of defense to keep the circulating pumps going would be electricity from backup diesel generators. Unfortunately, the offshore
An earthquake caused a massive tsunami that flooded the generators. The last redundancy left were batteries that power the circulating pumps. This worked as planned, but the batteries were only designed to power the pumps for a few hours as the grid is expected to come back online. However, the rest of Japan did not fare well from the enormous tsunami and electricity was not restored for days. Operators even trucked in new diesel generators many hours later, but this was already too late [20].

Without circulation from the pumps, the water in the reactor began boiling off. As the water boiled away, it exposed the cladding outside the nuclear fuel, which began cracking. Water then touched the nuclear fuel and began splitting into separate hydrogen and oxygen molecules, a process called thermolysis [20]. This buildup of hydrogen caused lots of pressure to build up, so the operator began to vent this to the atmosphere. The hydrogen vented so quickly that it exploded inside the containment structure. At this point, if the water continued to boil off, the nuclear fuel was guaranteed to melt and possibly breach the reactor vessel and possibly the containment structure. To prevent this, the operators decided to flood the reactors with seawater mixed with boron. Although this worked as a temporary fix to cool the reactor to prevent melting, the reactor was ruined from the seawater and a large amount of radiation was released, rendering cleanup to be very difficult [20]. A brief summary of the events can be seen below in *Figure 5.1*. 
5.3 WHERE TO GO FROM HERE

The question asked by many nations is, “Where do we go from here?” There are really only three options. Countries may phase out nuclear power altogether. They may implement newer/safer designs only in future builds as they phase out old plants. Alternatively, they may retrofit existing reactors in addition to implementing newer/safer designs in future builds. Either way, these older Gen 2 reactors are here to stay for a while longer.
Chapter 6

POTENTIAL RETROFITS

6.1 INTRODUCTION

The Fukushima nuclear power plant disaster has forced nations to rethink nuclear as part of their energy strategy. This tragic event has caused many nations to phase-out nuclear energy all together. This is unfortunate because eliminating nuclear energy from a nation’s energy portfolio can have many adverse effects such as increased energy prices, increased CO2 and particulate matter spewed into the atmosphere, and an increase in deaths due to energy generation other than nuclear.

Regardless of these nations phasing out nuclear power, other nations plan to increase their nuclear power production with lessons learned from Fukushima. In addition, there are countries without nuclear power that are actively seeking licenses to start new builds. Even the countries that plan on phasing out nuclear have to do so over time since getting rid of one energy source and replacing it with another cannot happen overnight. Moreover, they want to fully utilize their reactors to recoup their investment. A typical nuclear power plant has a lifespan of thirty years, so many nuclear energy experts are proposing retrofits to existing plants, especially since there are 92 other BWR’s worldwide that use the same GE BWR-3 design [19]. Retrofits can provide a somewhat quick way to safely utilize the full life of existing reactors. Therefore, many proposed retrofits are analyzed here.
6.2 LEVEES

Japan is currently spending billions of Yen to retrofit their flood vulnerable nuclear power plants with levees that protect the backup diesel generators as seen below in Figure 6.1 [22]. Some of the levees installed will be in excess of twenty meters in height [22]. This seems like a design that should be implemented for all nuclear reactors near a potential flood zone, especially in Japan since they have a history of tsunamis. Although this is an expensive endeavor, if the levees had been built around the Fukushima plant prior to the earthquake, this disaster might had been avoided since the generators would have properly circulated the water necessary to remove decay heat.

![Levees installed shortly after the Fukushima disaster](image)

**Figure 6.1** Levees installed shortly after the Fukushima disaster [22].

6.3 CONTAINMENT HYDROGEN VENTILATION

Another step other countries are taking is to redesign the containment ventilation system to better control the concentration and flow rate of hydrogen from the
containment structure to the atmosphere as to prevent an explosion [19]. This design would be an addition to radiation scrubbers in the ventilation system already in place in many reactors worldwide. This may have prevented the large release of radiation that occurred shortly after the hydrogen explosion at the Fukushima plant.

6.4 PRHRS

Although the two retrofits mentioned above may prevent a future nuclear plant disaster given the same scenario, there has not been much discussion about the feasibility of retrofitting existing nuclear reactors with a PRHRS. As mentioned before, there are PRHRS that work for both PWR’s and BWR’s that have already been simulated and experimentally validated. Furthermore, there are several nuclear plants with PRHRS that will come online over the next several years. Therefore, these designs will soon be tested in the real world [16].

The lack of discussion of PRHRS as a retrofit option may be due to cost or even design constraints. Fitting in heat exchangers will not pose a dimensional problem, but fitting in large pools requires large amounts of existing space, not to mention the existing support structure to handle the weight. In addition, the existing fuel bundle may not be geometrically ideal to even allow natural circulation. However, the AP1000 design uses modified basic square fuel bundles to reduce cost and the PRHRS performs properly [16].

The PRHRS for the PWR design may not work as a retrofit because the heat exchanger that moves heat from the containment structure to the atmosphere is the containment structure itself, and it must be metal. To build a brand new metal
containment structure, with a new concrete building surrounding it, would be an expensive project. It has been suggested, however, that this design can be modified similar to the BWR design [23]. It would use two heat exchangers in an NCL that would link the inside of the containment structure to a pool above. This process can be seen below in Figure 6.2. Air would then pass over the pool and aid in the heat removal process via evaporation. This only adds one additional NCL and would allow a retrofit to PWR’s without building an entirely new metal containment structure.

Figure 6.2 PWR containment structure heat removal modification [23].
6.5 FUEL ROD BUNDLE GEOMETRY

The fuel rods near the outlet of the core are typically the origin of problems for a nuclear reactor as it is the location where the temperature is the highest. The outlet has the highest temperature because the circulating water has already absorbed a lot of heat as it passed over the fuel rods. The already warm outlet water cannot absorb heat as quickly compared to the inlet, thus causing the fuel rods at the outlet to heat up. This non-uniform temperature distribution gets even worse at rods near the wall of the fuel rod bundle [24]. The temperature to avoid for BWR’s is the temperature at the CHF. The temperature to avoid for PWR’s is the melting temperature cladding. Either way, having a uniform temperature distribution along and between various fuel rods is ideal, given the weak driving force and low flow rate of natural circulation loops.

6.5.1 FUEL ROD BUNDLE SHAPE

There is a paper by Zhi Shang that investigates various vertical fuel rod bundle geometries under forced circulation [24]. He studied three different fuel rod bundle shapes with the same pitch to diameter ratio (P/D) using computation fluid dynamics, as seen below in Figure 6.3.
The study simulated a PWR forced circulation system using a 3-D k-ε turbulence model in STAR-CD. The fuel rods were modeled as uniform heat flux with a diameter of 8 mm and a pitch of 10mm, yielding a P/D of 1.25. The walls of the fuel rod bundle were assumed adiabatic and the outlet assumed fully developed. The parameters for the simulation were chosen to be similar to a typical PWR as shown below in Table 6.1.
Table 6.1 Parameters for simulating a PWR nuclear fuel rod bundle [24].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>System pressure</td>
<td>25</td>
<td>MPa</td>
</tr>
<tr>
<td>Temperature (inlet)</td>
<td>350</td>
<td>°C</td>
</tr>
<tr>
<td>Mass flux (inlet)</td>
<td>1050</td>
<td>kg/m² s</td>
</tr>
<tr>
<td>Heat flux (wall)</td>
<td>600</td>
<td>kW/m²</td>
</tr>
</tbody>
</table>

The circumferential temperature for specific rods at the outlet of all three geometries can be seen below in Figure 6.4. The left-hand-side of the rod wall is zero degrees and positive rotates counter-clockwise. The symmetric character of the three shapes means that only rods 1, 2, and 5 are needed for the square, and rods 1 and 4 are needed for both the hexagon and cylinder. Note the rod wall temperature distribution is non-uniform for all three geometries, with the highest temperature nearest the outside adiabatic wall of the fuel rod bundle. The highest rod wall temperature is only 440 °C for the hexagon compared to about 520 °C for the square and cylinder. Not only is the maximum temperature lowest for the hexagon, it also has the lowest rod temperature difference. The rod temperature difference for the hexagon is 40 °C compared to around 120 °C for the other two shapes. This means the hexagonal shape has a more uniform temperature distribution compared to the other two.
Although the hexagon is the optimal shape for forced convection flow in a PWR, varying the P/D will affect temperature and heat transfer rate as well. The results of varying the P/D on temperature can be seen below in Figure 6.5. Note that an increase in P/D decreases the rod wall temperature difference, meaning it has a more uniform temperature distribution, which is desirable.
Does a larger P/D ration always mean better? The rod wall temperature is just one parameter affected by the P/D ratio. The heat transfer efficiency, and thus the Nusselt number, is affected as well. To see this, the Nusselt number is plotted with the P/D ratio as seen below in Figure 6.6. Note that the maximum Nusselt number, and thus heat transfer efficiency, decreases with the P/D ratio.

**Figure 6.5 Rod wall temperature vs. P/D ratio [24].**
This is a tricky situation since a large P/D ratio will have a smaller rod wall temperature difference, but the heat transfer will not be as efficient. Therefore, engineers must consider a balance of what is desirable for the given situation. It is not desirable for the fuel rods to melt, but it is also desirable to transfer heat efficiently. Zhi Shang suggests a suitable P/D ratio for most application is around 1.25, but will vary depending on the situation [24].

6.5.3 APPLICATION TO NATURAL CIRCULATION LOOPS IN PRHRS

Can the lessons learned about the fuel rod bundle geometry investigation be applied to NCL’s in PRHRS given additional design constraints? If so, this gives engineers another tool to make PRHRS work given the challenge of overcoming the weak driving force in NCL’s.
Nowhere in the IAEA natural circulation handbook does it mention anything about optimizing the geometry of the fuel rod bundle. It may be because it is known that NCL’s in PRHRS already work, and have been simulated and experimentally validated. However, due to the weak driving force of NCL’s, any additional tool at the disposal of engineers will help in designing safer and more reliable PRHRS.
Chapter 7

CONCLUSION AND FUTURE WORK

7.1 FINAL REMARKS AND RECOMMENDATIONS

Nuclear energy is at a new turning point ever since the Fukushima disaster. However, the future of nuclear energy looks very promising in both the near and distant future. Therefore, it is suggested that nation’s, both with and without nuclear power, properly weigh all the consequences before redefining their stance on nuclear energy.

Each nation needs to rationally analyze the options with hard numeric evidence and not make decisions based on emotion or fear. Purely analyzing the numbers, nuclear energy is a great option and may prove to be so much more in the near future. A strong reason people may not be in favor of nuclear energy is due to irrational fear because they did not analyze the numbers. Unfortunately, the psychological effect of fear can force people to make irrational decisions not based on hard evidence. There is not much difference between this and the irrational fear of dying in a plane accident. Although many people know a person is many more times likely to die in a car accident than in a plane accident, the psychological effect is still there and many choose not to fly. For nuclear energy, this is understandable since words such as “nuclear” and “radiation” invoke fear in many, although the hard numbers say this is irrational.

For nations with nuclear power, it is recommended to explore all the options of a retrofit to existing reactors in addition to implementing a PRHRS on all future builds. The retrofit option applied to vulnerable plants will enable these nations to continue to fully utilize the lifespan of existing plants without much delay. Previously suggested
retrofits such as levees and hydrogen ventilation, and newly suggested retrofits in this paper such as PRHRS and fuel rod bundle geometry, may give nations what they need to safeguard their existing reactors from another Fukushima disaster.

7.2 FUTURE WORK

The research on Natural Circulation Loops in PRHRS is plentiful. There is plenty of work needed to improve the prediction tools that simulate an NCL in two-phase flow, transient/oscillatory flow, and under motion (as on a ship). The newly suggested retrofits presented in this paper, the PRHRS and fuel rod bundle geometry, need significantly more research. Retrofitting a reactor with a PRHRS may possibly work, but at what financial cost? The feasibility of this type of retrofit needs to be studied. In addition, the fuel rod bundle geometry needs to be applied to an NCL/NCS to see if the same effects exist for a forced circulation situation. If so, this gives engineers another tool overcome the low driving force of natural circulation. Increasing the driving force in this manner may also help engineers tackle the physical constraints of smaller nuclear power plants, such as those aboard smaller ships and submarines, since the power plants for these applications cannot have a tall loop necessary to increase flow.
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