David Tomás Sánchez Martínez
Lourdes García Rodríguez
(coordinadores)

Proceedings of the 7th International Seminar on ORC Power Systems

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ORC technology used in a Heat Removal System for Advanced Nuclear Power Plants

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ABSTRACT

This work concerns the design of a specific passive system for an advanced pressurized water reactor (PWR). The system studied is based firstly on passive safety condensers, which are increasingly used in the design of advanced nuclear power plants. These condensers are typically immersed in large water tanks that serve as a heat sink. They are located at a sufficient height to ensure a natural two-phase circulation mode. Such a heat removal system can be used for a relatively long period depending on the size of the tank.

The present research is based on using a fraction of the energy stored in this volume of boiling water as a heat source for an organic Rankine cycle via an immersed heat exchanger. The electrical energy produced will power various critical components, complementing existing systems.

Three unusual issues challenge the use of an ORC in this context: the nature of the hot source (boiling pool water), the low temperature of the hot source (100°C), and the requirement for system 130
reliability and robustness. Apart from these three challenges, the usual constraints associated with ORC systems still exist: maximizing energy performance, using an environmentally friendly fluid and minimizing space requirements.

An experimental test bench with a boiling water pool and an ORC with submerged evaporator was built to address the main questions. The first set of results shows the nominal operation of the coupling between the boiling water pool and the ORC when Novec649™ is used as working fluid. The reliability of the system is then studied through the investigation of the immersed evaporator and the implementation of a theoretical model. The theoretical model of the system will be used to scale the system.

1 Introduction

With approximately 450 nuclear power plants (NPP), nuclear power generates approximately 10% of global electricity [1], [2]. Three major nuclear accidents occurred in the last five decades: Three Mile Island (1979), Chernobyl (1986), and Fukushima Daiishi (2011) [3]–[5]. The experience feedback of these accidents is taken into account in the design of the new generation NPPs (generation III and beyond) with a view to improving safety. The state of the art of these accidents is incorporated into new generation NPPs (generation III and beyond) to improve safety systems for nuclear new builds. As a result, a safety enhancement program has been developed, with a focus on passive safety systems for new-generation NPPs, able to handle with highly severe conditions resulting in a long period of loss of offsite power inducing a global loss of heat sink event. These systems can function during station blackout (SBO).

Passive systems, like the passive residual heat removal system (PRHRS), derive their effectiveness from the lack of rotating machinery (such as pumps or diesel engines). These systems only rely on natural forces, such as natural convection, to transfer the residual heat from the core to the cold source (water or air). The use of passive systems simplifies plant systems, as well as their operation and maintenance [6].

Some new generation NPPs already include PRHRS [7]. This PRHRS can be connect directly to the primary loop as on the AP1000 [8] or the CAP1400 [9]. Indeed, a PRHR transfers the residual heat from the core to the in-containment refuelling water storage tank (IRWST) through a heat exchanger (HX). To ensure natural convection, the IRWST is located above the reactor. Another existing solution is to connect the PRHRS through the secondary loop in order to cool the steam generator (SG) which removes the decay heat from the primary loop, as existing on the HPR1000 [10] or the CPR1000 [11]. This system is named secondary side passive residual heat removal system (SSPRHRS). Because the SSPRHRS is connected to the secondary side, the PRHR HX acts as a safety condenser (SACO).

Moreover, while passive cooling systems are effective and dependable, they should not be the only focus. Thus, another safety concern raised by various safety authorities is the installation of an emergency power supply in addition to the existing power supplies [12]. Then, one concept is to use the water tank as a hot source for a thermodynamic cycle such as a Stirling engine or an Organic Rankine Cycle (ORC). The electricity generated by the cycle will provide electricity for its own use (pump) as well as a production surplus [13], [14]. The Figure 1 illustrates the coupling of a PRHRS and an ORC.

ORC is a thermal-driven power cycle that generates electricity by using a heat source and a low-boiling-point fluid as the working fluid [15], [16]. ORC has been identified as one of the best thermal engines for producing electricity with a low heat source (150 °C) [17]. The majority of the heat sources used are geothermal, with approximately 3 GW of cumulative installed capacity in 2020, with power output ranging from a few kW to several dozen MW [18].

A tubular evaporator immersed in the boiling water tank enhances the coupling between the ORC and the boiling water tank. Natural convection is used to transfer heat from the boiling water to the tubes outer walls. Additionally, mini-channel type tubes have been selected to enable heat transfer over a maximum surface area while maintaining acceptable heat transfer coefficients inside the tubes. This kind of tube is widely used to dissipate heat in confined spaces [19].

Thus, despite the fact that ORC are a well-established system, their use in nuclear safety necessitates a focus on their reliability. Indeed, the ORC must be capable of producing electricity on any situation (extreme climatic conditions, aging of components etc.) continuously. In addition, the innovative design of the heat exchanger also necessitates an experimental investigation of the heat transfer coefficients inside and outside the tubes in order to scale it up for a full-scale application. This article will concentrate on these two research directions. 131

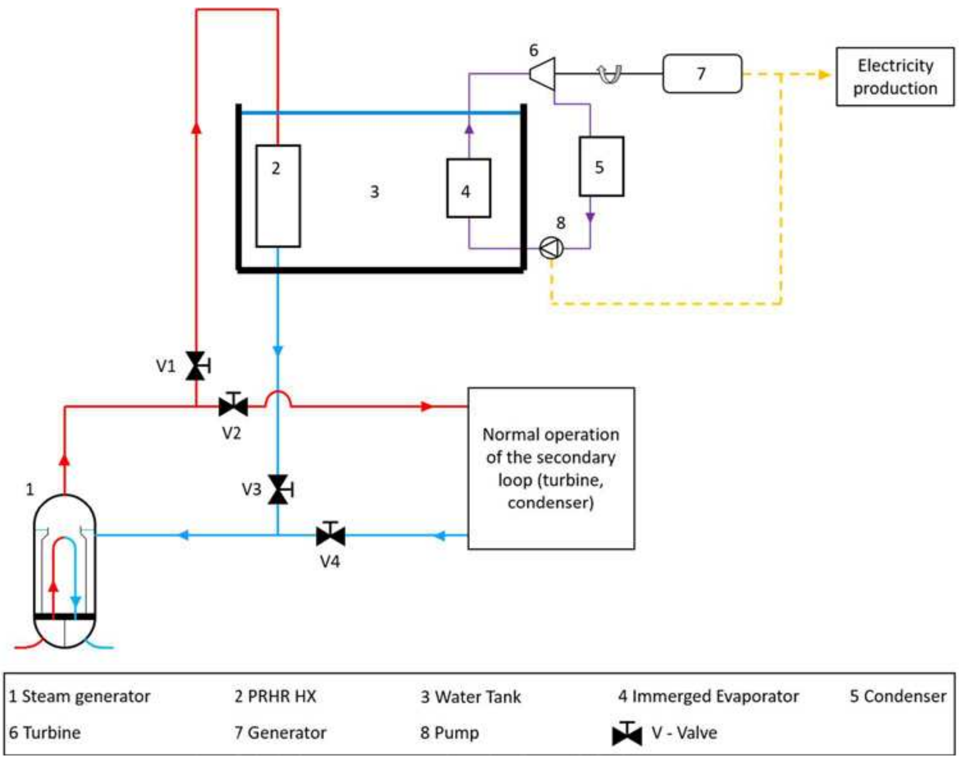

Figure 1 : PRHRS and ORC coupling - simplified diagram

2 Experimental test bench

2.1 The experimental ORC

The experimental test bench is composed of two main parts:

- The ORC composed of an immersed evaporator.
- The boiling water tank, which is supposed to replace the SACO pool, composed of heating rods, which are supposed to replace the operation of the passive SACO.

The test bench objective is to operate as a small-scale demonstrator and, through the results obtained, to enable scale transposition. At the volumetric pump inlet, the working fluid is liquid. The volumetric pump raises the working fluid pressure to a high level. The fluid is evaporated in the boiling water tank using an immersed evaporator. This vapour is then expanded in a partial admission axial micro-turbine with a maximum power of about 1 kW. A generator transforms the mechanical power produced by this expansion into electricity. The low-pressure vapor is cooled by a plate condenser, which uses an active external water circuit as a cold source, before it is sent back to the pump.

The system lubrication is provided by the working fluid itself. An external circuit designed specifically for the generator keeps it cool. A small centrifugal pump is placed just before the volumetric pump to slightly increase the pressure and avoid cavitation. A tank, located between the condenser and the centrifugal pump, ensures a sufficient net positive suction head (NPSH) at the centrifugal pump inlet. An additional system comprised of a heat exchanger and a bypass system allows for the investigation of a wide range of cold source temperatures. The use of a pump in combination with a needle valve allows for the investigation of a wide range of mass flow rates and pressures.

The boiling water tank has a capacity of 1.5 m3. It includes ten 20 kW heating rods. Every heating rod has a heat flux density of 10.1 W/cm^2, which is roughly the same order of size as a SACO [20]. The power in the pool varies between 0 kW and 100 kW (five heating rods maximum). The maximum power ratio between heating rods and immersed exchanger is approximately five.

Temperature sensor rods are used to measure the temperature gradient in the tank. The positioning of the rods in the water tank is described in Figure 2. A level sensor system linked to an automatic valve controls the amount of water in the tank.

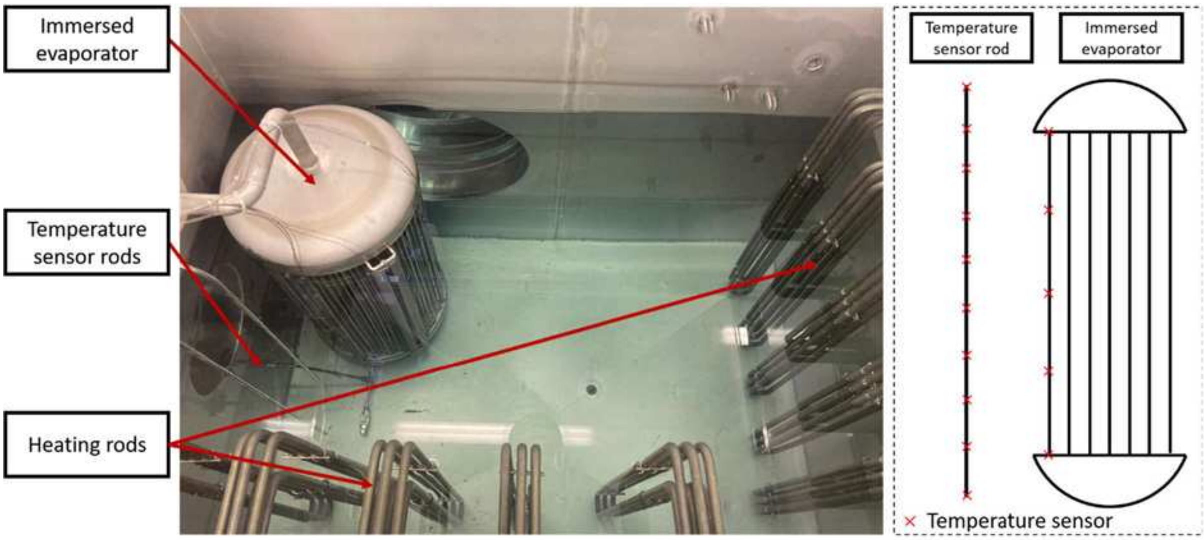

Figure 2 : Boiling water tank

2.2 Measurement

The characteristics of the measuring equipment used for measurement and data acquisition are listed in Table 1.

The working fluid, the water tank and cold source loops are equipped with Type-T thermocouples to measure the temperatures between the various components. Figure 2 shows the temperature sensors at the evaporator exterior tube wall. The working fluid circuit is instrumented with absolute pressure sensors (APS) at the turbine inlet and outlet to measure the two pressure stages within the plant. The volume flow measurements of the cold circuit are made with electromagnetic flow meters (EFMs) while the fluid flow is measured with a Coriolis-type mass flow rate meter. The gross power produced at the turbine is measured with a power meter.

Table 1: Measurement characteristics

Variable	**Equipment**	**Range**	**Uncertainty**
Electrical power	Wattmeter	0–3250 W	± 0.3%
Volume flow (cold source)	EFM	0–2500 L/h	± 0.33%
Mass flow rate (working fluid)	Coriolis	50–500 kg/h	± 0.30%
Temperature	Thermocouple Type-T	−200–200 °C	± 0.1 °C
Pressure	APS	0–7 bar	± 1%

3 Working fluid

The working fluid used in this work is the Novec649^{TM}. This fluid is neither toxic nor flammable [21]. Furthermore, Novec649^{TM} is exempt from the Kyoto and Paris agreements on refrigerant working fluids due to its environmental characteristics (ozone depletion potential (ODP) = 0 and global warming potential (GWP) = 1) (Table 2) [22], [23]. Moreover, Novec649^{TM} is a dry fluid ($\partial T/\partial s > 0$) which avoid any risk of erosion on the turbine. A other interest lies in its moderate high pressure.

The thermodynamic properties of the Novec649^{TM}, come from EES (engineering equation solver) software [24]. 133

Table 2: Novec649^{TM} properties

Properties	**Novec649^{TM}**
Fluid type	Dry
Fluid class	Fluoroketone
Formula	$CF_3CF_2C(O)CF(CF_3)_2$
Critical temperature (°C)	169
Critical pressure (bar)	18.7
Normal glide	0
ODP	0
GWP	1
Flammability	No
Toxicity	Null

4 Global ORC results

The experimental test bench initial results allowed for the determination of the ORC nominal operating point. The cycle T-s diagram is shown in Figure 3.

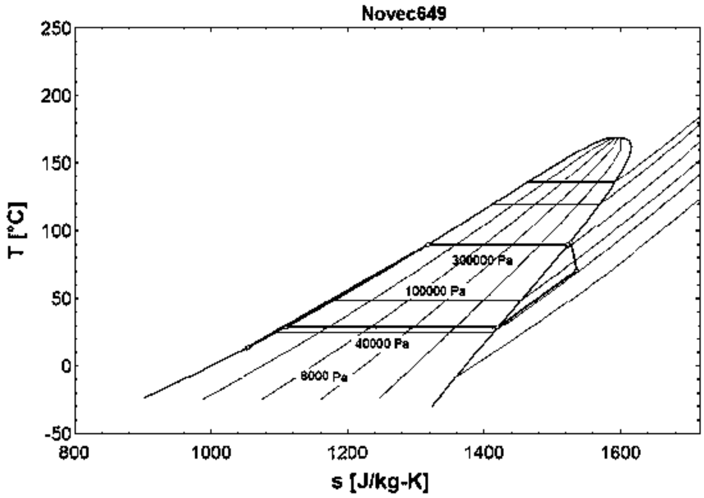

Figure 3 : Novec649^{TM} T-s Diagram

The ORC overall efficiency during nominal operation is around 2%. Because of moderate hot source temperature, overall efficiency is low. Furthermore, due to the ORC small size, partial admission machine has been chosen, leading to an isentropic turbine efficiency of 50%. Detailed elements on turbine type and efficiency can be found in a recent article [25]. Projected full scale machine (i.e. without partial admission) would lead to an isentropic turbine efficiency of nearly 75%.

The low efficiency value of the global system is not a central problem as the amount of recoverable hot source is significantly higher than the amount of hot source required for the cycle to operate properly in real operation (~150 kW), where the hot source is the residual power of a nuclear reactor core (30 MW). Furthermore, the size of the turbo machine will be larger during scaling up, which will increase turbine and system efficiencies. 134

Table 3 : Nominal point

Specification	Unit	Data
Electrical power	Watts	138
Overall efficiency	%	2
Turbo generator efficiency	%	16
Pressure rate	[-]	7.4
Temperature of hot source	°C	≈100
Cold source temperature	°C	13

The experimental ORC can generate about 140 Watts of electrical power under nominal operation. According to the initial calculations, the ORC will need to be able to generate about 10 kW of power at scale 1. Thus, theoretical models of the ORC components under the EES software are realized in order to scale up the ORC.

The present analysis is focused on the submerged evaporator model. An axial turbine model in nominal and degraded conditions (partial evaporation condition at turbine inlet) was realized and experimentally validated in a recent article [25]. A condenser model in normal and off-normal conditions (cold source temperature variation) was realized and experimentally validated in a separate paper.

5 Immersed evaporator

The ORC immersed evaporator was designed to validate experimentally inside and outside heat transfer coefficients. The validation of these models will support a scale transposition via the conservation of some dimensionless numbers (Re; Ra).

The size of the experimental immersed evaporator is summarized in the

Table 4.

Table 4 : Experimental immersed evaporator design.

Specification	Unit	Data
Length in height	[mm]	800
Distance between heat transfer tube	[mm]	18
Outside tube diameter	[mm]	3.17
Tube thickness	[mm]	0.89
Number of tubes	[-]	551
Total exchanger diameter	[mm]	406.4

5.1 Natural convection

Since the tubular evaporator is submerged in a tank of water, the heat transfer is processed by natural convection. Since the Rayleigh number (eq (1)) value at the wall is around 10^5, the flow is laminar. In this context, two correlations have been examined.

$$Ra = Gr.Pr \tag{1}$$

$$Gr = \frac{\rho^2 g\beta(T_{water} - T_{wall})d^3}{\lambda\mu^2} \tag{2}$$

The Churchill and Chu (1975) correlation, used in the MARS code for vertical surfaces with Gr.Pr> 0.1 [26], [27].

$$Nu_d = \left\{0.825 + 0.387Ra^{\frac{1}{6}} / \left[1 + \left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}\right\}^2 \tag{3}$$

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For laminar flow on vertical surfaces, the Ostrach laminar theory (1953) has been used [28], [29].

$$Nu_d = 0.555Ra^{\frac{1}{4}} \tag{4}$$

Figure 4 shows the comparison between the theoretical and experimental convective heat transfer coefficients. It has been noted that Ostrach (1953) correlation calculates a convective heat transfer coefficient for the entire test in a +/- 30% range. Additionally, the estimated convective exchange coefficient values are of an order of magnitude consistent with the literature [30]. Thus, this correlation has been selected for the next step.

Other natural convection models have been tested, based on a revised Ra* [31], [32]. The results presentations required a more detailed paper.

5.2 Inside tubes

Bibliography concerning working fluid evaporation correlation is very limited due to the facts that Novec649™ is a relatively recent working fluid used in ORC systems and that the Reynolds number inside the tubes is small (due to the small mass flow rate).

In single phase, the Nusselt number of the fluid is calculated using eq (5), which is a classic correlation in single-phase laminar flow $Re_{lo} < 2300$.

$$Nu_{sp} = 4.36 \tag{5}$$

A previous study on a plate evaporator demonstrated that the Gullapalli correlation was adapted for for low Reynolds in Novec649^{TM} in two-phase conditions [33], [34].

$$Nu_{tp-Gullapalli} = 1.926.Bo_{eq}^{0.3}.\left[(1-x)+x.\left(\frac{\rho_l}{\rho_v}\right)^{0.5}\right].Re_l^{0.5}.Pr_l^{\frac{1}{3}} \quad (6)$$

The Gullapalli correlation estimates the two-phase heat transfer coefficient with an approximate value of 400 W/m².K. The results are coherent with low Reynolds numbers results of the literature [35]. However, the Gullapalli correlation overestimates the value of the heat transfer rate; it would be interesting to correct this value using a corrective coefficient.

However, the goal of this model is to predict a shift in scale for an exchanger size. The accuracy in exchanged power that this model can provide is therefore crucial. The size of the components at scale 1 will then reflect this accuracy. Then, as we can see on the Figure 5 this model predicts the global heat transfer between the theoretical model results and the correlated ones within 5%.

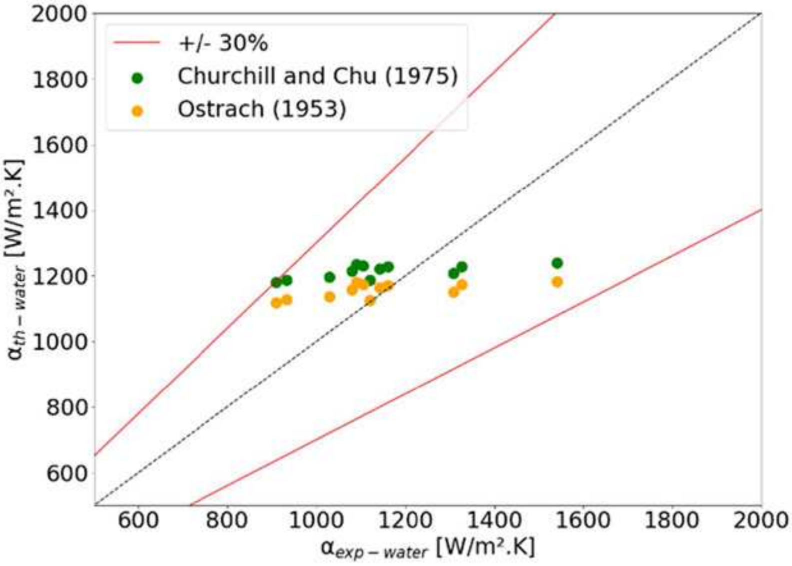

Figure 4 : Experimental and correlated natural convection heat transfer coefficients comparison

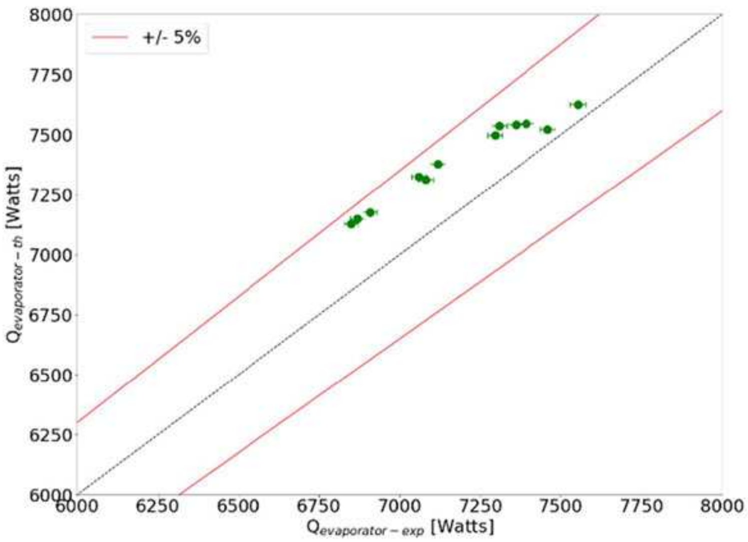

Figure 5 : Comparison of the experimental and correlated global power exchanged in the evaporator

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6 CONCLUSIONS

To conclude, this study has shown by experiments that it is possible to recover low grade heat through an immersed heat exchanger and convert it to electricity.

An evaporator model has been developped, using the Ostrach [28], [29] correlation in natural convection and the Gullapalli [33], [34] correlation inside the tubes. This model predicts the global heat transfer between the theoretical model results and the correlated ones within 5%. This model, coupling through a global ORC system description enable the quantification of electricity production in various conditions.

The experimental study is still in progress in order to investigate off nominal situations and other ORC fluids performances.

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NOMENCLATURE

Symbols		
d	tube diameter	(m)
g	acceleration of gravity	(m/s^2)
T	temperature	(K)
x	vapour quality	(-)
Greek letters		
α	heat transfer coefficient	($W/m^2.K$)
β	coefficient of thermal expansion	(K^{-1})
λ	thermal conductivity	(W/m.K)
μ	dynamic viscosity	(Pa.s)
ρ	density	(kg/m^3)

Subscripts

d	diameter
eq	equivalent
exp	experimental
l	liquid
sp	single-phase
th	theoretical
tp	two-phase
v	vapor

GLOSSARY

EES	engineering equation solver
GWP	global warming potential
HX	heat exchanger
IRWST	in-containment refuelling water storage tank
NPSH	net positive suction head
NPP	nuclear power plants

ODP	ozone depletion potential
ORC	organic Rankine cycle
PRHRS	passive residual heat removal system
SACO	safety condenser
SBO	station blackouts
SG	steam generator
SSPRHRS	secondary side passive residual heat removal system

References

[1] 'Nuclear Power Today | Nuclear Energy - World Nuclear Association'. https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx (accessed Nov. 28, 2022).

[2] '95/06080 Energy, electricity and nuclear power estimates for the period up to 2015', *Fuel Energy Abstr.*, vol. 36, no. 6, p. 430, Nov. 1995, doi: 10.1016/0140-6701(95)95132-6.

[3] G. R. Skillman and J. L. Rempe, 'The Three Mile Island Unit 2 Accident', in *Encyclopedia of Nuclear Energy*, E. Greenspan, Ed., Oxford: Elsevier, 2021, pp. 17–29. doi: 10.1016/B978-0-12-409548-9.12146-3.

[4] A. R. Sich, 'The Chernobyl Nuclear Power Plant Unit-4 Accident', in *Encyclopedia of Nuclear Energy*, E. Greenspan, Ed., Oxford: Elsevier, 2021, pp. 30–52. doi: 10.1016/B978-0-12-819725-7.00080-5.

[5] Internationale Atomenergie-Organisation, Ed., *The Fukushima Daiichi accident*. in STI/PUB. Vienna, Austria: International Atomic Energy Agency, 2015.

[6] T. L. Schulz, 'Westinghouse AP1000 advanced passive plant', *Nucl. Eng. Des.*, vol. 236, no. 14, pp. 1547–1557, Aug. 2006, doi: 10.1016/j.nucengdes.2006.03.049.

[7] J. Li *et al.*, 'Experimental investigation on the heat removal capacity of secondary side passive residual heat removal system for an integrated reactor', *Appl. Therm. Eng.*, vol. 204, p. 117973, Mar. 2022, doi: 10.1016/j.applthermaleng.2021.117973.

[8] S. Estévez-Albuja, G. Jiménez, and C. Vázquez-Rodríguez, 'AP1000 IRWST numerical analysis with GOTHIC', *Nucl. Eng. Des.*, vol. 372, p. 110991, Feb. 2021, doi: 10.1016/j.nucengdes.2020.110991.

[9] Y. Q. Li *et al.*, 'Analyses of ACME integral test results on CAP1400 small-break loss-of-coolant-accident transient', *Prog. Nucl. Energy*, vol. 88, pp. 375–397, Apr. 2016, doi: 10.1016/j.pnucene.2016.01.012.

[10] D. C. Sun, Y. Li, Z. Xi, Y. F. Zan, P. Z. Li, and W. B. Zhuo, 'Experimental evaluation of safety performance of emergency passive residual heat removal system in HPR1000', *Nucl. Eng. Des.*, vol. 318, pp. 54–60, Jul. 2017, doi: 10.1016/j.nucengdes.2017.04.003.

[11] M. Wang, H. Zhao, Y. Zhang, G. Su, W. Tian, and S. Qiu, 'Research on the designed emergency passive residual heat removal system during the station blackout scenario for CPR1000', *Ann. Nucl. Energy*, vol. 45, pp. 86–93, Jul. 2012, doi: 10.1016/j.anucene.2012.03.004.

[12] *Éléments de sûreté nucléaire - Les réacteurs de recherche*. EDP Sciences, 2019. doi: 10.1051/978-2-7598-2301-7.

[13] K. P. Singh, H. Sound, I. Rampall, C. Hill, and J. Rajkumar, 'Autonomous self-powered system for removing thermal energy from pools of liquid heated by radioactive materials and method of the same', p. 14.

[14] E. Tatli, J. G. Belechak, B. Lu, C. Stansbury, C. Guler, and M. J. Ostrosky, 'Power generation from decay heat for spent nuclear fuel pool cooling and monitoring', p. 7.

[15] M. Astolfi, '3 - Technical options for Organic Rankine Cycle systems', in *Organic Rankine Cycle (ORC) Power Systems*, E. Macchi and M. Astolfi, Eds., Woodhead Publishing, 2017, pp. 67–89. doi: 10.1016/B978-0-08-100510-1.00003-X.

[16] J. B. Obi, 'State of Art on ORC Applications for Waste Heat Recovery and Micro-cogeneration for Installations up to 100kWe', *Energy Procedia*, vol. 82, pp. 994–1001, Dec. 2015, doi: 10.1016/j.egypro.2015.11.857.

[17] N. Tauveron, S. Colasson, and J.-A. Gruss, 'Available systems for the conversion of waste heat to electricity', presented at the ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE), 2014. doi: 10.1115/IMECE2014-37984.

[18] C. Wieland, F. Dawo, C. Schifflechner, and M. Astolfi, 'Market report on organic rankine cycle power systems: recent developments and outlook', p. 10, 2021.

[19] S.-M. Kim and I. Mudawar, 'Universal approach to predicting saturated flow boiling heat transfer in mini/micro-channels – Part II. Two-phase heat transfer coefficient', *Int. J. Heat Mass Transf.*, vol. 64, pp. 1239–1256, Sep. 2013, doi: 10.1016/j.ijheatmasstransfer.2013.04.014.

[20] B.-U. Bae, B.-J. Yun, S. Kim, and K. H. Kang, 'Design of condensation heat exchanger for the PAFS (Passive Auxiliary Feedwater System) of APR+ (Advanced Power Reactor Plus)', *Ann. Nucl. Energy*, vol. 46, pp. 134–143, Aug. 2012, doi: 10.1016/j.anucene.2012.03.029.

[21] '3m-novec-engineered-fluid-649.pdf'. Accessed: Jan. 07, 2022. [Online]. Available: https://multimedia.3m.com/mws/media/569865O/3m-novec-engineered-fluid-649.pdf

[22] *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on fluorinated greenhouse gases*. 2012. Accessed: May 30, 2022. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A52012PC0643

[23] 'United Nations Climate Change, Kyoto Protocol Reference Manual on Accounting of Emissions and Assigned Amounts, 2008'. Accessed: Jan. 06, 2022. [Online]. Available: https://unfccc.int/resource/docs/publications/08_unfccc_kp_ref_manual.pdf

[24] 'EES: Engineering Equation Solver | F-Chart Software : Engineering Software'. https://fchartsoftware.com/ees/ (accessed Jul. 12, 2021).

[25] G. Lhermet, N. Tauveron, N. Caney, Q. Blondel, and F. Morin, 'A Recent Advance on Partial Evaporating Organic Rankine Cycle: Experimental Results on an Axial Turbine', *Energies*, vol. 15, no. 20, Art. no. 20, Jan. 2022, doi: 10.3390/en15207559.

[26] S. W. Churchill and H. H. S. Chu, 'Correlating equations for laminar and turbulent free convection from a vertical plate', *Int. J. Heat Mass Transf.*, vol. 18, no. 11, pp. 1323–1329, Nov. 1975, doi: 10.1016/0017-9310(75)90243-4.

[27] J.-J. Jeong, K. S. Ha, B. D. Chung, and W. J. Lee, 'Development of a multi-dimensional thermal-hydraulic system code, MARS 1.3.1', *Ann. Nucl. Energy*, vol. 26, no. 18, pp. 1611–1642, Dec. 1999, doi: 10.1016/S0306-4549(99)00039-0. 139

[28] S. Ostrach, 'An analysis of laminar free-convection flow and heat transfer about a flat plate paralled to the direction of the generating body force'. Jan. 01, 1953. Accessed: Apr. 05, 2023. [Online]. Available: https://ntrs.nasa.gov/citations/19930092147

[29] C. Y. Warner and V. S. Arpaci, 'An experimental investigation of turbulent natural convection in air at low pressure along a vertical heated flat plate', *Int. J. Heat Mass Transf.*, vol. 11, no. 3, pp. 397–406, Mar. 1968, doi: 10.1016/0017-9310(68)90084-7.

[30] Q. Men, X. Wang, X. Zhou, and X. Meng, 'Heat Transfer Analysis of Passive Residual Heat Removal Heat Exchanger under Natural Convection Condition in Tank', *Sci. Technol. Nucl. Install.*, vol. 2014, p. e279791, Nov. 2014, doi: 10.1155/2014/279791.

[31] J. Xu, X. Xie, M. Ding, C. Yan, and G. Fan, 'A one-dimensional code of double-coupled passive residual heat removal system for the swimming pool-type low-temperature heating reactor', *Nucl. Eng. Des.*, vol. 374, p. 111070, Apr. 2021, doi: 10.1016/j.nucengdes.2021.111070.

[32] D. Lu, Y. Zhang, X. Fu, Z. Wang, Q. Cao, and Y. Yang, 'Experimental investigation on natural convection heat transfer characteristics of C-shape heating rods bundle used in PRHR HX', *Ann. Nucl. Energy*, vol. 98, pp. 226–238, Dec. 2016, doi: 10.1016/j.anucene.2016.08.009.

[33] Q. Blondel, N. Tauveron, G. Lhermet, and N. Caney, 'Zeotropic mixtures study in plate heat exchangers and ORC systems', *Appl. Therm. Eng.*, vol. 219, p. 119418, Jan. 2023, doi: 10.1016/j.applthermaleng.2022.119418.

[34] V. S. Gullapalli, 'Estimation of Thermal and Hydraulic Characteristics of Compact Brazed Plate Heat Exchangers'.

[35] P. Horák, M. Formánek, T. Fečer, and J. Plášek, 'Evaporation of refrigerant R134a, R404A and R407C with low mass flux in smooth vertical tube', *Int. J. Heat Mass Transf.*, vol. 181, p. 121845, Dec. 2021, doi: 10.1016/j.ijheatmasstransfer.2021.121845.

This book contains the compilation of works contributed to the *7th International Seminar on Organic Rankine Cycle Power Systems* (ORC 2023), held in Seville between the 4th and 6th of September 2023. The event was hosted by Universidad de Sevilla on behalf of the Knowledge Centre on Organic Rankine Cycle Technology (KCORC), incorporated in The Netherlands.

The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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