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PASSIVE RESIDUAL ENERGY UTILIZATION SYSTEM IN THERMAL CYCLES ON WATER-COOLED POWER REACTORS

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ABSTRACT

This work presents a concept of a residual energy utilization in nuclear plants thermal cycles. After taking notice of the causes of the Fukushima nuclear plant accident, an idea arose to adapt a passive thermal circuit as part of the ECCS (Emergency Core Cooling System). One of the research topics of IEAv (Institute for Advanced Studies), as part of the heat conversion of a space nuclear power system is a passive multi fluid turbine. One of the main characteristics of this device is its passive capability of staying inert and be brought to power at moments notice. During the first experiments and testing of this passive device, it became clear that any small amount of gas flow would generate power. Given that in the first stages of the Fukushima accident and even during the whole event there was plenty availability of steam flow that would be the proper condition to make the proposed system to work. This system starts in case of failure of the ECCS, including loss of site power, loss of diesel generators and loss of the battery power. This system does not requires electricity to run and will work with bleed steam. It will generate enough power to supply the plant safety system avoiding overheating of the reactor core produced by the decay heat. This passive system uses a modified Tesla type turbine. With the tests conducted until now, it is possible to ensure that the operation of this new turbine in a thermal cycle is very satisfactory and it performs as expected.

1. INTRODUCTION

This contribution can be seen as a first proposal and presentation of the passive multi fluid turbine (TPMF), as an auxiliary passive system to be added to a commercial nuclear power plant, to its Emergency Core Cooling System (ECCS). This proposition occurs in the wake of the Fukushima accident [1] where the ECCS was completely shut down after both events an earthquake followed by a tsunami. The first event destroyed the off-site power and the second one the diesel generating system. At the end of a nine-hour period, the backup batteries went dead and the ECCS shut down permanently. The shut down reactor core started to warm up due to the decay heat produced. One of the results of the decay heating is the production of steam. This energy excess, in form of steam, was the root cause of the Fukushima accident. Recently, Dos Santos [2] has proposed that this steam could be used to produce electricity, which in turn could be used to reactivate the ECCS. Dos Santos [2] has proposed that a steam turbine be used as an alternative emergency drive to secure removal of this residual heat. This proposal is called the Ultimate Emergency Core Cooling System (UECCS) [2]. A brief description of this UECCS is presented at item 2.1. Dos Santos did not specify the type of steam turbine to be used.

The “Instituto de Estudos Avançados” (IEAv) has a multi fluid passive turbine as a research topic. This type of turbine is to be used as part of the heat conversion system for a space nuclear power plant. So far, for this specific objective three passive multi fluid turbines have been produced. Fig. 1 shows the third prototype produced. It is believed that the passive multi fluid turbine fits the requirements suggested by Dos Santos [2]. This paper presents a few results using steam as a working fluid that corroborates this belief.

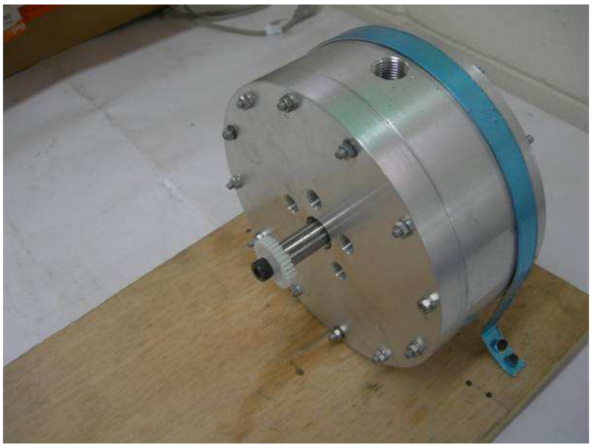


Figure 1: Multi fluid passive turbine - TPMF-3.

2. HISTORIC

The first multi fluid passive turbines developed at IEAv were based in a simple and robust Tesla turbine [3], patented in 1913 by Nicola Tesla. Fig. 2 shows the Tesla turbine original schematic concept.

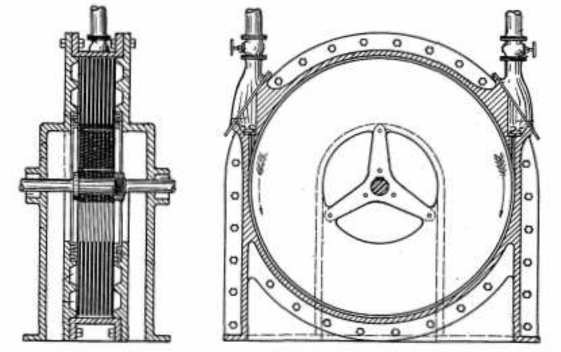


Figure 2: Original Tesla turbine design.

The first multi fluid passive turbine, developed in 2010 at IEAv, was named TPMF-I [4]. This TPMF-I was built to test the concept. It worked in an open cycle with compressed air. It was tested in several disks configuration, starting with 7 disks and up to 14 disks. This change in the number of disks was possible keeping constant the distance between the first and the last disk and actually changing the distance between disks. Another controlled parameter was the compressed air inlet pressure, which was changed between the values of 100 up to 600 kPa.

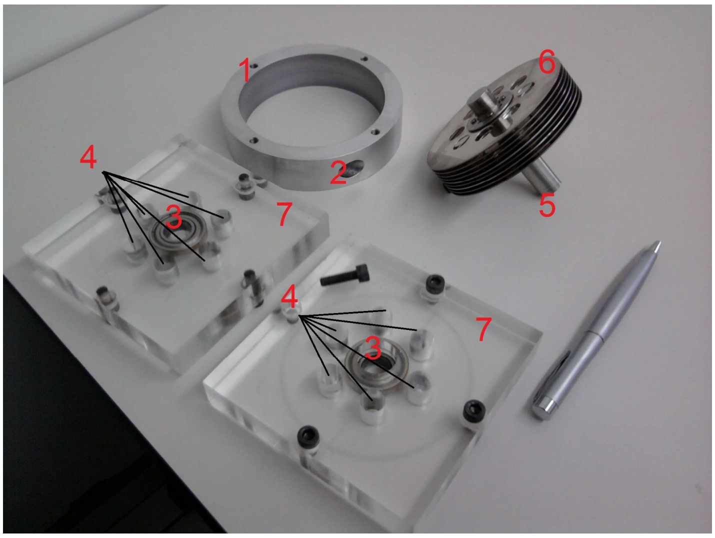


Figure 1. First Tesla turbine disassembled: 1- casing, 2- fluid inlet, 3- bearings, 4- fluid outlet, 5- shaft, 6- discs and 7- lateral case.

In 2011, the second multi fluid passive turbine was built TPMF-2. This one was built in a stain less steel case in such a way that it would resist operations with temperatures up to 300°C [5]. This fact allows testing using steam [6], but still on an open cycle. The results with the operation with heated steam were as good as the ones obtained with the first turbine. Fig. 4 shows TPMF-2 disassembled.

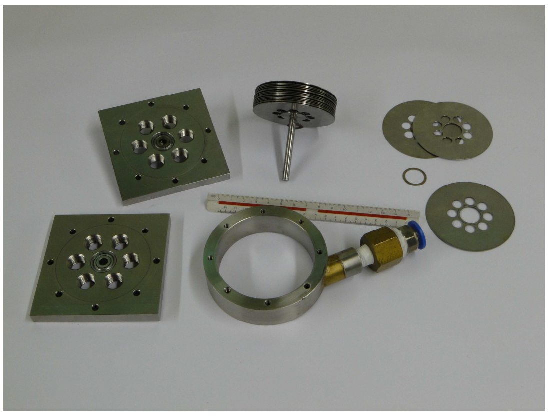


Figure 4: Second multi fluid passive turbine shown disassembled.

2.1. Ultimate Emergency Core Cooling System

This item presents a brief description of the UECCS proposed by Dos Santos. The shutdown heat removal from nuclear power plants is a subject of great importance, as evidenced in Fukushima accident. Adequate heat removal is related to public safety and to overall plant design. In LWR, the shutdown heat is generally removed via a forced flow of the primary coolant through the reactor core. The electric power required should usually be provided by independent and guaranteed source, what did not happen in Fukushima. There, the power interruption caused the main steam isolation valves to automatically close, disconnecting the reactor core from its normal heat sink and disabling the normal source of makeup water to the reactor vessel. Even in a PWR, if the ECCS lost electric power, the main cooling pumps would stop to deliver water to the core. Since heat, ultimately, is the energy to be dissipated through the cooling system, the same energy in the form of steam can be used to its own cooling. This is the basis of Ultimate Emergency Core Cooling System (UECCS) [2] proposal, shown in Fig. 4.

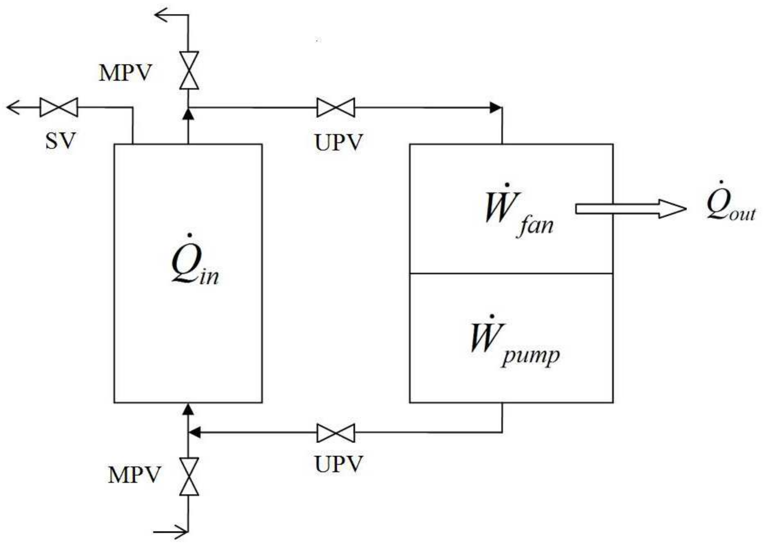
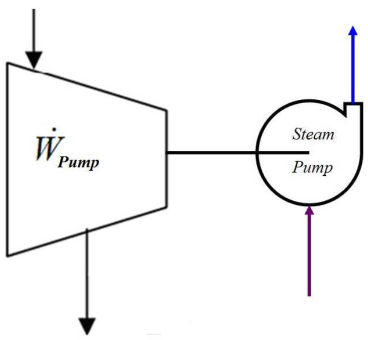


Figure 4. Passive Ultimate Emergency Core Cooling System for LWR [2].

When UECCS is activated, a safety valve maintains the system pressure at a level as close as possible in the operating pressure. That is the best way to use thermal energy to convert it into mechanical energy to drive the fluid by pumps, and to drive fan for cooling the steam exhausted from the turbine. A closed circuit cooling serves to keep the radioactivity contained in the coolant. Fig. 5 [2] shows the Turbine-Pump components, while Fig. 6 [2] shows the Turbine-Fan components. These components form the basis of UECCS.



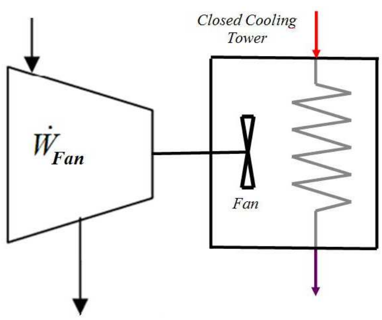


Figure 5: UECCS Turbine-Pump Components. **Figure 6: UECCS Turbine-Fan Components.**

3. RESULTS

3.1 First Multi Fluid Passive Turbine Working with Compressed Air

Fig. 5 shows the power versus air inlet pressure measured for the first multi fluid passive turbine. It is observed that the increase of power with inlet air pressure is non-linear for the pressure range of interest. This pressure range was established based on the requirements for the energy conversion cycle for the Brazilian space nuclear reactor.

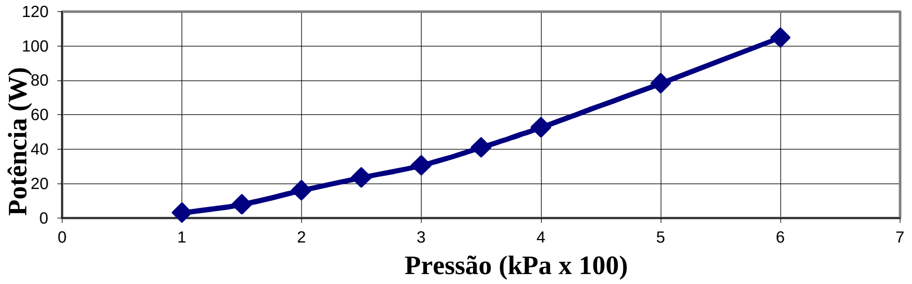


Figure 5: Power X inlet pressure for the first multi fluid passive turbine.

3.2 Second Multi Fluid Passive Turbine Working with Steam

For the second multi fluid passive turbine (TPMF-2) a computational simulation and an experimental test were performed. The computational test was performed with an airflow modeling for the turbine inlet orifice. This model was built using a CFD (Computational Fluid Dynamics) tool called ANSYS FLUENT 12.0. The experimental was performed with a Schlieren photograph device built in the Thermal Systems Laboratory. Both, the computational modeling and the experimental test generated an image of the shock wave for the air flow. Fig. 16 is a composite of both results. The colored part is a representation with the FLUENT simulation data of the flow shock wave, whereas the underneath black and white picture is the photo captured from the airflow obtained with the Schlieren device. Both images were made to the same scale in such a way that it can be seen a very good agreement between the simulated and the measured shock waves. The experimentation shows that the design of the air inlet orifice was performed very nicely, one can identify the wave clearly. It also allows identifying that some vibration would result from fluttering, that would occur as air flow would hit the edge of the disk. That problem must be addressed in future designs. It is important to emphasize that composite image validates the CFD calculation in the sense that the imposed boundary conditions are linked directly with what is observed in the images. The equation below relates the Mach number (M) with the sine of the half angle produced by the shock wave,

$$M = \frac{1}{\sin\alpha} \quad (1)$$

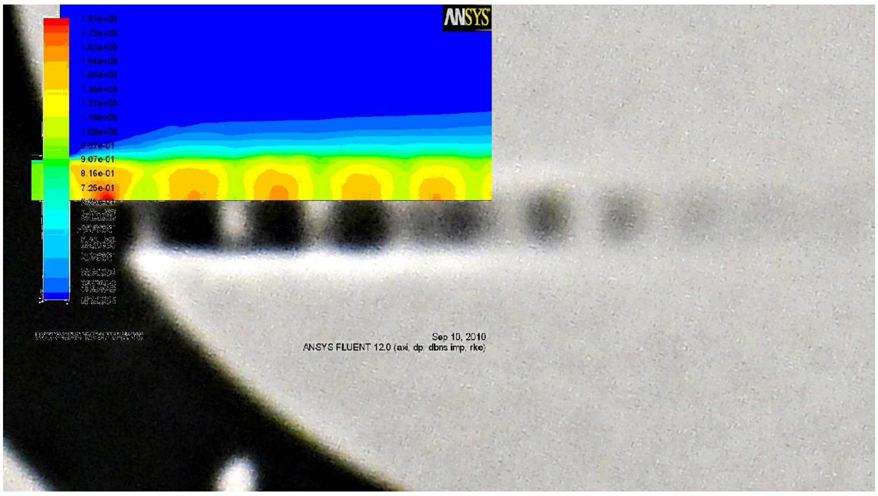


Figure 6: Composite of the FLUENT and the Schlieren images of the airflow coming out of the turbine inlet orifice.

Also, for the TPMF-2 a device to measure mechanic power was devise. This device was assembled on a testing table, and is schematically shown in Fig. 7. It is assembled with a leverage that has a brake on F1 side and a digital balance on the F2 side. The digital balance has a measurement precision of 1g. The digital balance acts as dynamometer measuring force. Coupled with this system, but not shown on the schematic there is a tachometer with a precision of 1 RPM.

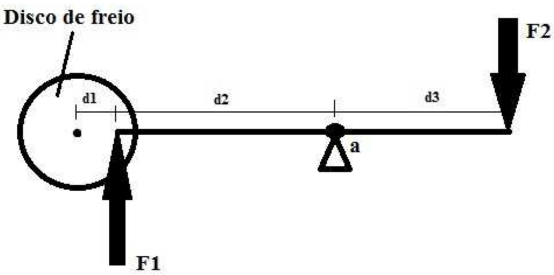


Figure 7: Schematic of the leverage system used to measure mechanic power for the TPMF-2.

The value of power is actually obtained by the following equation, where: *P* represents power in Watts, *F* is force in Newton, *d* is the leverage arm in meters and *f* is the turbine angular velocity in rad/s.

$$P = F \times d_1 \times 2 \times \pi \times f \tag{2}$$

A linear monotonically growing behavior is presented in Fig. 8, which presents the mechanic power versus steam pressure at the turbine inlet. It is worth to note that these measurements are in same range (200 and 500 kPa) of pressure of the data for the TPMF-1 in Fig. 5. Also, it is interesting to note that the power generated with steam is higher than the one generated with air, as a working fluid. That has to do, probably, with a combined effect of density and viscosity of the steam and air. Several runs were performed with this turbine, and the most impressive number is the maximum rotation achieved, around 65,000 RPM.

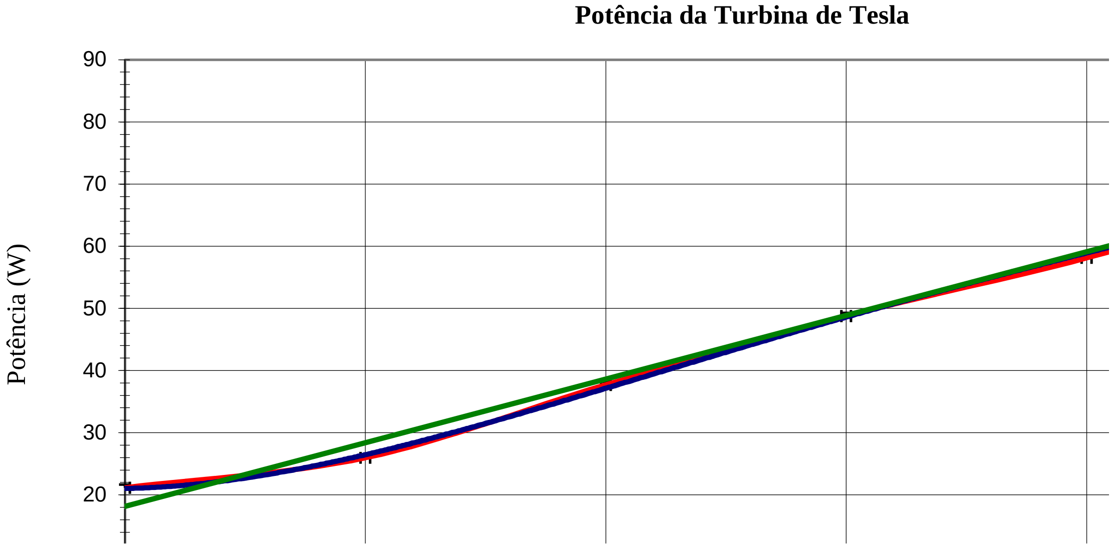


Figure 8: Mechanic power versus pressure at the turbine inlet, data for TPMF-2.

It is also clear from the Fig. 8 that the power behavior is nonlinear. However, linearity could be assumed inside a smaller range of pressure, as for instance 300 and 450 kPa. Over this range, a characteristic equation is obtained by linear interpolation. This equation is a nice formulae for computer codes that deals with the modeling of this type of device.

$$P = 0,2049 \times p - 22,838 \quad (3)$$

3.3 Control System for the Multi Fluid Passive Turbine, TPMF-3

A third multi fluid passive turbine was developed and built, at IEAv. This new turbine, named TPMF-3, incorporates a few design features in order to improve its operation. Unfortunately, these new design features are under a patent claim and will not be discussed here. Rather, this new turbine will be treated here as a black box. Nevertheless, a flow control system was built using this turbine. This system is shown in Fig. 9. In this experiment, compressed air is used as working fluid. A description of this system, basically, can be put in this way: compressed air goes through a rotameter (7), following through a controlled valve (3) and the TPMF-3 to exit to the atmosphere after that. As the compressed air goes through the turbine it makes the turbine axis rotates. Connected with the turbine axis is a small electric generator, which produces a voltage. This voltage is going to feed the LED lamps (1). The voltage is measured by a complex electric system, which includes a PLC and a computer. This electric system regulates the voltage to a 4 V value. That regulation implies acting on the valve actuator to reduce the pressure at the turbine inlet and, hence, reducing the air flow.

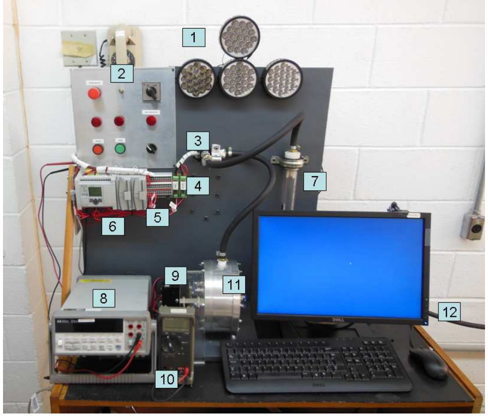


Figure 9: Open loop system for the TPMF-3 turbine. This open loop runs with compressed air. The meaning of the numbers is, as follows: 1 – Set of LED lamps to be fed by the TPMF-3 power. 2 – Panel guiding lamps to display the devices operational status. 3 – Airflow regulating valve. 4 – Coupling relay set. 5 – Borne set. 6 – CLP. 7 – Flow meter. 8 – Current meter. 9 – Alternator. 10 – Voltmeter. 11 – TPMF-3 turbine. 12 – System compressed air inlet.

The whole system is automatic due to a computer program built in the PLC programing language. The system works perfectly as desired. A film showing the workings of this system, may be found at http://www.ieav.cta.br/enu/projetos_enu.php. This turbine has its shell made of stain less steal and its disks made of aluminum. It was built to run with steam. A closed Rankine cycle was designed and built to run with the TPMF-3. As to this writing, this Rankine cycle is starting to be mounted. With this closed Rankine cycle a full characterization of the TPMF-3 turbine will be realized, these results will be published elsewhere.

4. A TPMF as a passive component from the ECCS or the UECCS

It is important, at this point, to clarify a few points. It is not the intention of this paper to propose a new type of ECCS for the new proposed reactors, such as: Generation IV or any advanced type of reactors. In spite of the fact, that this idea could be a consideration. The proposed safety system, actually, is a good back-up for the old type of reactors (BWRs and/or PWRs). The authors find this idea interesting once most of the thermal reactors are reaching their expected life limit, and their operators are applying for life extension. What Fukushima has, painfully, demonstrated, is that in certain cases an addition to the ECCS may well become a requirement, before an extension license is granted. Analyzing the events that took place in Fukushima indicates that steam was a surplus during all the phases of the accident. The TPMF experiments reported here indicates that with very little steam, electricity may be generated either to power batteries or to power any required demands such the ones required in the UECCS. Sure more investigation is required, but the basic concept is sound. In summary, a new steam line, including a properly designed TPMF, would be added parallel to the existing ECCS or as suggested in the description of the UECCS. This could work in many forms, as for instance, a steam bleed would be taken from the inlet reactor turbine pipe. That steam would go through a series of TPMF. After producing electric power, the steam would be dump directly into the condenser. The generated electricity in this way would either power directly the primary pumps, or power up the reactor backup batteries which will continue to power the main pumps. The actual working of this scheme would certainly be a matter of very interesting further investigation. Also, the number of TPMFs to be used, the size of each turbine, geometrical arrangement of the turbine set and several other issues must be investigated. More data to enrich this idea will be put forward when the new Rankine closed cycle is ready and working.

3. CONCLUSIONS

In this article a short description of the multi fluid passive turbine is presented. So far, three of these turbines were designed and built at IEAv's Thermal Systems Laboratory.

These turbines were built to be used as alternative means of electric power production in the heat electric conversion system to be applied for the Brazilian nuclear space reactor.

These turbines are an evolution of the old Tesla turbines. They are robust, reliable and work with very low flow. With very little steam flow it generates reasonable amounts of power. Also, very high RPM numbers may be reached.

A description of a proposed UECCS was briefly described and the data presented here for TPMF seems to indicate that the latter could be part of the former. Further investigation for matching is required though.

In the wake of the Fukushima accident it was realized that a few component concepts being developed for a nuclear reactor space application, may have a relevant hole to be played in the life extension of old Earth nuclear reactors. This hole would be to increase the safety margin in de ECCS of old nuclear thermal reactors. The increased safety margin will increase the chance of this plant to be accepted as a candidate to further life extension without significant increase in Capital cost. And obviously, the consequence of this life extension is more MWs without CO_2 component effect, which is good for the environment.

So far, it is believed that the results presented here show that the idea is sound. Further investigation is required.

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REFERENCES

1. C. R. Ghezzi, W. Cravero and N. S. Fornillo, "The Fukushima Disaster:Cold Analysis", Current Reasearch in Nuclear Reactor Technology in Brazil and Worldwide, Chapter 13, pp. 304-336, http://dx.doi.org/10.5772/54262, 2013.
2. R. S. Dos Santos, "Steam Turbine: Alternative Emergency Drive For The Secure Removal of Residual Heat From The Core of Light Water Reactors in Ultimate Emergency Situation," *PHYSOR 2012 – Advances in Reactor Physics*, Knoxville, Tennessee, USA, April 15-20, 2012.
3. N. Tesla, "Turbine", Estados Unidos Patente nº. 1061206, May 6, 1913.

4. G. M. Placco, L.N.F. Guimarães, G. P. Camillo, 2010 “Parâmetros de Funcionamento de uma Turbina de Tesla Funcionando a Ar Comprimido”, Congresso Nacional de Engenharia Mecânica, CONEM, Campina Grande, PB, Brasil, 2010.
5. ASME “Handbook: metals properties”, McGraw-Hill, New York, 1954.
6. G. M. Placco, "Construção e Análise de uma Turbina de Tesla a Vapor", Trabalho de Conclusão de Curso, Faculdade de Tecnologia São Francisco, FATESF, Jacareí, SP, Brasil, 2012.