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Jedrske elektrarne in termoelektrarne so energetski objekti, ki so pretežno namenjeni pridobivanju električne energije. Poleg kvalitetne električne energije sodobne elektrarne proizvajajo tudi kvalitetno paro, ki jo lahko koristimo za soproizvodnjo toplotne energije oz. daljinsko ogrevanje, za soproizvodnjo biogoriv s pomočjo biomase ali za soproizvodnjo vodika iz vode. Soproizvodnja tako omogoča zelo učinkovit način dodatne izrabe energije. Prva elektrarna v svetu, ki je omogočala soproizvodnjo, je bila postavljena po načrtih podjetja Edison Illuminating Company, ki jo je vodil izumitelj Thomas Edison. Elektrarna, imenovana Pearl Street Station, je bila zgrajena leta 1882 in je razen z električno energijo bližnja podjetja oskrbovala tudi s tehnično paro. Tudi v Sloveniji nekateri energetski objekti, kot na primer Termoelektrarna Šoštanj, s pomočjo sistema soproizvodnje proizvajajo električno energijo in ogrevajo Velenje in bližnje kraje.

Želja po uporabi obnovljivih virov energije je za soproizvodnjo toplotne in električne energije vse večja. Biomasa in bioplin se v ta namen že koristita. Tudi solarna tehnologija omogoča zelo učinkovito soproizvodnjo električne in toplotne energije. Tako lahko na primer močno izboljšamo skupen izkoristek solarnim celicam, ki jih hladimo, hladilno vodo pa nato uporabimo za ogrevanje stavb.

Jurij AVSEC
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Dear Readers of the Journal of Energy Technology (JET)

Nuclear power plants and thermal power plants are primarily intended for generating electricity. In addition to high-quality electricity, modern power plants can also produce high-quality steam, which can be used for co-generation of heat (district heating) and electricity, co-generation of biofuels and electricity, and the use of biomass or co-generation of hydrogen from water. Cogeneration of heat and electricity is a very efficient form of additional energy usage. The first power plant in the world that enabled cogeneration was built according to the plans of the Edison Illuminating Company, headed by Thomas Edison in 1882. In addition to electricity, the power plant supplied local businesses with steam. Also in Slovenia, some energy facilities, such as Šoštanj Thermal Power Plant, produce electricity and heat by cogeneration systems. With district heating systems, it is possible to heat the city of Velenje and nearby towns.

In the future, the cogeneration of heat and electricity, including renewables should be applied to a much greater extent. Biomass and biogas are already being used for this purpose. Solar technology enables highly efficient cogeneration of electricity and heat. Thus, for example, solar cells are cooled with water; the cooling water could then be used for the heating of buildings and other facilities.

Jurij AVSEC
Editor-in-chief of JET

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SMART GRID DESIGN FOR EFFICIENT BUILDING MANAGEMENT

ZASNOVA PAMETNEGA OMREŽJA ZA UČINKOVITO UPRAVLJANJE ZGRADB

Robert Rozman[R], Igor Godec[1]

Keywords: smart grid, smart building, HVAC, IoT, cloud

Abstract

The existing methods of automated building management are faced with critical challenges in the modern smart grid movement. Remote data transmission, efficient data processing and the ability to adapt rapidly to changes are severely limited as a result of the poor connectivity and rigidity of the existing systems. As an effective solution to such challenges, a new generation of smart microcontroller systems has been designed, which in addition to the above-described factors delivers many new features and holds yet relatively unexplored potentials for further development. The major advantage of these systems is integration with a cloud service that already enables the more efficient management of remote buildings and delivers enhanced user and environment-friendly solutions. In addition, with the quick adaptation ability, these systems also offer effective solutions for new, yet unforeseen, smart building challenges in the future.

In the first part of this article, we present the basic module for controlling an individual smart building and its integration into the wider concept of smart grids and smart city networks: DIALOG EQ microcontroller system, which is aimed at the efficient, distributed management of smart buildings. We describe the process of its development and current capabilities. The basic guideline for the development was user and environment friendliness. The second part is dedicated to the development potentials of the system, the challenges of the future and certain aspects of automatic (machine) learning from the data obtained through the operation of these systems in individual buildings.

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Povzetek

Obstoječi načini avtomatiziranega upravljanja zgradb so v sodobnem trendu pametnih omrežij postavljeni pred pomembne izzive. Prenos podatkov na daljavo, njihova učinkovita obdelava in zmožnost hitrega prilagajanja spremembam so zaradi nepovezanosti in togosti obstoječih sistemov zelo težko uresničljivi. Kot učinkovito rešitev tovrstnih izzivov smo zasnovali novo generacijo pametnih mikrokrmilniških sistemov, ki prinašajo poleg opisanih še veliko novih, tudi še dokaj neraziskanih potencialov za nadaljnji razvoj. Bistvena prednost teh sistemov je povezljivost z oblačno storitvijo, ki že v tem trenutku omogoča bolj učinkovito upravljanje zgradb na daljavo in uporabniku ter okolju bolj prijazno rešitev. Z dodano zmožnostjo hitrega prilagajanja, ponujajo ti sistemi učinkovito rešitev tudi za nove, še nepredvidene izzive pametnih stavb v prihodnosti.

V prvem delu predstavljamo osnovni gradnik upravljanja delovanja posamezne zgradbe in njenega povezovanja v koncept pametnih omrežij in mest – mikrokrmilniški sistem DIALOG EQ, ki je namenjen učinkovitemu porazdeljenemu upravljanju pametnih zgradb tudi na daljavo. Opisujemo proces njegovega razvoja in njegove trenutne zmožnosti. Osnovno vodilo razvoja je bila prijaznost do uporabnika in okolja. V drugem delu pa se posvečamo razvojnim potencialom sistema, morebitnim izzivom prihodnosti ter nekaterim konceptom avtomatskega učenja iz podatkov, pridobljenih pri delovanju teh sistemov v posameznih zgradbah.

1 INTRODUCTION

Buildings are major consumers of energy on a global scale. In developed countries, buildings account for at least a third of all energy consumed. Approximately half of the energy consumption in a building is accounted for by facilities for heating, ventilation and air conditioning (HVAC). Due to this fact, HVAC system is subjected to intensive research and improvements. Unfortunately, this is more a result of rising energy costs than a higher level of environmental consciousness. In spite of this, the fact that buildings' energy consumption and its impact on the environment have never been dealt with as intensely as right now is of great significance.

The field of HVAC systems management in buildings has a few unresolved problems. With the development of technology and knowledge, most of the problems are gradually solved, but some remain quite prominent. The efficiency of HVAC systems is an example of an optimization problem that can be continuously improved. It is influenced by many internal and external factors. Both groups vary considerably among individual buildings. Therefore, it is necessary that the solution consistently adapts to the specific characteristics of each building separately. In doing so, we usually have to satisfy two often contradictory constraints:

- energy consumption,
- user comfort.

Regardless, we always want to consume a minimal amount of energy, but we also have to attempt to meet users' requirements: to ensure their comfort and well-being.

With the help of modern technologies and (above all) smart grids, we can solve many problems in a more efficient, faster and cheaper way. This can be done mainly because of modern concepts of connectivity and accessibility of devices (the so-called "Internet of Things" (IoT)) and device-oriented online data warehouses and services – often generally denoted as "the cloud".

It is well known that each building has unique characteristics; weather conditions also vary significantly in time and space. Therefore, the adjustment to each case and current weather conditions is inevitable and must be carried out very carefully. A significant step in this direction is a new generation of smart controllers that enable two-way communication between the building and the cloud (Internet) service; therefore, both sides can exchange adequate data about current weather and building status. On this basis, the optimal process control procedure for building management can be determined more efficiently.

The article is structured as follows. The following section presents the basic building block of the proposed smart grid system design for efficient building management: DIALOG EQ (DEQ) HVAC controller. More specifically, it describes its development and current functionalities. The next section includes an analysis of its future potentials in line with the latest findings in the interconnected areas of building management and smart grids. The article is concluded with a short practical demonstration of an example of a contemporary self-learning software model, which is also applicable for efficient building management: Evolving Fuzzy Neural Network (EFuNN). This universal model represents the advanced use of the self-learning paradigm in this field of research interest.

2 SMART GRID BUILDING MANAGEMENT MODULE – DIALOG EQ

PROF.EL Ltd. is a SME that is engaged in research and development in the field of control systems for heating, cooling, ventilation (HVAC) and building management. Since the year 2000, we have had our own production line for controllers. Over the years, we have acquired quite a substantial number of users of our products. In contrast to legacy systems, a new generation of smart controllers must be properly maintained and continuously complemented, if we want to continue to ensure competitiveness and user satisfaction.

Maintenance of building controllers is not an easy task. They are commonly installed in grounded electrical cabinets in dedicated technical rooms. The most effective maintenance would be on the spot, but this is often related to time- and money-consuming logistics. Another possibility is that the controller is removed from the system to be tested in our development laboratory, but only a basic test can be performed outside its native environment. Coping with such problems over the years, we have realized that it would be most effective if controllers could be maintained and tested remotely from our development laboratory. This way, we can also remotely maintain and control the entire structure of various subsystems in buildings.

These needs, as well as the users' demands, have led to the development of a new generation of smart grid building controllers named DIALOG EQ (DEQ) with the following features:

- remote control operation,
- over-the-network maintenance and upgrades,
- remote monitoring of the operation,
- optimization of control algorithms,
- storage for user and system settings,

- chronological logging of selectable events,
- multi-level access (security),
- multilingual user interface,
- and many other options.

With the DIALOG EQ line of controllers, the majority of tasks became much simpler and cheaper to perform; moreover, substantial time savings can be noted, as a physical presence at the locations of the systems is generally no longer necessary.

2. 1 Development of DIALOG EQ controller

Today, when most of the electronic assemblies (HW) are produced in China for a very low price, the decision to develop one's own product is quite difficult. Furthermore, the market is crowded with a variety of microcontrollers and printed circuit boards. Nevertheless, it is difficult to find a product that offers high-quality production, the possibility of upgrades, longer-term availability, and acceptable pricing. The products that would meet all of the above criteria are practically non-existent. In addition to this fact, we (as developers) are also interested in having a declaration for the product's robustness, electromagnetic compatibility, temperature resistance and the influence of aging on components' speed and their tolerances. However, users are not interested in all of these details; it only matters that the controllers work without problems and can be easily managed.

At the beginning of 2013, we embarked on the development of a microcontroller system, which was named DIALOG EQ (Figure 1) at the end of the project. HW development was entrusted exclusively to local experts who specialized in the development of telecommunications hardware equipment. Standards in the telecommunications sector are much more stringent than standards for industrial and home electronics, which comprise the DEQ. Consequently, telecommunications standards were used to a certain extent. Selection of the microcontroller was not easy. In the end, we chose the ARM-based microcontroller from the Kinetis family (manufacturer Freescale, now NXP). It has the MQX RTOS operating system with integrated TCP/IP stack and other needed software modules (web server, FTP client, etc.).

***Figure 1:** The basic component of smart grid – DIALOG EQ controller*

2. 2 Internet connectivity and cloud services (cloud)

Our development policies included the advantages offered by two rapidly evolving technologies: the Internet of Things ("IoT") and cloud computing ("cloud").

The dilemma of whether the DEQ will use the wireless or wired connection to the Internet ended with the selection of the latter. Wireless (Wi-Fi) access is a more "elegant" solution (mostly also less invasive), but in the grounded metal electrical cabinets (where controllers are usually located) wireless signals are often weak or non-existent. In contrast, wired access can be easily extended with Wi-Fi access point or data transmission through domestic electric installation ("Ethernet over Powerline") to the nearest router.

DEQ can be considered to an IoT device. For such devices, it is vital to work properly as soon as they are connected to the network ("Plug&Play"). If we want to offer direct remote access to DEQ from an external network, the settings for domestic routers and networks can be quite complex. It is much simpler to communicate in the opposite direction; DEQ is programmed to connect automatically to the nearest gateway router and then through the Internet to the chosen cloud service.

Server facilities for our cloud services were hired from a selected provider, who (according to our criteria) offers an acceptable level of safety and reliability. We have registered the dedicated domain name (www.deq.si). In addition to offering cloud services, there is also a central database with all the necessary software modules. Everything is accessible to users through a Web interface application. All communications between the user and the server take place over a secure, encrypted connection (SSL/TLS protocols).

2. 3 User interfaces

Nowadays, users are reasonably entitled to expect simple and user-friendly interfaces from virtually all computing devices. During the development of DEQ, we devoted particular attention to this segment. In order to offer the user the greatest possible freedom in the control and management of the system, we prepared user interfaces for all common devices of an average user: phones, tablets, and laptops. A user can freely choose the device he will use: either a computer with a large screen or a phone/tablet with a small screen. In any case, the user can use the device that is available at the moment or which is the most convenient for him to communicate over the Internet. Since users have different preferences and lifestyles, we have prepared three types of user interfaces in five different languages:

- Local access (LAN)

  There is a local, embedded web server on DEQ and it provides the user with direct access to configuration parameters and a few basic visualization screens. Because of the safety of the local network, the user is not required to enter any special identification. The internal server also works without an Internet connection.

- WEB application (WAN)

  This interface is intended for users with PCs connected to the Internet; they can access the WEB application from anywhere. The program is stored on the cloud server, and the user is required to enter proper password identification. The visual appearance is similar to that of local access but offers a richer graphical representation of the measured data (Figure 2). Data is also available for a shorter amount of time.

- Application for smartphones (Android, iOS, Windows Phone)

A smartphone application has been implemented for users preferring mobile devices. The application only needs to be installed on the phone and provided with proper access credentials. A screenshot of the application is shown in Figure 3.

With such a variety of user interfaces, the user can monitor and manage the heating, cooling, ventilation or any other subsystem or device in his building at any time and from any place.

Figure 2: *Main screen of the WEB application – www.deq.si*

2. 4 Description and installation of DIALOG EQ

DEQ is designed as a basic block for building automation systems and represents a two-way connection link to the concept of smart grids. In addition to the basic HVAC regulation functions (heating, cooling, ventilation), it can also control other aspects of smart buildings, e.g. illumination, shading, security, and others.

DEQ is essentially a device with the following connectors:

- 20 inputs (16 analog, 4 digital),
- 16 outputs (2 analog and 14 digital).

These connectors are sufficient for most heating, cooling and ventilation control applications. For other smart building segments, DEQ offers local wired connectivity to additional extended automation modules that can connect through CAN or serial buses that are present exclusively for this purpose.

DEQ already embeds software modules for the control of heating and cooling systems (oil and gas boilers, biomass boilers, heat pumps, solar panels) as well as modules for in-building energy distribution (direct and mixing branches). We have also implemented software functions for the measurement of power consumption, the production of heat and electricity, and other functions.

Figure 3: *Main screen of the Android smartphone application*

The integrator in the process of DEQ installation only has to select (tick) the appropriate software modules and adjust the values of the selected operating parameters. After purchase, each DEQ user receives the identification code that provides access to the system through the web or mobile applications. Servicemen and technicians receive special service codes that allow them to have a higher level of access rights for setting up the systems they maintain. The user is allowed to change the basic settings (e.g. temperature set points), while the adjustment of systems settings requires a service code access level. DEQ is not freely programmable, so it is even more necessary to adapt the functionality to the user's demands. However, this task can be pursued remotely with minimal cost and effort for the manufacturer and integrators. Software modules simply need to be prepared, selected, transferred and activated.

2. 5 DIALOG EQ and cloud service

During the development process, the effective cooperation and communication between DEQ and the customer were our main goal. At the same time, we were also aware of possible pitfalls related to this standpoint. Nonetheless, the primary task of DEQ is the management of various systems in the building, and it is necessary to ensure adequate priority for this task. Cloud connectivity, remote control, and access certainly affect the stability of the controller. We have tried to minimize such risk to the lowest possible level. Therefore, DEQ establishes communication with the cloud server only once a minute. First, data is uploaded to the server and then a query for any waiting messages is performed. If they exist, they are sent back to DEQ and processed. If this is not the case, DEQ then suspends communication with the server until the next transfer. Any remote changes in DEQ's settings can only happen within the active connection.

To monitor the operation of each DEQ, there is a built-in virtual "black box" device (similar to flight recorders in airplanes) that monitors and logs all events that affect system performance. Circular log memory (FIFO) is large enough to record events in the period of the previous six months. Based on user's choice, the data can also be saved on a cloud server.

The memory for logging alerts and alarms is organized in a similar, circular way. All software modules can generate events, warnings, and alarms at three priority levels:

- "Minor" – lower,
- "Major" – higher,
- "Critical" – the highest.

Remote upgradeability is also one of the strongest features of DEQ. Therefore, we can remotely update the firmware on each DEQ. This is a critical process, because if anything goes wrong, the device could become dysfunctional and require manual intervention. To prevent this, an extended level of safety was implemented for this particular case. Two instances of firmware are constantly saved in external Flash memory: "main" and "backup" FW. If anything goes wrong with the main FW (including corruption), then the backup FW is activated; it connects to the cloud server and enables fixing problems remotely (even repeat remote upgrade process). Main FW damage could theoretically happen in the remote upgrade process although current practice demonstrates the extraordinary reliability of this procedure.

3 SYNERGETIC POTENTIAL OF SMART GRID AND DIALOG EQ IN BUILDINGS

Among the most important aspects of buildings, we must highlight at least two: first, they are the major energy consumers; second, we spend the majority of our everyday life in them (as residential or professional environments). In accordance with the principles of sustainable development, the former energy consumption aspect deserves special attention: it represents one of the most significant impacts of human activity on the environment at present and especially in the future. In addition to the research and development of renewable energy sources, there is also much space for improvement in the optimization of energy consumption in buildings. Of course, we must take into account the fact that we live in buildings, and therefore it is necessary to ensure optimal living conditions. Aspects of energy consumption and user comfort are to some degree in conflict, but both must be considered major factors in the optimization process of building management.

3. 1 Model-based effective management of smart buildings

The common approach to the optimal management of buildings takes into account the two above-mentioned main factors: energy consumption and user comfort. Typically, the major component of the system is a ThermoDynamic Model (TDM) that simulates the operation of the building. The model's main purpose is to predict the building's state or response to various external and internal factors or events. On this predictive basis, more optimal process settings for the acceptable outcome of the regulation process in the building can be found. Examples of the most significant external factors are outside temperature, insulation, the wind, dynamic energy prices, renewable energy sources, etc. There are also many internal factors that are sometimes even more difficult to predict in advance; typical examples include users' presence, needs, and habits, the number of inhabitants, internal heating or cooling resources, etc.

As already explained, for effective building management, we need a model that predicts the impact of all (internal and external) factors on the "internal state" of the building. On this basis, we are able to determine the optimal control or regulation procedure that will satisfy the constraints of user comfort, minimize the energy consumption and the impact on the environment. This approach is quite common today and is denoted as "Model-based Predictive Control" (MPC) of buildings. Since this approach is quite generic, it exists in many different variants, but a common feature to all is to sense the available information from the environment and use predictive model-based regulation procedures (on local or remote computing resources) for optimal control of the smart building *[1, 2]*.

The basic process model

In order to create a good basic model, we usually need domain-specific knowledge about the process or problem. In our case, we also need a more generic model that will be able to adapt to the actual data of a particular building. Doing this, we can utilize only knowledge or actual data aspects individually, or both together. According to this decision, we distinguish three main groups of such models, which are commonly used in the management of buildings:

- Mathematical and physical models ("White Box")

The building's behaviour is modelled using expressions and equations that express the relation and the impact of input data on the output of the model. This approach requires the greatest level of domain-specific knowledge and often results in a quite complex model that is difficult for non-professionals to understand.

- Empirical models ("Black Box")

In this approach, we do not have any predetermined structure or expressions; the model is freely determined according to the existing data. Domain expertise is not required, but it is often difficult to understand or explain the models' predictions. Normally, we do not mind as we can effectively use these models even without an explanation feature.

- Hybrid models ("Grey Box")

This type of model is a combination of "White Box" and "Black Box" models. Here we need less domain-specific knowledge and more extensively empirical data in comparison to "White Box" models. Predetermined, but unknown parameters in expressions are adjusted accordingly to real data from the operation of a specific building. This approach produces simpler models (expressions) that are typically more understandable.

The reader can find more details and comparisons between different groups of models in *[2, 3]*.

Using the basic process model in smart buildings

Thus far, we have mentioned only a few basic aspects of using predictive models for effective building management, especially in terms of energy consumption and user comfort. However, these models contain a more generic potential for further development. Among the most significant potentials, we highlight the following inherent features of predictive models that already are or could be exploited in the near future:

- Modelling the operations of elementary processes and devices

We can form specific predictive models for each elementary process or device in the system. Therefore, we can predict the behaviour of smaller scale devices and make deductions for a whole building's behaviour.

- Detection of irregularities in the operation of elementary processes and devices

Based on the discrepancy between the output of the predictive model and the actual data, we could identify the irregularities or inefficiencies in the operation of devices or elementary processes. This feature could vastly improve the self-diagnostic capabilities of such systems.

- Self-learning and model adjustments during operation

One of the essential features of the self-learning type of predictive models is the ability to adapt to the real situation and data and gain domain-specific knowledge during operation processes. In most cases, there is a huge gap between learning and working environments; therefore, laboratory-based models need to adapt to real operation data continuously. If this is not done, the whole concept can become quite useless in practice.

- Distributed building management optimization based on predictive models

In control theory, we always strive to adjust our actions to the expected outcome, which comes only after some time. Therefore, in this case, the availability of the environment data and accurate prediction is of extreme importance. Both give us the opportunity to perform optimal regulation algorithms regardless of the location of computing resources: local, remote or both (distributed paradigm).

3. 2 The role of smart grids in building management

Efficient building management processes rely on the predictive model(s) and optimal control procedure or (better said) algorithm. To perform both optimally, we also need a large amount of accurate empirical data from actual building operation and both types of influence factors (internal and external). Nonetheless, we need to process data to gain information that is used for adaptation of the models and determination of optimal control procedures. All this usually requires the establishment of sensor networks and the availability of computing resources for the necessary analysis and calculations.

For the optimal performance of the model, we need to obtain accurate data from the environment. In most cases, their resources at a lower level are regulators and controllers of individual processes by themselves. For them, it is vital to provide two-way communication with higher levels of the system management structure. Smart grids offer the arbitrary allocation of computing resources; models and control procedures can be implemented at a local or distant location. In the latter case, the key element is the existence of a connection. This way the buildings can be easily integrated into the broader context of smart grids or smart cities, *[4]*.

DIALOG EQ as a smart grid gateway in the smart building

DEQ is a modern microcontroller-based system that allows the implementation of all the described optimal strategies for the effective management of buildings. It transmits operational data (only with the user's consent) to the cloud service. Currently, data is stored in the cloud database. In the next development cycle, we also plan to process data locally to a certain extent, particularly focusing on the creation of corresponding predictive models and optimal control algorithms for individual buildings.

3. 3 An example of the predictive model for sanitary water heating process

To illustrate our development strategy for the future, we present selected example from preliminary research on the mixed "black and gray" type of predictive model in the form of an Evolving Fuzzy Neural Network (EFuNN) shown in Figure 4. This type of network merges concepts of neural networks and fuzzy logic, *[5]*. More details about preliminary research can be found in *[6]*. Here we will present only a brief summary of the results and a short discussion.

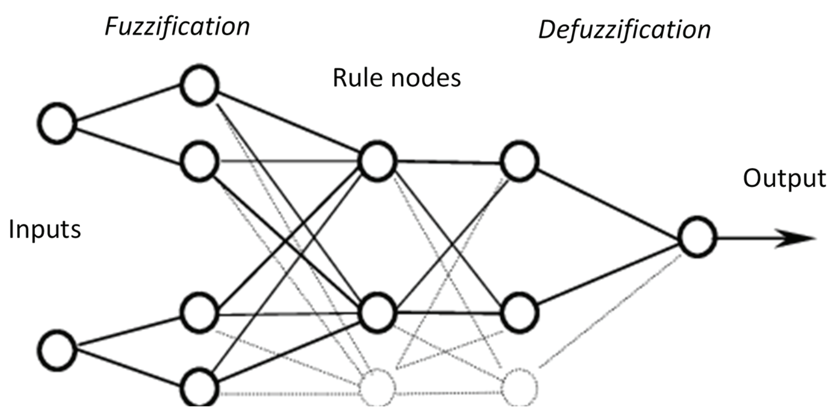

Figure 4. *Architecture of Evolving Fuzzy Neural Network (EFuNN)*

In this selected case, we have modeled the operation of a sanitary water heater (boiler). Cooling of the water is influenced by its surroundings (parameter "ambient temperature") and consumption (parameter "hot water consumption") through showers and taps. This parameter was artificially estimated from the derivative of current sanitary water temperature. Its value can only be 1 (on) or 0 (off). Water temperature is increased by the heating process (parameter "water heating"). All these parameters represent the input data to the model (all values except the last, are at time instance t):

- ambient temperature (in degrees Celsius),
- water heating (1-heating, 0-inactive),
- hot water consumption (1-consumption, 0-inactive),
- current hot water temperature (in degrees Celsius),
- "previous" hot water temperature at time t-1 (in degrees Celsius).

The output of the model predicts the temperature of the water in the boiler at the next time instance t+1. We have tested the performance of the model on two separate datasets. The first dataset covers the period from 20th to 24th of May (spring season), and the second from 9th to 14th of June (early summer season). The first dataset was used as a training set and the second dataset as a test set. The network was initially used in its on-line self-learning mode when processing the first (training) dataset. In this self-learning mode, the network first predicts the value of the output parameter (water temperature at the time instance of t+1) and then learns (adapts) from the actual measured value of the same parameter at the time instance of t+1. The network, therefore, learns and improves with each new vector of input and output parameters. After processing the training set, the network was used to process the test set with slightly different season conditions in the same on-line self-learning mode.

For assessment of model predictions, Root Mean Square Error (RMSE) metrics between predicted and measured values was used. Figures 5 and 6 show RMSE on the discrete time axis for the training and test sets. The time instances on the time axis (t) are uniformly distributed with a spacing of 100 seconds and numbered sequentially (t and t+1 are 100 seconds apart in time). It can be seen that the EFuNN model learns during operation. In both figures, the prediction error is bigger at early time instances and then degrades with time. The graph in Figure 5 shows that after a relatively short time (approximately when t>400), we can obtain quite accurate predictions of water temperature during processing the training dataset. However, if we also check the model's performance on the test set (Figure 6), it is shown that the prediction becomes more accurate even faster. This is surely caused by accumulated knowledge from the training set. We can conclude from both figures that using this acceptably accurate predictive model; we could determine a more optimal control procedure for heating sanitary water that will simultaneously consider user's hot sanitary water needs and energy consumption.

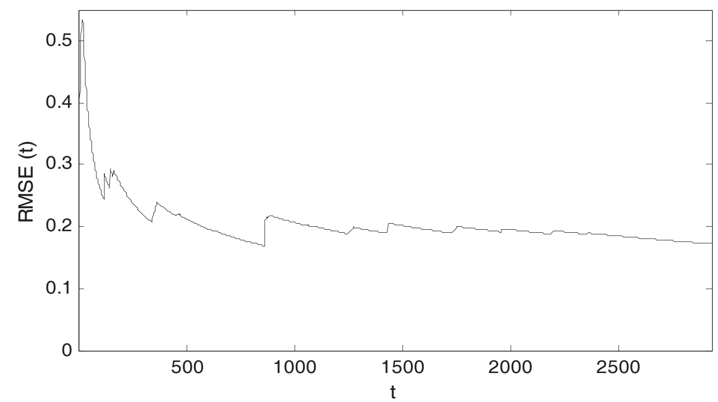

Figure 5. *Root Mean Square Error (RMSE) of EFuNN model prediction on the training set*

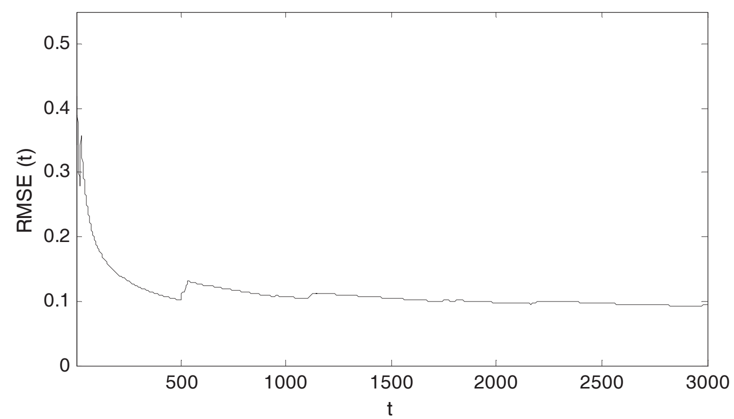

Figure 6. *Root Mean Square Error (RMSE) of EFuNN model prediction on the test set*

4 CONCLUSION

The described smart grid building controller DIALOG EQ is a result of our initial development cycle. In this paper, we have presented the present features of DIALOG EQ and its major development potentials for the future: first in more general and then also in more concrete terms that will influence its further development. Above all, DIALOG EQ is a reliable smart building controller, which is also capable of connectivity to cloud services and acts like an IoT and smart grid gateway. On this basis, it also holds potential for further development and integration of smart buildings, IoT, and smart grids into a common smart network system of the future. During this process, we will continue focusing on synergetic connection points between present and upcoming concepts in this field.

On the applicative side of the development, we will focus primarily on enhancing our cloud and customer service, in the sense of better visualization of the operation, easier control of user parameters, the addition of efficiency analysis, the creation of a thermodynamic model of individual buildings, etc.

The research focus will remain on the efficient creation of thermodynamic models for individual buildings and optimization of the control procedure for each building individually. Furthermore, we will attempt to enhance the efficiency of automatic learning from data, self-detection of malfunctions and inefficiencies of the system and many other aspects of efficient smart building management.

References

[1] **R. Kwadzogah, M. Zhou and S. Li:** *Model predictive control for HVAC systems — A review,* 2013 IEEE International Conference on Automation Science and Engineering (CASE), Madison, WI, pp. 442-447, 2013

[2] **S. Ghosh, S. Reece, A. Rogers, S. Roberts, A. Malibari, and N. R. Jennings:** *Modeling the Thermal Dynamics of Buildings: A Latent-Force- Model-Based Approach*, ACM Trans. Intell. Syst. Technol. *6, 1, Article 7, March 2015*

[3] **Z. Yu, L. Jia, M. C. Murphy-Hoye, A. Pratt and L. Tong**: *Modeling and Stochastic Control for Home Energy Management*, IEEE Transactions on Smart Grid, vol. 4, no. 4, pp. 2244-2255, Dec. 2013

[4] **R. Rozman:** *Pametna zgradba: osnovni gradnik pametnega mesta*, Osemindvajseta delavnica o telekomunikacijah, Pametna mesta: zbornik referatov, Elektrotehniška zveza Slovenije, 2012

[5] **N. Kasabov:** *Evolving Connectionist Systems for On-line, Knowledge-based Learning: Principles and Applications*, Technical Report TR99/02, Department of Information Science, University of Otago, 1999

[6] **R. Rozman, A. Štrancar, D. Šonc:** *On the use of evolving fuzzy neural networks in intelligent environments,* ZAJC, Baldomir (ed.), TROST, Andrej (ed.). Proceedings of the twenty-fourth International Electrotechnical and Computer Science Conference – ERK 2009

Nomenclature

t	time
MPC	Model Predictive Control
TDM	ThermoDynamic Model
RMSE	Root Mean Square Error
EFuNN	Evolving Fuzzy Neural Network

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UNDERGROUND COAL GASIFICATION – POSSIBILITIES IN SLOVENIA

PODZEMNO UPLINJANJE PREMOGA – MOŽNOSTI V SLOVENIJI

Milan MedvedR, Damjan Konovšek[1]

Keywords: coal, underground coal gasification, recommendations, and findings

Abstract

Slovenia still has significant amounts of unexploited coal; consequently, this article explores the additional option of using this domestic primary energy source, using the underground coal gasification (UCG) methodology.

We described the general recommendations and findings from the UCG tests conducted throughout the world, relating to the testing performed in Velenje. Based on the recommendations and findings of the UCG tests, the descriptions of different technologies and the characteristics of the Velenje coal deposit, we established the most appropriate technology for the gasification of Velenje coal, which is the UCG technology using the ELW method in combination with the modified CRIP method for ignition and underground gasification.

The test geometry and the operating parameters for UCG Velenje have been assessed on the basis of the modular gasification scheme of the company Carbon Energy Pty Ltd (CEPL), which was produced in the scope of the testing conducted in Bloodwood Creek, Australia.

Povzetek

Slovenija ima še veliko zalog neizkoriščenega premoga, zato smo v tem članku raziskovali dodatno možnost izrabe domačega primarnega energetskega vira s podzemnim uplinjanjem premoga (PUP).

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Opisali smo splošna priporočila in ugotovitve iz testov PUP po svetu, ki se navezujejo na izvedbo poskusa v Velenju. Glede na priporočila in ugotovitve iz testov PUP, opise različnih tehnologij PUP in lastnosti ležišča velenjskega premoga, smo podali najustreznejšo tehnologijo podzemnega uplinjanja premoga v Velenju, ki je PUP tehnologija metoda vzporednih vrtin ELW v kombinaciji z modificirano CRIP metodo za vžig in podzemno uplinjanje.

Geometrija poskusa in obratovalni parametri za PUP Velenje so ocenjeni na podlagi modularne uplinjevalne sheme podjetja Carbon Energy Pty Ltd (CEPL), ki je bila narejena v okviru testa v Bloodwood Creeku, Avstralija.

1 INTRODUCTION

Coal will remain a leading energy source in the coming decades, and it is expected that the development of clean technologies allowing for and preserving its competitiveness compared to other energy sources will be accelerated. The recent period has witnessed a spread of so-called clean coal technologies (CCT), which includes underground coal gasification (UCG), a combination of the technologies of excavation and transformation of coal into useful energy. The seam of lignite in the Šaleška Valley is one of the thickest in the world, which gave rise to the development of innovative quarrying methods and other technologies, such as UCG, which is gaining popularity throughout the world. In spite of the lack of tests with lignite, attempts have been made to introduce it in Slovenia ell. The Velenje Coal Mine is one of the few in the world to research the UCG methodology for the application of the test on lignite. The method is particularly interesting for those coal deposits in which conventional excavation methods cannot be used, for various reasons.

In fact, the Velenje Coal Mine launched CCT activities in 2009 when a special task group within the R&D department was established. At the end of the same year, the CCS (Carbon Capture and Storage) activities started. The method was introduced by the Georis Research Organization. A project called "Pilot Methodology Fixation of CO_2 using the Fly Ash" applied for Slovene Government and EU funds in 2010and was started in February 2011.

The aim of this paper is to research the UCG method, adjust it, and patent it for the exploitation of thick lignite and coal seams, similarly to the globally known Velenje excavation method, which is known to be the most productive long-wall excavation method in the process of underground coal mining in thick seams.

Many countries still have deposits of low calorific value coal that have thus far not been exploited for various reasons, one of the most important of which is the cost of lignite transportation over long distances, as well as dust and gas emissions in direct use of coal or combustion in thermal power plants. Because of high transportation costs and low calorific value, a practice was established to use the lignite in thermal power plants for production of electricity and heat, which were constructed in the vicinity of the source or deposit. The research was therefore focused on clean technologies for the commercial production of various lignite and coal products, similar to the lignite in the Velenje basin. Not many UCG tests have been performed on lignite and hard coal (most of them were made on soft coal). The reason for this lies in the questionable economic viability of lignite exploitation, while hard coal is not usually exploited for UCG purposes.

UCG technology enables the use of coal energy in an economically viable and environmentally-friendly manner. The UCG process further opens the possibility of exploiting natural coal with minimized environmental impact, because the emissions of gases and solid remains after the combustion of the coal have been significantly reduced compared to the conventional coal-based thermal power plants. UCG technology is a process in which coal is gasified underground, producing various gases that are purified on the surface and used in the gas-steam assembly, where it is converted into useful electricity and heat.

The primary purpose of the underground gasification of coal was to alleviate some of the heavy workload from the miners working underground. This was followed by the oil crisis, while at present, we are facing the period of economic growth and problems related to the provision of energy sources. Another reason is the current energy, financial, and environmental crises, considering that there are sufficient coal deposits all over the world that could be exploited using the UCG method, which would guarantee a reliable supply of energy products in the future. Therefore, the number of underground coal gasification R&D programmes and the number of underground coal gasification tests are constantly growing. Also expanding are the various possibilities of the application of UCG for different purposes, all in favour of the development of this technology. It is essential to maximize the use of experience and know-how obtained from the tests carried out in the past, which would also provide efficient commercial UCG technology. The UCG project in the Velenje Coal Mine, which took place from 2011 to 2015, shows an additional possibility of using the Velenje lignite for supplying electricity and heat to the Šaleška Valley and Slovenia, as an alternative to the Šoštanj Thermal Power Plant.

The previous reports provided a preliminary assessment of UCG based on the results of the pilot testing carried out in the scope of the Rocky Mountain 1 test in the USA, where coal was gasified using the Controlled Retraction Injection Point method. The recent literature provides no data on the actual method of implementing the UCG method for commercial purposes. Of all the companies exploring the possibilities of introducing the UCG method for commercial purposes, only the company Carbon Energy from Australia presented a plan on how to move from pilot testing to commercial procedures and what amount of coal deposit would be gasified.

The scheme of the test conducted in Bloodwood Creek, Australia, by Carbon Energy, which is the best source of data, could be used as the basis for conducting a pilot test in Velenje. The presented method of exploiting the coal deposit is the only source from which it is possible to obtain the estimate of gas flows. Reference [1] provides the foreseen operational period of the assembly and the geometry of the anticipated coal deposit where the gasification is planned to be carried out. Based on this, the necessary flows of reagents and the amount of products or obtained syngas can be assessed. In other deposits with different dimensions or cross-sections, different feeding flows will have to be taken into account, proportionally to the cut-off ratios. These ratios will have to be taken into account in the future estimates of underground coal gasification. To ensure the full use of the oxygen for the even combustion of coal in the entire cross-section, certain operational (optimal, if possible) conditions must be met, which can only be determined on the basis of pilot testing. Additionally, the combustion and the initial gasification phase also require a special operational regime, which is not mentioned in the available literature.

The basic unit for determining the energy facility, related to the underground coal gasification, is one combustion cavity. Several combustion cavities represent one set, and several sets are linked into a module. The economic viability analysis is based on the module and volume of coal in it, which can be gasified (length × width × height (thickness)). Carbon Energy, which has been conducting the UCG tests using the CRIP method, proposed a module with the dimensions of length 600 m, width 180 m, and thickness 8 m with four injection, three production, and six combustion wells. The geometry of the gasification module enables good control of the size and height of gasifying coal seams thicker than 3 m, *[5].* If the seam is limited with the overburden and the footwall, the thickness of gasification is determined. Such a model, or several modules, would be used in the UCG testing in Velenje, which would be carried out in cooperation with one of the Australian companies, e.g. Carbon Energy, Linc Energy or another. These companies have already carried out the first UCG tests for commercial purposes or demonstrated the UCG technology in several-month test gasification processes. The gas that is created is used for energy purposes or for obtaining synthetic diesel fuel.

The minimum size of the facility will be determined on an economic basis, considering the investment and operational costs, with simultaneous production of modules. Based on the available coal deposits, depreciation and lifespan of the facility, and the foreseen energy prices, optimal production, and profitability of UCG will be determined.

The positions for determining the value of investment in the thermal power plant that would be using syngas, a product of UCG, for its operation, have also been taken into account. A syngas-powered thermal power plant is an additional opportunity for the Slovene energy segment, further development of the Šaleška region in terms of a reliable and environmentally acceptable energy producer, and for research and development activity.

2 FINDINGS AND RECOMMENDATIONS

The factors having a substantial impact on the implementation of UCG are:

- The geological features of the coal deposit site:
  - thickness, depth and inclination,
  - gas and fluid permeability.
- Coal characteristics:
  - type of coal (the content of humidity, ash, volatile substances, carbon, etc.),
  - chemical structure (hydrogen, sulphur).
- Overburden properties:
  - geology,
  - hydrology,
  - geo-mechanical properties,
  - drilling possibility.

- Operational conditions:
  - composition and speed of injected gas,
  - operating pressure,
  - drilling.
- Resulting (production) gas:
  - desired volume,
  - composition, calorific value,
  - flow speed.
- Process efficiency:
  - thermal,
  - chemical,
  - source.
- Environmental interaction
  - thermal,
  - chemical,
  - use of source and the related settlement of the surface, *[6].*

The principal differences between underground and surface gasification simultaneously represent the strengths and weaknesses of either process:

- on the surface, reactions take place in a closed reactor, where temperature and pressure can be measured and controlled, as well as the feeding of coal and oxidants into the reactor. This allows for the precise and controlled structure and quality of products,
- underground, the form and location of the reaction zone are constantly changing, and it is not possible to measure and control the operational conditions in the same manner as on the surface. During the UCG process, the coal burns, cavities are created and thermal deformations also in the surrounding vitrified clays. The reaction zone can shift into different parts of the coal deposit, and the movement cannot be foreseen or controlled. Part of the gas products can escape from the reactor zone into the environment; in contrast, the water flows into the reaction cavity from the surrounding areas cannot be fully controlled because the properties of the seam keep changing. Water inflow can be best controlled with the control of the operating pressure, *[6].*

The other advantages of the UCG over the conventional mining and further use in thermal power plants are:

- The economic advantages:
  - The cost of the UCG process is low, because there are no costs of coal excavation, transportation, and ash deposit,
  - CAPEX is also reduced, since there is no need to purchase and install the reactor/boiler on the surface,

- Greater flexibility of the syngas use: production of electricity, chemicals, fuels, also hydrogen H_2.
- Environmental advantages:
  - Most of the ashes remain underground, significantly reduced emissions of H_g and other heavy metals, SO_x and NO_x, which reduces the amount of gas purification,
  - Reduced CO_2 emissions.
- Treatment of CO_2:
  - Reduced CO_2 separation costs,
  - Possible storage of CO_2 in the cavities and the surrounding vitrified clays, *[7]*, *[8]*, *[9]*

Obstacles to the commercial development of the UCG:

- Operational risks due to untested large-scale UCG processes and many problems that arose during the tests conducted in the USA and Western Europe.
- Unreliability of the process from the point of view of environmental impact,
- Public acceptability,
- Lack of precise criteria or recommendations for the selection and characterization of the site/deposit to be gasified,
- Not enough experts with multidisciplinary know-how, *[10].*

All UCG tests have been conducted at different operating conditions, using various types of coal, at various depths and different seam thicknesses, and over different time periods. Due to such a diversity of conditions in which the UCG tests have been carried out, the results are too dispersed to allow for reliable conclusions. Nevertheless, it can be claimed that all types of coal can be gasified, using specific UCG methods determined on the basis of the specific conditions. This article lists brief general recommendations and findings from the UCG tests conducted all over the world, relating to the testing performed in Velenje.

The recommendations for the selection of a suitable site for the UCG, issued by the providers of tests or their national authorities, differ and are very general, depending on the country or its legislation, as well as the geological and hydrogeological conditions of the coal deposit.

Based on the experience from the conducted tests, published literature and some UCG demonstrations, certain recommendations can be drawn to be used as guidelines by potential investors, contractors, legislative bodies and others in devising and implementing the UCG tests. Such experience was used to compile data on how the differences in the geology, hydrogeology, coal composition, surrounding vitrified clays and underground waters, as well as the implementation of the gasification process, transportation of impurities and economic viability of the process impact the environment and population health.

The tests have been carried out over extended periods, using different coals at different depths, i.e. in different conditions, which means that it would be very dangerous to generalize the

results, which must instead be considered to be specific for a certain site or test. Over time, some techniques such as seismic research, drilling into coal seams, use of computers for data analysis and some other techniques have changed considerably and affected the interpretation of results.

Nevertheless, some general principles theses, and findings can be deducted from test results:

- The geological characterization of the potential site is crucial for the successful technical implementation of the test and its minimum environmental impact.
- The losses of gas in the tests conducted in shallow coal deposits are in general much bigger than in the case of deeper deposits.
- The same applies to the pollution of water, which is also more likely in deposits closer to the surface, where most of the aquifers are located.
- Lower-type coals (lignite, sub-bituminous coal) are less permeable and more reactive than higher-type coals (anthracites), which is a welcome feature in the establishment of links between the wells.
- Lower-type coals are softer, which can affect the stability of wells in the coal seam.
- The depth of the coal deposit is a key parameter affecting the operating pressure in the reaction cavity, particularly when the entire process must be conducted in such a manner that the pressure in the cavity is slightly below the hydrostatic pressure and that the water flows into the cavity during the process, and not vice versa, i.e. from the cavity to the surrounding aquifers.
- The calorific value of the syngas can be maximized by blowing oxygen-enriched air into the reaction cavity.
- The cavity “closure” procedure has also been introduced. This means that the reaction cavity is cleaned, i.e. rinsed with water after the test to avoid the potential leakage of certain contaminants.
- Preliminary simulations can help in the planning of the required devices on the surface and in preparing the environmental impact assessment, *[6].*

What all recommendations have in common is the fact that the size of the source or coal deposit should be suitable for long-term exploitation, which guarantees the better economic viability of the process. The geological conditions must be suitable for constant coal gasification, and the environmental impacts must be minimized to an acceptable level.

The UCG process requires a multidisciplinary approach to the production of syngas, comprising a broad range of different aspects. Additionally, there were certain limitations in all tests. The tests conducted were mostly small-scale, and none of them provided a commercially accessible technology that would be able to meet all the environmental requirements, *[10].*

In spite of the fact that many findings have been made in all tests and that several technologies have been developed, with recommendations and monitoring techniques, the UCG methodology is still not commercially recognized or accessible. It is expected that a commercially accessible UCG technology would be developed in the next few years when the currently ongoing and scheduled tests all over the world are completed.

Further studies will have to analyse the set goals and results of the UCG research carried out in Slovenia. Based on the comparison of the recent findings in the area of UCG, research activities will have to be defined that had been essential for devising the UCG technology and those that gave no valuable contribution to the development of the technology but were nevertheless conducted for other purposes. Research activities that might have been overlooked but are now crucial for the introduction of new technology into an environment will have to be proposed.

Based on the findings of the analysis of previous work performed in the UCG area in Slovenia, future research will have to indicate the key findings and propose the activities that should be carried out in the scope of research needed for the implementation of the first UCG test in Slovenia. The global UCG Association, *[11]*, has been informed of the work in UCG, as shown in Figure 1.

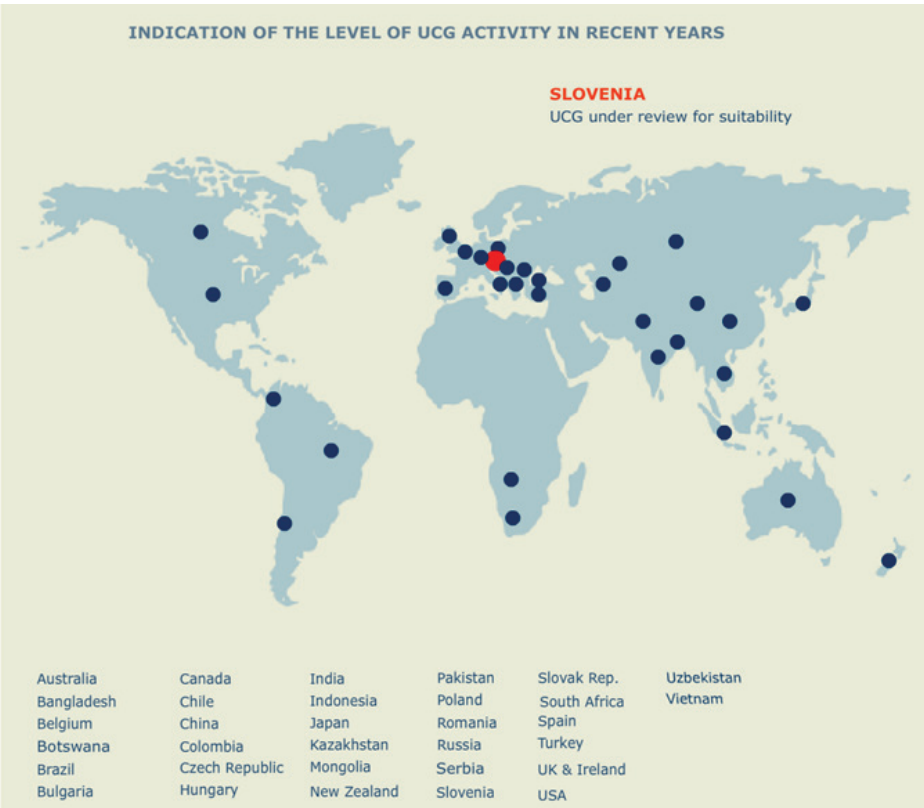

Figure 1: *Development projects and UCG tests, [11]*

Potential contractors for the UCG project are:

- CRIP: Carbon Energy (CEPL) in Australia, Gazprom Promgaz in Russia, Xinao in China, several companies - the USA,
- VLW: Sasol in South Africa,
- εUCG: Ergo Exergy Technologies Ltd. in Canada, Laurus Energy in Canada, Linc Energy Ltd. in Australia, Cougar Energy in Australia, Solid Energy New Zealand (SENZ) in New Zealand, Eskom in South Africa,
- general or UCG combinations: UCGEL (UCG Engineering Ltd.) in Great Britain, British Coal Gasification (BCG) Energy Ltd in Great Britain, Seamwell International in Great Britain, Alberta Ingenuity Centre for In Situ Energy in Canada, Glowny Instytut Gornictswa in Poland.

These contractors have rich experience in UCG, including at the level of pilot and semi-commercial tests. Based on such experience, some are already able to manage the UCG process and further technologies to exploit the produced gas.

Since the other gasification technologies or UCG methods are not known in detail, contact will have to be established with the providers of other technologies, such as Ergo Exergy Ltd. or Linc Energy Ltd. and partners in the projects HUGE1 and HUGE2.

If the UCG test were carried out in Velenje, domestic Slovene contractors could participate in all phases of the project. In particular, domestic know-how can be used in the construction of wells, preparation of all necessary infrastructure facilities on the surface, monitoring of production gas and monitoring of the quality of the underground water. The representatives of domestic institutions could gain new knowledge/findings about the UCG technology from potential foreign UCG contractors.

3 CONCLUSION

Each type of energy produced (coal, nuclear, hydro, gas and nonetheless the energy from renewable energy sources) impacts the environment, but people can no longer live without it. The energy sector merely meets the energy needs; it does not generate the consumption. Fossil fuels will continue to be the principal energy source at least until the mid-twenty-first century, according to all forecasts and the indicators of all international professional institutions. Slovenia has a limited amount of renewable energy sources (RES), as established in many studies based on which the goal of 25% energy production based on RES by 2020 was set. It is not possible to achieve a higher percentage, either technologically or economically. Nevertheless, we are aware that we have to strive for investment in the development of RES, which will take decades; in the meantime, we will have to make do with conventional sources, including coal. Among the fossil fuels, coal is the only source that will be available for the longest period on the energy market, mainly due to the enormous volume of deposits.

The strategic objectives of Velenje Coal Mine, a company with highly developed technology, comprise the modernization of coal production which could contribute to better working conditions and higher economic and ecological acceptability, also due to the adaptation to the environmental requirements that Slovenia has to meet in the framework of the European Union, which call for new and comprehensive strategic consideration in the area of energy - from the point of view of production and consumption. Velenje Coal Mine integrated the aspect of sustainable operation in its strategy, which it implements consistently. In spite of the fact that Velenje Coal Mine is an energy company, it is also very successful in the area of energy use efficiency, which also reduces coal costs and consequently contribute to lower prices of electricity and heat produced in the Šoštanj Thermal Power Plant.

According to the long-term plan of lignite extraction in the Velenje Coal Mine, i.e. until 2054, which currently provides one third of electricity produced in Slovenia, the Velenje Coal Mine decided to follow the global trends and set up a project team in charge of clean coal technology development issues. This project comprises the following sets: lignite degasification, capture, transportation and storage of CO_2 and underground lignite gasification. In the 2011-2015 period, the implementation of the CCT project was (among others) financed from the planned costs and assets for the project Razvojni center Energija d.o.o., for which the Velenje Coal Mine was a co-founder and co-owner. Even though it is difficult to predict what will happen in 40 years, the development and the application of the so-called BAT technologies presents the possibilities that these activities would be carried out in any case also when the coal deposits are depleted. The bases are presented for the implementation of the pilot testing of the underground coal gasification project in the coal seam of the Velenje basin, which is an opportunity to exploit the deposits of soft coal in north-east Slovenia.

UCG is gaining ground throughout the world as a leading branch in the production of syngas, mainly thanks to its economic viability, exploitation of coal in the areas not suitable for conventional mining, and production of electricity and heat, as well as clean fuels. Some companies have already made the comparisons between the processes of gasification of different types of coal and the knowledge of the strategy of conducting individual processes, and thus obtained the key parameters for planning and commercializing the UCG process. The developments in the UCG area clearly indicate that the process has potential, because many countries have already decided to undertake preliminary research or studies about the UCG possibilities. UCG is considered to be a viable option for resolving the energy problem in the near future and is being mentioned in the national long-term development plans for the exploitation of natural resources.

However, we should be aware that UCG is, above all, a very risky development research project, including the pilot test and afterwards the pilot device, because the underground transformation of coal involves very high technological risk. It is practically impossible without the support of the state in the form of an appropriate national energy development plan.

Underground coal gasification is a suitable method for producing energy from coal deposits without excavation. Only a handful of UCG tests has been conducted on lignite and other types of coal, which is a huge opportunity for Slovenia, and other countries, from the energy, environmental and business point of view.

References

[1] **I. Veber:** *Študija izvedljivosti podzemnega uplinjanja premoga v Premogovniku Velenje: RRP-02/2002 FL. Geološki del*, Velenje : Premogovnik Velenje, 21 str., 29 prilog, 2002

[2] **M. Medved, D. Konovšek:** *Energetski viri – Course Notes*, The Faculty of Energy Technology, University of Maribor, 2015

[3] **S. Zavšek, J. Pezdič, L. Golob, M. Medved:** *CCS activities at the Coal Mine Velenje*. V: ICCS&T 2013, 2013 International Conference on Coal Science and Technology, State College, PA, USA. Proceedings. The Pennsylvania University, 2013

[4] **M. Medved, G Skubin, E. Dervarič:** *Introducing clean coal technologies for reduction of greenhouse gasses emissions = Uvajanje čistih premogovnih tehnologij za zmanjšanje emisij toplogrednih plinov*. RMZ - Materials and geoenvironment, ISSN 1408-7073, vol. 56, 2009

[5] http://www.carbonenergy.com.au/irm/content/default.aspx, 29.9.2012

[6] **A. Zapušek, G. Berčič:** *Možnosti podzemnega uplinjanja premoga: končno poročilo*: št. pogodbe 13/09: oznaka projekta 01_PVPOZPR_09. Ljubljana: Inštitut za raziskave v energetiki, ekologiji in tehnologiji (IREET), 2009

[7] **E. Bureton, J. Friedmann, R. Upadhye:** *Best Practices in Underground Coal Gasification*, 2006

[8] **B. H. Bowen:** A Review & Future of UCG, Underground Coal Gasification. Coal Briefing, Hammond, 2008

[9] **M. Green:** *Lessons from the European Trial of Deep UCG*. International Workshop on Underground Coal Gasification. DTI Conference Centre, London, 1–2. 10.2003, 2003

[10] **G. Couch**: *Underground coal gasification, Draft Report*, IEA Clean Coal Centre, 2009

[11] http://www.ucgassociation.org/, 20.9.2012, 2012

Nomenclature

(Symbols)	(Symbol meaning)
CCT	Clean Coal Technologies
CCS	Carbon Capture and Storage
CEPL	Carbon Energy Pty Ltd
CRIP	UCG method with Controlled Retraction Injection Point
ECC	Energy-chemical combine

ELW	Extended Linked Wells method
EUR	euros
HUGE	Hydrogen Oriented Underground Coal Gasification for Europe
UCG	Underground Coal Gasification
PV	Velenje Coal Mine
IMGE	Institute for Mining, Geotechnology and Environment
SG	syngas
TEŠ	TEŠ Power Plant
UCG	underground coal gasification
VLW	Vertically Linked Wells method
USA	United States of America
εUCG	Ergo Exergy's Underground Coal Gasification technology

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DIFFERENTIAL EQUATIONS, DIFFERENCE EQUATIONS AND FUZZY LOGIC IN CONTROL OF DYNAMIC SYSTEMS

DIFERENCIALNE ENAČBE, DIFERENČNE ENAČBE IN MEHKA LOGIKA V UPRAVLJANJU DINAMIČNIH SISTEMOV

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Keywords: dynamic system, differential equations, Laplace transform, difference equations, z-transform, fuzzy logic

Abstract

In this article, the use of certain mathematical tools to create a dynamic system control is described; such a control could be applied to a power supply system. In continuous dynamic systems, the control of the system is described by one or more differential equations; however, in discrete dynamic systems, this control is described by one or more difference equations. Both differential and difference equations are highly effective tools in conventional mathematical analysis. In the previous twenty years, algorithmic principles of fuzzy logic in the control of the dynamic systems have been very useful. In this article, the applications of all three approaches are presented. In the case of the fuzzy logic approach, there is an example of the energy efficiency in the employment of biomass with an emphasis on developing the environmental sustainable biomass index.

Povzetek

V članku so predstavljene matematične metode pri kreiranju upravljanja sinamičnega sistema, ki je lahko tudi energetski sistem. V primeru dinamičnih sistemov je upravljanje opisano z eno ali več diferencialnimi enačbami, v primeru diskretnih sistemov pa je njihovo upravljanje opisano z eno ali več diferenčnimi enačbami.

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Oboje, diferencialne in diferenčne enačbe, so izjemno uporabno orodje v klasični matematični analizi. V zadnjih dvajsetih letih pa se je kot zelo uporabna algoritmična osnova upravljanja dinamičnih sistemov uveljavila uporaba principov mehke logike. Kot hibridni pristop upravljanju dinamičnih sistemov se v zadnjih letih uveljavlja tudi možnost sinteze diferencialnih/diferenčnih enačb ter mehke logike. V članku prikazujemo možnosti uporabe vseh treh pristopov. Za uporabo mehke logike in mehkega sklepanja je podan numerični primer za energetsko izrabo biomase s poudarkom na trajnostnem indeksom varovanja okolja.

1 INTRODUCTION

To solve some technical problems, all the fields of classical mathematics can be used: sets, matrix and vectorial algebra, sequences, series, functions with one and more variables, differential calculus, indefinite integral, definite integral, double, triple and more integrals, line and surface integrals, differential equations, Laplace transform, vector analysis, probability calculus, discrete analysis, difference equations, z-transform and so on, *[1]*. In the last fifty years, the technical solutions using fuzzy logic have been very successful *[2].*

In recent years, as a hybrid approach in the control of the dynamic systems, the option of synthesis of differential/difference equations and fuzzy logic have been made, specifically with regards to fuzzy differential equations *[3]*, *[4]*, *[5]* and fuzzy difference equations *[6]*, but they still do not have significant applications, and therefore are not considered here.

In this article, the control of the dynamic system by application of differential equations is shown in the first chapter, the application of the difference equation in the second chapter and one application of fuzzy reasoning in the third chapter.

Every model of optimal control is determined by a system, input variables, and the optimality criterion function. The system is represented as a regulation circle, which generally consists of a regulator, a control process, a feedback loop, and input and output information. In this article, only linear dynamic stationary systems will be discussed, *[7], [8], [9].*

Let us consider a production model in a linear stationary dynamic system in which the input variables indicate the demand for products manufactured by a company. These variables can be a one-dimensional or multi-dimensional vector function.

Let us take a stationary random process X with the known mathematical expectation E(X) and autocorrelation $R_{XX}(t)$ as the demand in a stochastic situation that should be met, if possible, by current production. The difference between the current production and demand is the input function for the control process, the output function of which is the current stock/additional capacities. When the difference is positive, the surplus will be stocked, and when it is negative, the demand will also be covered from stock. Of course, in the case of power supply, we do not have stock in the usual sense (such as with cars or computers, etc.); energy cannot be produced in advance for a known customer nor can stock be built up for unknown customers. The demand for energy services is neither uniform in time nor known in advance. It varies, has its ups (peaks) and downs (minima), and it can only be met by installing and activating additional proper technological capacities. Because of this, the function of maintaining stock in the energy supply process belongs to all the additional technological potential/capacities, large enough to meet periods of extra demand. The demand for energy services is not given and precisely known in advance. With market research, we can only learn about the probability of our specific expectations of the intensity of demand. The demand is not given with explicitly expressed mathematical function; we only know the shape and type of the family of functions. Accordingly, demand is a random process for which all the statistical indicators are known.

The output function measures the amount of unsatisfied customers or unsatisfied demand in general. When this difference is positive, i.e. when the power supply capacity exceeds the demand, a surplus of energy will be produced. When the difference is negative, i.e. when the demand surpasses the capacities, extra capacities will have to be added or, if they are not sufficient, extra purchasing from outside will have to be done. Otherwise, there will be delays, queues, etc. In the new cycle, there will be a system regulator, which will contain all the necessary data about the true state and which will, according to the given demand, provide basic information for the production process. In this way, the regulation circuit is closed (Fig. 1). With optimal control, we will understand the situation in which all customers are satisfied with the minimum involvement of additional facilities. On the basis of the described regulation circuit, we can establish a mathematical model of power supply control.

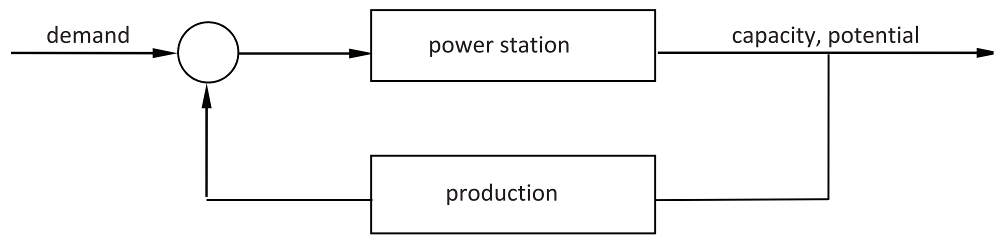

Figure 1: *Regulation circuit of the power supply system*

The task is to determine the optimum production and stock/capacities so that the total cost will be as low as possible.

2 CONTINUOUS SYSTEM, DIFFERENTIAL EQUATIONS

A differential equation is a mathematical equation that relates a function with its derivatives. In applications the functions usually represent physical quantities, and the derivatives represent their rates of change. Differential equations play a critical role in many disciplines including engineering, physics, economics and so on. All of these disciplines are concerned with the properties of differential equations of various types. Differential equations play an important role in modelling technical process, i.e. in dynamic systems.

When the inputs and output of the regulation circuit of the power supply system are continuous, a continuous system given by one or more differential equations is obtained.

Notations for $t \geq 0$ are as follows:

$Z(t)$ - additional capacities (stocks) at a given time *t*,

$u(t)$ - production at time *t*,

$d(t)$ - demand for product at time *t*,

λ - lead time

Let $Z(t)$, $u(t)$ and $d(t)$ be stationary continuous stationary random variables/functions.

Now the system will be modelled with the known equations, *[10]*, *[11]*, *[7]*:

$$\dot{Z}(t)=v(t)-d(t) \qquad (2.01)$$

$$v(t)=u(t-\lambda) \qquad (2.02)$$

$$u(t)=-\int_0^t G(\tau)Z(t-\tau)d\tau \qquad (2.03)$$

In Equation (2.03), the function $G(t)$ is the weight of the regulation that must be determined at optimum control so that the criterion of the minimum total cost is satisfied. The parameter λ, named lead time, is the period needed to activate the additional capacities in the power supply process. Assuming that the input variable demand is a stationary random process, we can also consider production and stock/additional capacities to be stationary random processes because of the linearity of the system. Let us express the total cost, the minimum of which we are attempting to define, with the mathematical expectation of the square of random variables $Z(t)$ and $u(t)$: $Q(t)=K_Z E\left(Z^2(t)\right)+K_u E\left(u^2(t)\right)$. Here, K_Z and K_u are positive constant factors, attributing greater or smaller weight to individual costs. Both factors have been determined empirically for the product and are therefore in the separate plant, *[12]*, *[13]*.

Equations (2.01)-(2.04) represent a linear model of control in which we have to determine the minimum of the mean square error, if by means of a parallel shift we cause the ideal quantity to equal zero.

The functions of the system are transferred into the complex area by means of the Laplace transform. Let *L* be the Laplace operator and $Z(s)$, $D(s)$, $u(s)$, $v(s)$ Laplace transforms:

$Z(s)=L\{Z(t)\}$, $D(s)=L\{d(t)\}$, $U(s)=L(u(t))$, $V(s)=L\{v(t)\}$

When the Laplace transform is performed on the functions of the system (2.01)-(2.03), the following expressions are obtained:

$$Z(s)=\frac{1}{s}\left[v(s)-d(s)\right]$$

$$v(s)=e^{-\lambda s}u(s)$$

$$u(s)=-G(s)Z(s)$$

In the simplified version, the expressions are defined, as follows

$$D(s)=G_p(s)d(s)$$

$$V(s)=G_f(s)u(s)$$

$$G_f(s)=\tilde{G}_f(s)G_p(s)$$

$$W(s)=\frac{G(s)}{1+G(s)G_f(s)}$$

The flowchart may be drawn in a cascade form (Figure 2).

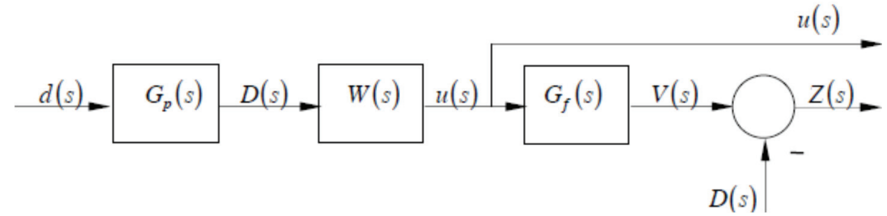

Figure 2: *The cascade flow-chart*

The function, the minimum of which we are trying to determine, is written in accordance with the definition of the autocorrelation in the following form $Q=K_z R_{zz}(0)+K_u R_{uu}(0)$ or, divided by $K_z \neq 0$

$$P=R_{zz}(0)+A^2 R_{uu}(0)$$
$$P=\frac{Q}{K_z},\ A^2=\frac{K_u}{K_z} \qquad (2.04)$$

From Figure 2, it can be seen that $u(s)=W(s)D(s)$ and $Z(s)=\left[W(s)G_f(s)-1\right]D(s)$.

Spectral densities from $R_{zz}(t)$ and $R_{uu}(t)$ are as follows:

$$\Phi_{zz}(s)=L\{R_{zz}(t)\}=\int_0^{\infty} R_{zz}(t)e^{-st}dt=\left[W(s)G_f(s)-1\right]\times\left[W(-s)G_f(-s)-1\right]\Phi_{DD}(s) \qquad (2.05)$$

$$\Phi_{uu}(s)=L\{R_{uu}(t)\}=\int_0^{\infty} R_{uu}(t)e^{-st}dt=W(s)W(-s)\Phi_{DD}(s) \qquad (2.06)$$

Both Equations (2.05) and (2.06) are transformed in the real time space and inserted into Equation (2.04):

$$\begin{aligned}P=R_{ZZ}(0)+A^2R_{uu}(0)=R_{DD}(0)-2\int_{-\infty}^{\infty}W(t_1)dt_1\int_{-\infty}^{\infty}G_f(t_2)R_{DD}(t_1+t_2)dt_2+\\+\int_{-\infty}^{\infty}W(t_1)dt_1\int_{-\infty}^{\infty}G_f(t_2)dt_2\int_{-\infty}^{\infty}W(t_3)dt_3\int_{-\infty}^{\infty}G_f(t_4)R_{DD}(t_1+t_2-t_3-t_4)dt_4\\+A^2\int_{-\infty}^{\infty}W(t_1)dt_1\int_{-\infty}^{\infty}W(t_2)R_{DD}(t_1-t_2)dt_2\end{aligned} \tag{2.07}$$

We are looking for the minimum of Equation (2.07). This minimum is obtained with the variation calculus:

$$W(t)=W_{opt}(t)+\xi W_\eta(t) \tag{2.08}$$

In (2.08), the function $W_\eta(t)$ is a variation of the function $W(t)$, ξ represents a variation parameter and $W_{opt}(t)$ is the optimal solution of (18). Function $W(t)=0$ for $t<0$. From (2.07) and (2.08), the Wiener-Hopf equation is derived

$$\begin{aligned}\int_{-\infty}^{\infty}W_{opt}(t_3)dt_3\left[\int_{-\infty}^{\infty}G_f(t_2)dt_2\int_{-\infty}^{\infty}G_f(t_4)R_{DD}(t_1+t_2-t_3-t_4)dt_4+A^2R_{DD}(t_1-t_3)\right]-\\-\int_{-\infty}^{\infty}G_f(t_2)R_{DD}(t_1+t_2)dt_2=0 \quad for \quad t_1\geq 0\end{aligned} \tag{2.09}$$

The second variation $\frac{d^2P(\eta)}{d\eta^2}$ is positive for every $t_1\geq 0$ and the solution $W_{opt}(t)$ of Equation (2.09) is the minimum.

The Wiener-Hopf equation (2.09) is solved by the spectral factorization method. From (2.09), the Wiener-Hopf equation is obtained in the following form:

$$\int_{-\infty}^{\infty}W_{opt}(\tau)\Theta^+(t-\tau)d\tau-\pi^+(t)=0 \quad for \quad t\in(-\infty,\infty).$$

This equation is an ordinary integral equation of the first order, which can be solved by the Fourier/Laplace transform:

$$W_{opt}(s)\Theta^+(s)-\pi^+(s)=0$$

and finally

$$W_{opt}(s)=\frac{\pi^+(s)}{\Theta^+(s)} \tag{2.10}$$

The function $\Theta^+(s)$ has its zeros (i.e. poles of (2.10)) only on the left-side of the complex plane. Similarly, the function $\Theta^-(s)$ has its zeros on the right-side of the complex plane. The optimal solution for the cascade operator is obtained in formal design by (2.10). The functions in the formula (2.10) are defined with expressions in the Laplace form:

$$\pi^+(s)=\left(\frac{G_f(-s)\Phi^+_{DD}(s)}{\left(G_f(s)G_f(-s)+A^2\right)^-}\right)^+$$

$$\Theta^+(s)=\left(G_f(s)G_f(-s)+A^2\right)^+\Phi^+_{DD}(s)$$

3 DISCRETE SYSTEMS, DIFFERENCE EQUATIONS

Difference equations are the discrete analogy of a differential equation. The term “difference equation” sometimes refers to a specific type of recurrence relation.

Differential equations play an important role in modelling technical processes in dynamic systems.

A similar problem as in the previous chapter is given (Figure 1). The task is to determine the optimum production and stock/capacities so that the total cost will be as low as possible.

In the building of the model, we will restrict ourselves to the dynamic linear system, in which the input is a random process with known statistical properties. The system provides the output, which is, due to the condition of linearity, also a random process. These processes are now discrete, and we will set up the mathematical model for discrete stochastic processes.

The optimization model of dynamic system regulation is determined by the system and by the optimality criterion.

Let us denote:

$Z(k)$ - activated facilities (resources) at given moment k, $k\in\{0,1,2,\ldots\}$

$u(k)$ - the amount of services performed (production) at given moment k, $k\in\{0,1,2,\ldots\}$

$d(k)$ - the demand for services at given moment k, $k\in\{0,1,2,\ldots\}$

λ - time elapsed between the moment the data are received and the carrying out of a service,

Q - criterion function, complete costs,

K_z - constant coefficient, dependent from activated resources, derived empirically,

K_u - constant coefficient, dependent from performed services, derived empirically.

Assuming that the input variable demand is a stationary random process, we can also consider production and stock/additional capacities to be stationary random processes because of the linearity of the system. Let us consider the functions $Z(k)$, $u(k)$ and $d(k)$ to be discrete stationary random processes.

Let the system be formed with these three difference equations, [*14]*:

$$Z(k)=\sum_{\kappa=0}^{\infty}G_P(\kappa)\left[v(k-\kappa)-d(k-\kappa)\right] \tag{3.01}$$

$$v(k)=\sum_{\kappa=0}^{\infty}\tilde{G}_f(\kappa)u(k-\kappa) \tag{3.02}$$

$$u(k)=-\sum_{\kappa=0}^{\infty}G(\kappa)Z(k-\kappa) \tag{3.03}$$

Let $\{Z(k)\}$, $\{v(k)\}$, $\{u(k)\}$ and $\{d(k)\}$ denote stationary discrete random processes for all $k\in\mathbf{Z}$ in equations (3.01)–(3.06). Let the autocorrelation of input process $\{d(k)\}$ be known. For the criterion of optimality, we shall use a Wiener filter, so we have to determine the minimum of the mean of square error.

$$Q=E\left(Z^2(k)\right)+A^2E\left(u^2(k-1)\right) \tag{3.04}$$

Now let us perform a z-transformation on equations (3.01)-(3-03) of our mathematical model. Without loss of generality, it can be assumed that all initial conditions are equal to zero. We then obtain the equations:

$$Z(z)=G_P(z)v(z)-G_P(z)d(z)$$
$$v(z)=\tilde{G}_f(z)u(z)$$
$$u(z)=-G(z)Z(z)$$

If we denote $D(z)=G_P(z)d(z)$ and $G_f(z)=\tilde{G}_f(z)G_P(z)$ we can easily calculate

$$Z(z)=\frac{1}{-1-G(z)G_f(z)}\cdot D(z)$$

Now we can write:

$$u(z)=W(z)D(z) \tag{3.05}$$

$$Z(z)=\left[W(z)G_f(z)-1\right]D(z) \tag{3.06}$$

$$V(z)=G_f(z)u(z) \tag{3.07}$$

$$W(z)=\frac{G(z)}{1+G(z)G_f(z)} \tag{3.08}$$

With all of these denotations, we can draw a block diagram in cascade form, similar to Figure 2, but all functions are discrete functions.
If we denote $E\left(Z^2(k)\right)=R_{ZZ}(0)$ and $E\left(u^2(k)\right)=R_{uu}(0)$, we can also write the optimality criterion

$$P=R_{ZZ}(0)+A^2R_{uu}(0) \tag{3.09}$$

To obtain a shorter and clearer form, take $S(z)=G_f(z)D(z)$ and write expression (3.06) as:

$$Z(z)=W(z)S(z)-D(z)$$

Spectral densities of autocorrelations $R_{ZZ}(k)$ and $R_{uu}(k)$ are:

$$\Phi_{ZZ}(z)=\mathcal{Z}\{R_{ZZ}(k)\}=W(z)W(z^{-1})\Phi_{SS}(z)-W(z)\Phi_{SD}(z)-W(z^{-1})\Phi_{SD}(z)+\Phi_{DD}(z)$$
$$\Phi_{uu}(z)=\mathcal{Z}\{R_{uu}(k)\}=W(z)W(z^{-1})\Phi_{DD}(z)$$

Now, let us transform these two equations in the time zone and insert them in (3.09). Since $W(k)=0$ for $k<0$, we have

$$\begin{aligned}P&=R_{ZZ}(0)+A^2R_{uu}(0)=\\&=\sum_{k=0}^{\infty}W(k)\sum_{j=0}^{\infty}W(j)R_{SS}(k-j)-2\sum_{k=0}^{\infty}W(k)R_{SD}(k)+R_{DD}(0)+A^2\sum_{k=0}^{\infty}W(k)\sum_{j=0}^{\infty}W(j)R_{DD}(k-j)\end{aligned} \tag{3.10}$$

From (3.10), we can calculate the optimum, using a calculus of variations. First, we suppose that solution $W_{\text{opt}}(t)$ exists and after that fix

$$W(t)=W_{\text{opt}}(t)+\eta W_\eta(t) \tag{3.11}$$

In (3.11), expression $W_\eta(t)$ is a possible weight, which represents the response of a given system to input signals; therefore, it means a variation of function $W(t)$, η is calling variation parameter, which can be changed with regard to conditions, while $W_{\text{opt}}(t)$ is a solution of equation (3.10). Functions $W(t)$ and $W_\eta(t)$ have to meet the causality condition, meaning $W(k)=0$ for $k<0$.
If we write (3.11) in optimality criterion (3.10), then $P=P(\eta)$ and

$$P=\sum_{k=0}^{\infty}W_{\text{opt}}(k)\sum_{j=0}^{\infty}W_{\text{opt}}(j)R_{SS}(k-j)-2\sum_{k=0}^{\infty}W_{\text{opt}}(k)R_{SD}(k)+R_{DD}(0)+A^2\sum_{k=0}^{\infty}W_{\text{opt}}(k)\sum_{j=0}^{\infty}W_{\text{opt}}(j)R_{DD}(k-j)+$$
$$+2\eta\left\{\sum_{k=0}^{\infty}W_{\eta}(k)\left[\sum_{j=0}^{\infty}W_{\text{opt}}(j)\left(R_{SS}(k-j)+A^2R_{DD}(k-j)\right)-R_{SD}(k)\right]\right\}+$$
$$+\eta^2\left[\sum_{k=0}^{\infty}W_{\eta}(k)\sum_{j=0}^{\infty}W_{\eta}(j)R_{SS}(k-j)+A^2\sum_{k=0}^{\infty}W_{\eta}(k)\sum_{j=0}^{\infty}W_{\eta}(j)R_{DD}(k-j)\right]$$

The extreme of function $P(\eta)$ will exist if expression at η would be equal to zero. For a minimum, the coefficient of the second variation must be positive. Thus, we have:

$$\sum_{k=0}^{\infty}W_{\eta}(k)\left[\sum_{j=0}^{\infty}W_{\text{opt}}(j)\left(R_{SS}(k-j)+A^2R_{DD}(k-j)\right)-R_{SD}(k)\right]=0 \tag{3.12}$$

Due to the causality condition, the expression in square brackets is equal to zero, and equation (3.12) will always be true.

$$\sum_{j=0}^{\infty}W_{\text{opt}}(j)\left[R_{SS}(k-j)+A^2R_{DD}(k-j)\right]-R_{SD}(k)=0\ \ ,k\geq 0 \tag{3.13}$$

Equation (3.13) is the Wiener-Hopf equation for stationary discrete stochastic systems described with equations (3.01)- (3.03).
With a one-sided z-transformation, we obtain the solution of the Wiener-Hopf equation, [14]:

$$W_{opt}(z)=\frac{\left[\dfrac{G_f(z^{-1})\Phi_{DD}^{+}(z)}{\left(G_f(z)G_f(z^{-1})+A^2\right)^{-}}\right]_{+}}{\left(G_f(z)G_f(z^{-1})+A^2\right)^{+}\Phi_{DD}^{+}(z)}$$

where:

$$\Phi_{DD}(z)=\Phi_{DD}^{+}(z)\Phi_{DD}^{-}(z)$$

4 FUZZY APPROACH

Fuzzy logic is a technology that allows a description of the desired system behaviour by using spoken language. Many successful applications are achieved not by conventional mathematical modelling but with fuzzy logic *[11]*, *[17]*. Fuzzy logic allows something to be not only “true” or “false”; it also allows for partial or multi-valued truths. This discipline is especially useful for problems that cannot be simply represented by conventional mathematical modelling. Statements using subjective categories have a major role in the decision-making process. These statements perhaps do not have quantitative contents, they are perhaps uncertain, imprecise or ambiguous, but people can use them successfully for complex evaluations.

Fuzzy logic operates with terms such as “fuzzy set”, “fuzzy variable”, “fuzzy number”, “fuzzy relation” and so on. Fuzzy sets are always functions that map a universe of objects onto the unit interval [0, 1]. The degree of membership in a fuzzy set *A* becomes the degree of truth or a statement and is expressed by a continuous membership function.

The combination of imprecise logic rules in a single control strategy is called approximate or fuzzy reasoning (inference). Thus, the fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic.

In principle, every system can be modelled, analysed and solved by means of fuzzy logic. Due to the complexity of the given problem and the subjective decisions of customers, which are better described with fuzzy reasoning, it is advisable to introduce a fuzzy approach. Some basic solutions of the control problems using fuzzy reasoning were presented by other researchers *[10]*, *[12]*. For some problems about the control of the dynamic system, we propose fuzzy reasoning.

Construction of a fuzzy system takes several steps: selection of decision variables and their fuzzification, establishing the goal, and the construction of an algorithm (base of rules of fuzzy reasoning), inference, and defuzzification of the results of fuzzy inference.

The output of a fuzzy process can be the logical union of two or more fuzzy membership functions defined on the universe of discourse of the output variable. Defuzzification is the conversion of a given fuzzy quantity to a precise, crisp quantity. Our model is created with FuzzyTech 5.55i software, and we use the Centre of Maximum (CoM) defuzzification method.

A graphic presentation of a fuzzy system is given in Figure 3, *[15]*. The entire system demonstrates the course of inference from input variables against output and it is built on a base of “if-then” fuzzy rules.

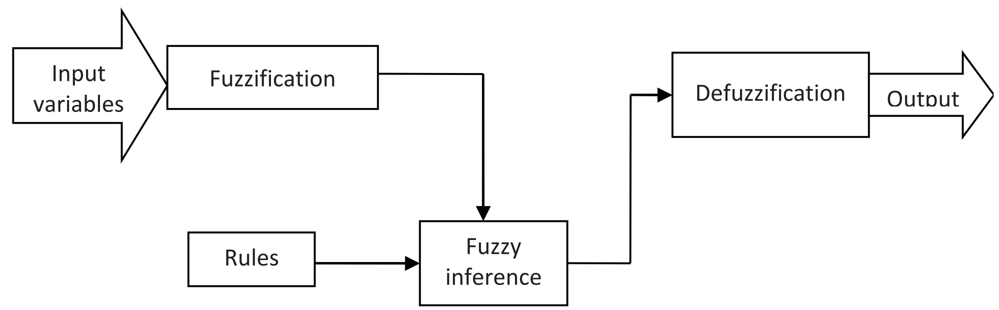

Figure 3: *Elements of fuzzy system*

4.1 Fuzzy system for determining the sustainability index of energy using biomass

In this article, we represent one possibility of the fuzzy approach on the example of the energy efficiency in the biomass employment with emphasis on the developing of the environmental sustainable biomass index. The idea of sustainable energy is founded on three main principles: production pertaining to technologies for generating energy using renewable sources, environmental impact in terms of pollution and the use of natural resources, *[16]*. Energy crops are specifically targeted in the production of bio-fuel and development of vegetable products suitable for industrial processing and transformation into energy. The procedure of measuring sustainability is very complex, and it must operate with attributes that are not defined precisely in most cases. For such problems, the proper choice is the use of fuzzy logic, which deals with uncertainty in environmental topics. Following *[16]* and generalizing it, in this chapter, a fuzzy system to determine the sustainability of production and use of biomass for energy purposes is proposed.

In the building the fuzzy system based on the fuzzy inference, we have to make these steps: fuzzification, fuzzy inference (rules, algorithm), defuzzification and optimization.

4.1.1 Fuzzification

We wish to make a fuzzy system determine an index that measures the sustainability grade of energy crops. In this manner, four inputs and one output fuzzy variable are defined. The input variables are energy, energy index, animal manure, fertilizers and pesticides; the output variable is the sustainability index (Figure 4).

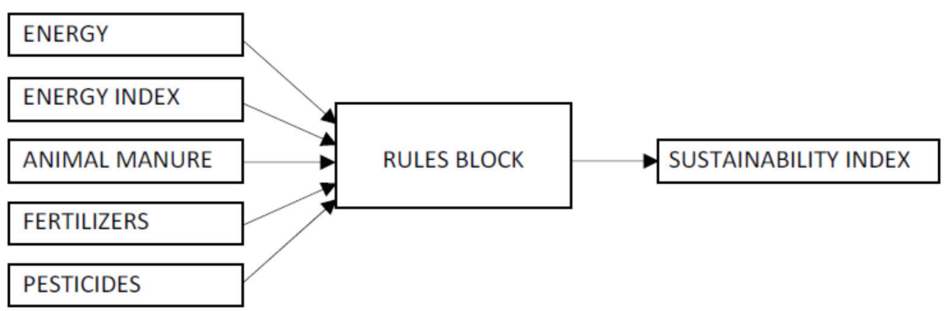

Figure 4: *Fuzzy system*

Every fuzzy variable has to be defined by its linguistic terms (fuzzy sets) and presented by membership functions. The first two input variables, energy, and energy index, include information about the energy quantity in the sustainability, and the last two, fertilizer and pesticides involve the information about the chemical pressure deriving from crop cultivation. Every use of chemical substances (chemical fertilizers, pesticides) releases contamination into the environment. These variables are in string correlation to the index of environment sustainability.

The input fuzzy variable ENERGY means biomass production in energy terms and is represented by the following fuzzy sets: LOW, MEDIUM, HIGH.

The input fuzzy variable ENERGY INDEX means a balance (ratio) between the amount of energy used for the production phase and the energy that the biomass will supply and is also represented by the following fuzzy sets: LOW, MEDIUM, HIGH.

The input fuzzy variable ANIMAL MANURE means the quantity of animal manure needed for developing the crops and is represented by the following fuzzy sets: FEW, MEDIUM, MUCH.

The input fuzzy variable FERTILIZERS means the quantity of fertilizers needed for developing the crops and is represented by the following fuzzy sets: FEW, ACCEPTABLE, MUCH.

needed to increase agricultural production and is represented by the following fuzzy sets: LOW, MEDIUM, RISK.

The output variable SUSTAINABLE INDEX measures the sustainability grade of energy crops and is represented by five fuzzy sets: VERY LOW, LOW, MEDIUM, HIGH and VERY HIGH.

In all fuzzy variables, the measure unit from 0 to 100 is defined. Of course, for separate crops, we could take physical units, such as kg/ha or GJ/ha and so on.

In Figures 5 and 6, the membership functions of fuzzy variables ANIMAL MANURE and SUSTAINABLE INDEX are shown.

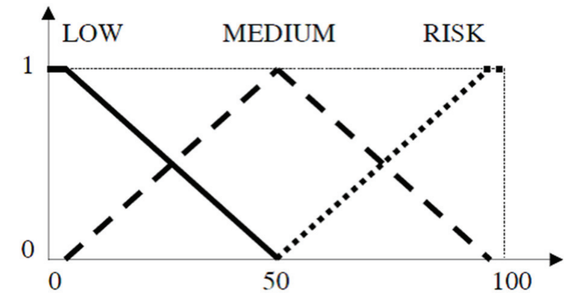

Figure 5: *Fuzzy variable PESTICIDES*

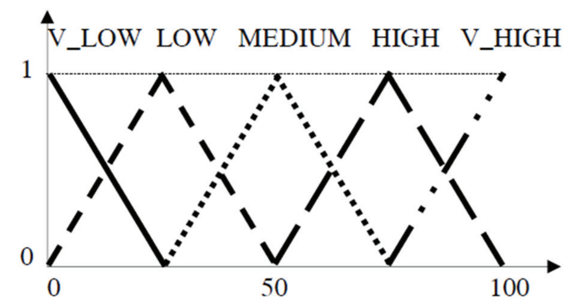

Figure 6: *Fuzzy variable SUSTAINABLE INDEX*

4.1.2 Fuzzy inference

Fuzzy inference is a process in which a certain conclusion is derived from a set of fuzzy statements. In addition to linguistic variables, there are basic widgets of a fuzzy logic system as well as sets of rules that define the behaviour of a system. If variables x and y are defined by the sets X and Y, then a single fuzzy rule (implication) assumes the following form: if x is A, then y is B, where A and B are linguistic values defined by fuzzy sets on the universes of discourse X and Y, respectively. With fuzzy inference, we must put all values and facts in a definite order and connect them to the procedure of inference execution, so that it will be feasible to do so with a computer. This order is given as a list or system of rules (rule block). In our article, we applied FuzzyTech software, *[17]*. In the rule block, 243 rules are automatically created. Some of them are represented in Table 1.

Table 1: Some rules of the Rule block

IF					THEN
ANIMAL MAN.	ENERGY	ENERGY INDEX	FERTILIZERS	PESTICIDES	SUSTAIN. INDEX
MEDIUM	HIGH	LOW	MUCH	LOW	MEDIUM
MEDIUM	HIGH	LOW	MUCH	ACCEPTABLE	HIGH
MEDIUM	HIGH	LOW	MUCH	RISK	HIGH
MEDIUM	HIGH	MEDIUM	FEW	LOW	LOW
MEDIUM	HIGH	MEDIUM	FEW	ACCEPTABLE	MEDIUM
MEDIUM	HIGH	MEDIUM	FEW	RISK	MEDIUM
MEDIUM	HIGH	MEDIUM	MEDIUM	LOW	MEDIUM
MEDIUM	HIGH	MEDIUM	MEDIUM	ACCEPTABLE	MEDIUM
MEDIUM	HIGH	MEDIUM	MEDIUM	RISK	HIGH
MEDIUM	HIGH	MEDIUM	MUCH	LOW	MEDIUM
MEDIUM	HIGH	MEDIUM	MUCH	ACCEPTABLE	HIGH
MEDIUM	HIGH	MEDIUM	MUCH	RISK	HIGH
MEDIUM	HIGH	HIGH	FEW	LOW	MEDIUM
MEDIUM	HIGH	HIGH	FEW	ACCEPTABLE	MEDIUM
MEDIUM	HIGH	HIGH	FEW	RISK	HIGH
MEDIUM	HIGH	HIGH	MEDIUM	LOW	MEDIUM
MEDIUM	HIGH	HIGH	MEDIUM	ACCEPTABLE	HIGH

4.1.3 Defuzzification

Defuzzification is the conversion of a given fuzzy output to a precise, crisp output. There are many procedures for defuzzification, which can give some different results. In our example, the fuzzy model is created with FuzzyTech 5.55i software, and we use the Centre of Maximum (CoM) defuzzification method.

4.1.4 Optimisation

When the system structure is set, and the membership functions and rules in all the rule blocks are defined, the model must also be tested and checked. During optimization, the entire definition area of input data is verified.

4.1.5 Numerical example

Starting with the fuzzy model using FuzzyTech software, we can simulate all possible situations interactively. Some numerical results are shown in Table 2.

Table 2: Some numerical results

ANIMAL MAN.	ENERGY	ENERGY INDEX	FERTILIZERS	PESTICIDES	SUSTAIN. INDEX
10	10	10	50	30	39.2
50	50	50	50	50	50.0
100	50	50	100	100	75.0
80	80	50	10	20	37.6
90	80	80	10	50	43.6
100	30	40	100	80	55.3

With rising quantities of input data, the output also rises and vice versa, because the rules in the rule block are made in this manner. The optimization procedure will verify the rules, the weights of rules and shapes of all membership functions.

5 CONCLUSION

In this article, the use of certain mathematical tools to create a dynamic system control is described. The concrete examples are highly varied. Differential equations are often used to look for minima or maxima, analysing dynamic functions one or more variables, in the control of continuous dynamic systems, describing a nature of physical experiments and so on. For describing and analysing discrete mathematical phenomena, we have used various equations.

In all situations in which some problems cannot be simply represented by conventional mathematical modelling, we need to use fuzzy logic and its theorems. In recent years, as a hybrid approach to the control of dynamic systems, the option of the synthesis of differential/difference equations and fuzzy logic has been used. In this case, fuzzy differential equations *[3]*, *[4]*, *[5]* and fuzzy difference equations *[6]* are used, but they still do not have significant application possibilities, and therefore are not considered in this article. However, for the control of dynamic systems, these quantitative (mathematical) tools will also be required for further research.

References

[1] **E. Kreyszig:** Advanced Engineering Mathematics, *John Wiley & Sons, Inc., New York, 1999*

[2] **T.M. Guerra, A. Sala, K. Tanaka:** *Fuzzy control turns 50: 10 years later*, Fuzzy sets and systems 281, pp. 168-182, 2015

[3] **J. J. Buckley, T. Feuring**: *Fuzzy differential equations*, Fuzzy sets and systems 110, pp. 43-54, 2000

[4] **A. Khastan, R. Rodriguez-Lopez**: *On the solution to first order linear fuzzy differential equations*, Fuzzy Sets and Systems 295, pp. 114-135, 2016

[5] **D. Qui, W. Zhang, C. Lu:** *On fuzzy differential equations in the quotient space of fuzzy numbers*, Fuzzy sets and systems 295, pp. 72-98, 2016

[6] **R. Memarbashi, A. Ghasemabadi**: *Fuzzy difference equations of volterra type*, Int. J. Nonlinear Anal. Appl. 4, No.1, pp. 74-78, 2013

[7] **J. Usenik, M. Vidiček, M. Vidiček, J. Usenik;** *Control of the logistics system using Laplace transforms and fuzzy logic*, Logistics and sustainable transport, Vol. 1, issue 1, pp. 1-19, 2008

[8] **J. Usenik, M. Repnik**: *System control in conditions of discrete stochastic input process*, Journal of Energy Technology, Vol. 5, Iss. 1, pp. 37 - 53, 2012

[9] **J. Usenik, T. Turnšek:** *Modeling Conflict Dynamics: System Dynamic Approach, Suistainable Logistics and Strategic Transportation Planning, IGI Global book series*

Advanced in Logistics, Operations, and management, Business Science Reference, Hershey PA, USA, pp. 273-294, 2016

[10] **M. Bogataj, J. Usenik**. *Fuzzy approach to the spatial games in the total market*, Int., j. prod. econ., Vol. 93-94, pp. 493-503, 2005

[11] **D. Kovačič, J. Usenik, M. Bogataj:** *Optimal decisions on investments in urban energy cogeneration plants - extended MRP and fuzzy approach to the stochastic systems*, International journal of production economics, 2016

[12] **J. Usenik, M. Bogataj:** *A fuzzy set approach for a location-inventory model*, Transp. plan. technol., Vol. 28, pp. 447-464, 2005

[13] **J. Usenik:** *A fuzzy model of power supply system control*, JET Journal of Energy technology, Vol. 5, Iss. 3, pp. 23–38, 2012

[14] **T.J. Ross:** *Fuzzy Logic with Engineering Applications*, Second Edition, John Wiley & Sons Ltd., The Atrium, Southern Gate, Chichester, West Sussex, England, 2007

[15] **H. J. Zimmermann:** *Fuzzy Set Theory and its Applications,* Fourth Edition, Kluwer Academic Publishers, Boston, pp. 352-370, 2001

[16] **F. Cavallaro:** *A Takagi-Sugeno Fuzzy Inference System for Developing a Sustainability Index of Biomass,* Sustainability 7, pp. 12359-12371, 2015

[17] **FuzzyTech 5.5:** *User`s Manual*, INFORM GmbH, 2002

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FRACTURE PROPERTIES OF TITANIUM BONE IMPLANTS CORRODED BY SIMULATED BODY FLUID

LOMNE LASTNOSTI TITANOVIH KOSTNIH IMPLANTANTOV KORODIRANIH S SIMULIRANO TELESNO TEKOČINO

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Keywords: titanium, bone implants, hip prosthesis, body fluid, fracture test, fracture properties, crack tip opening displacement

Abstract

Titanium has been widely used for medical implants and restorations due to its excellent osseointegration, corrosion resistance, biocompatibility in biological fluids, and high resistance/weight ratio.

The aim of this paper is to determine the fracture properties of two bone implants of a hip prosthesis made from commercially pure titanium and Ti-6Al-4V titanium alloy. Both bone implants were before fracture mechanics testing corroded by simulated body fluid. The presence of different microstructures along the pre-crack fatigue front has significant effects on the critical crack tip opening displacement (CTOD). The CTOD values were calculated in accordance with standard ASTM E1290-08e1. This value can be the relevant parameter for the safe servicing of hip prostheses.

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Povzetek

Titan se v veliki meri uporablja za medicinske implantante in obnavljanje že vgrajenih sklopov zaradi dobre trdnosti, korozijske obstojnosti in biokompatibilnosti v bioloških tekočinah in visoke odpornosti glede na njegovo težo.

Namen članka je določitev lomnih lastnosti dveh kostnih implantantov, ki sta vgrajena v protezo kolka in narejena iz komercialno čistega titana in titanove zlitine Ti-6Al-4V. Kostna implantanta sta bila pred lomnomehanskim preizkušanjem korodirana s simulirano telesno tekočino. Prisotnost različnih mikrostruktur na fronti utrujenostne razpoke ima pomemben vpliv na kritično odpiranje konice razpoke (CTOD). CTOD vrednosti so izračunane v skladu s standardom ASTM E1290-08e1. Ta vrednost je lahko relevanten parameter za varno uporabo protez kolka.

1 INTRODUCTION

The high strength, low weight, and excellent corrosion resistance of titanium and titanium alloys have led to an extensive and diversified range of successful applications which demand high levels of reliable performance in surgery and medicine as well as in aerospace, automotive, chemical plant, power generation, oil and gas extraction, sports, and other major industries. More than 1000 tonnes of titanium devices of every description and function are implanted in patients worldwide every year. Requirements for joint replacement continue to grow as people live longer or damage themselves more through strenuous sports or jogging, or are seriously injured in road traffic and other accidents. Light, strong and totally biocompatible, titanium is one of the few materials that naturally match the requirements for implantation in the human body. Medical grade titanium alloys have a significantly higher strength-to-weight ratio than competing stainless steels. The range of available titanium alloys enables medical specialists and designers to select materials and forms closely tailored to the needs of the application. The full range of alloys reaches from high ductility commercially pure titanium used where extreme malleability is essential, to fully heat treatable alloys with strength above 1300 MPa. Shape-memory alloys based on titanium, further extend the range of useful properties and applications. A combination of forging or casting, machining and fabrication are the process routes used for medical products. Surface engineering frequently plays a significant role, extending the performance of titanium several times beyond its natural capability, *[1]*.

Approximately one million patients worldwide are treated annually for total replacement of arthritic hips and knee joints. The prostheses come in many shapes and sizes. Hip joints normally have a metallic femoral stem and head that is placed in an ultrahigh molecular weight low friction polyethylene socket, both secured in position with polymethyl methacrylate bone cement. Some designs, including cement-less joints, use roughened bioactive surfaces (including hydroxyapatite) to stimulate osseointegration, limit resorption and thus increase the implant lifetime for younger recipients. Internal and external bone-fracture fixation provides a further major application for titanium as spinal fusion devices, pins, bone-plates, screws, intramedullary nails, and external fixators, *[2-3]*.

The aim of this paper is to determine the fracture properties of two bone implants of a hip prosthesis made of commercially pure titanium and Ti-6Al-4V titanium alloy, corroded by simulated body fluid. The presence of different microstructures along the pre-crack fatigue front has important effects on the critical crack tip opening displacement (CTOD) which can be the relevant parameter for the safe servicing of hip prostheses.

2 EXPERIMENTAL PROCEDURE

Bone implants of hip prostheses (Figure 1) are medical devices intended to restore mobility and relieve pain usually associated with arthritis and other hip diseases or injuries. Every bone implant has a distinct set of benefits and risks. The key design features of each implant including size, material and dimensions make each system unique. In addition, the same bone implant system will have different outcomes in different patients. It is also important to recognize that bone implants may need to be replaced after a certain amount of time. Factors that influence the longevity of the device include the patient's age, sex, weight, diagnosis, activity level, conditions of the surgery, and the type of implant chosen, *[3]*.

In the European Union, there are currently five types of total bone implant replacement devices available with different bearing surfaces. These are:

- Metal-on-Polyethylene: The ball is made of metal, and the socket is made of plastic (polyethylene) or has a plastic lining.
- Ceramic-on-Polyethylene: The ball is made of ceramic and the socket is made of plastic (polyethylene) or has a plastic lining.
- Metal-on-Metal: The ball and socket are both made of metal.
- Ceramic-on-Ceramic: The ball is made of ceramic and the socket has a ceramic lining.
- Ceramic-on-Metal: The ball is made of ceramic and the socket has a metal lining.

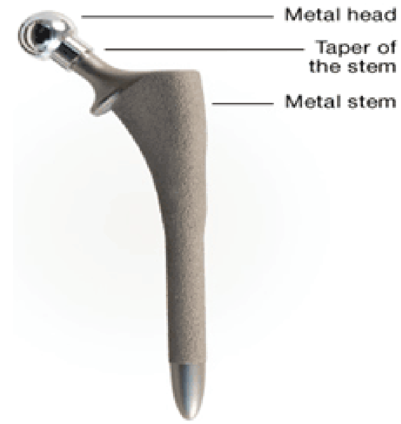


Figure 1: *Bone implant of hip prosthesis*

For fracture mechanics testing single edge notch bend (SENB) specimens were used, and they were loaded in a three-point bending to fracture (Figure 2).

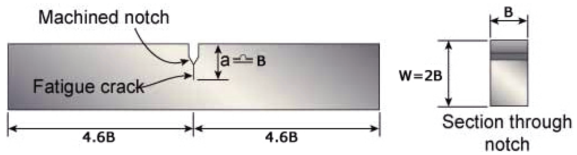


Figure 2: *Fracture mechanics SENB specimens with B=15 mm*

All specimens were extracted from the stem of the bone implant in the direction of loading (Figure 1 and Figure 3) and immerged for 720 hours (30 days) in the simulated body fluid. Ringer's solution (9.0 g/l NaCl, 0.43 g/l KCl, 0.24 g/l CaCl2 and 0.2 g/l NaHCO3) is used as body fluid and maintained in the p_H as 7.4 and a temperature of 37.4 ±1 °C to simulate the body fluid condition, *[6]*.

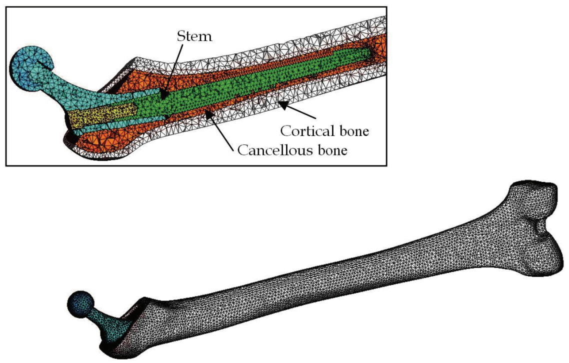


Figure 3: *Fitting of titanium bone implant into the thighbone*

The fracture toughness of fracture specimens made of commercially pure titanium (TiCP) and titanium alloy Ti-6Al-4V was evaluated using a standard static Crack Tip Opening Displacement (CTOD) test, *[4-5, 8]*. Mechanical properties of bone implant materials for this research are shown in Table 1.

Table 1: *Mechanical properties of Ti CP (ASTM F 67) and Ti6Al4V alloy (ASTM F 136)*

Material	Yield strain (MPa)	Tensile strain (MPa)	Elongation (%)
TiCP-grade 4	485	550	15
Ti6Al4V	795	860	10

All CTOD tests were conducted using Zwick and Schenk testing machines. Specimen loading was carried out with constant crosshead speed v = 0.5 mm/min. The test temperature was 37 °C, following the recommendation of the ASTM (the American Society of the International Association for Testing and Materials). For CTOD testing, the single specimen method was used. To evaluate the fracture toughness of titanium bone implants, standard bending specimens, *[4]*, with shallow (a/W = 0.2) notches were used. For all specimens, fatigue pre-cracking was carried out with the Step-Wise High R ratio method (SHR) procedure, *[5]*. Shallow fatigue notches simulate the real cracks the can appear in the stem of bone implants during hip prosthesis operations. Specimens with fatigue notches were immerged for 720 hours (30 days) in the simulated body fluid causing the real corrosion at the fatigue crack front. Titanium implants usually fail as a result of high cyclic loading resulting in peri-implant bone resorption; increased bending moments on implants and eventual metal fatigue and implant fracture.

During the CTOD tests, the potential drop technique was used for monitoring stable crack growth, *[7,9]*. The load line displacement (LLD) was also measured with a reference bar to minimize the effects of possible indentations of the rollers. The CTOD values were calculated in accordance with ASTM E1290-08e1, *[4]*.

3 RESULTS AND DISCUSSION

The critical CTOD was obtained via the clip-gauge displacement *Vg* measured across the notch mouth by using a specific converting equation. In the current ASTM E1290-08e1 standard, the CTOD be calculated from the new equation as follows:

$$\delta = \frac{K^2}{2\sigma_Y E'} + \frac{0.4(W-a)\,V_p}{0.4W + 0.6a + z} \tag{3.1}$$

where the first term is the elastic component of CTOD, the second term is the plastic component, and *Vp* is the plastic component of the clip-gauge displacement. The stress intensity factor for the elastic CTOD calculation is obtained from the following relationship.

$$K = YP / BW^{1/2} \tag{3.2}$$

where *P* is the applied load, and *Y* is the stress intensity coefficient given as a function of the crack length-to-width ratio.

In this standard, the type of critical CTOD was clearly defined according to the nature of the observed fracture event. The four kinds of critical CTOD, i.e. δ_c, δ_u, δ_m and δ_i, are measured (Fig. 4). At low temperatures, the steel fails by cleaving and δ_c is measured empirically.

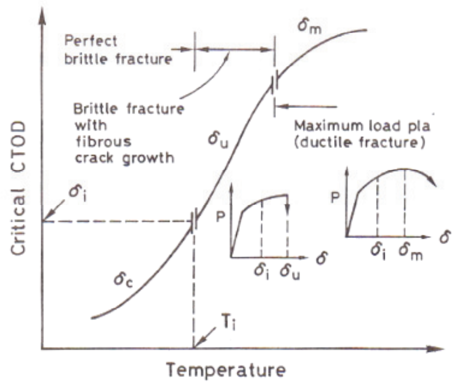


Figure 4: *Definition of critical CTODs in ASTM E1290-08e1.*

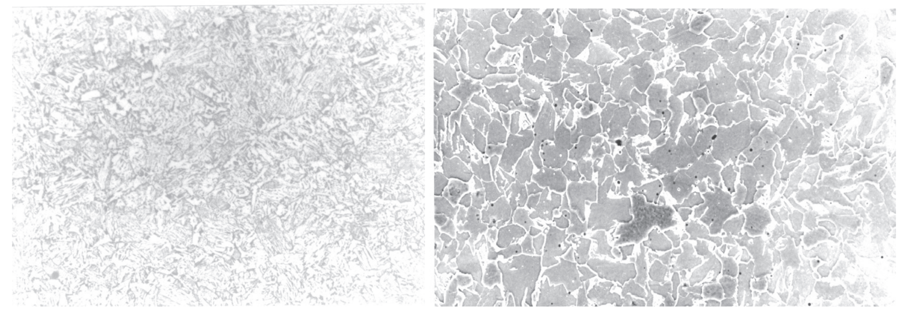
As the test temperature increases, cleavage becomes less favourable, and the fracture toughness increases. The fracture mode changes to micro-void coalescence, and the crack grows in a stable manner. δ_i is defined as the value of CTOD at the onset of tearing. At temperatures slightly above the fracture mode change, stable tearing can be followed by unstable cleavage. In this case, the critical measure is δ_u at the instability point. On the upper level of toughness, the steel reaches a point of plastic collapse when the work-hardening cannot keep pace with the decrease in ligament area caused by stable crack growth. δ_m is then measured at the point of maximum load in a bend test. The real fracture properties and results of fracture toughness CTOD are shown in Table 2.

Table 2: *The real fracture properties of titanium bone implants and results of CTOD fracture toughness at temperature testing at* 37 °C

Specimen SENB	Yield strain (MPa)	Tensile strain (MPa)	CTOD (mm)	Event
TiCP-grade 4	479	542	0,201	δ_m
TiCP-grade 4	465	555	0,234	δ_m
Ti6Al4V	761	834	0,292	δ_m
Ti6Al4V	743	871	0,301	δ_m

All specimens reached the CTOD event δ_m measured at the point of maximum load in a bend test. CTOD fracture toughness of Ti6Al4V specimens is slightly higher than CTOD fracture toughness of TiCP-grade.

Microstructures at the brittle fracture initiation point and around it, as well as the nature of crack path deviation, were evaluated using the fracture surface cross-section method, *[7,8]*, through the brittle fracture initiation point.



a) b)

Figure 5: *Microstructure at the crack tip of a) TiCP-grade 4 and b) Ti6Al4V specimen during* δ_m fracture event

A detailed analysis of material at the crack tip region and along a deviated crack path was made with an optical microscope and scanning electron microscope (SEM). In this way, the critical microstructure (local brittle zones) at the fatigue crack tip surroundings, where the brittle fracture was initiated, and the microstructure where it propagated later, were identified. The SEM analysis of fractured titanium implants reveals consistent uniformity of the microstructure with no indications that major inclusions or porosities are present and refutes the possibility of implant failure due to manufacturing errors.

4 CONCLUSIONS

Bone implants of hip prostheses are medical devices intended to restore mobility and relieve pain usually associated with arthritis and other hip diseases or injuries. Every bone implant has a distinct set of benefits and risks. The key design features of each implant including size, material and dimensions make each system unique. Exact evaluation of real material mechanical properties of the bone implant is essential for the safe servicing of hip prostheses. All fracture specimens reached the CTOD event δ_m measured at the point of maximum load in a bend test. Shallow fatigue notches simulate the real cracks which can appear in the stem of bone implants during hip prosthesis operations. The CTOD fracture toughness of Ti6Al4V specimens is slightly higher than CTOD fracture toughness of TiCP-grade.

The SEM analysis of fractured titanium implants reveals the consistent uniformity of the microstructure with no indications that major inclusions or porosities are present; thus, both titanium bone implants made of commercially pure titanium (TiCP-grade 4), and titanium alloy Ti-6Al-4V can be used for the manufacturing of bone implants of hip prostheses.

References

[1] **M. Koike, H. Fujii H:** *In vitro assessment of corrosive properties of titanium as a biomaterial. Journal of Oral Rehabilitation, Vol. 22, Iss.6, p.p. 540–548, 2001*

[2] **N. Sykaras, A. Lacopino, V. Marker***: Implant materials, designs, and surface topographies: Their effect on osseointegration, A literature review. Int. J. Oral Maxillofac. Implants, Vol.15, Iss.1, p.p. 675–690, 2000*

[3] **H. Grandin, S. Berner, M. Dart***: A review of titanium alloys for use in endosseous bone implants, Materials, Vol.2, Iss.5, p.p. 1348–1360, 2015*

[4] ASTM E1290-90. Standard test method for crack-tip opening displacement (CTOD) fracture toughness measurement, American Society for Testing and Materials; 1998

[5] GKSS Forschungszentrum Geesthacht GMBH, *GKSS-Displacement Gauge Systems for Applications in Fracture Mechanics*

[6] ***S. Marčič, A. Praunseis****: Development of simulated body fluid for corrosion test, Project study, Institute of Energy Technology, Krško, 2015*

[7] **Toyoda, M.:** *Fracture toughness evaluation of steel welds, Book of Mechanics, Osaka University, 1989*

[8] **T. Anderson***: Fracture mechanics, Fundamentals and applications. Boca Raton: CRC Press; 1995*

[9] **K.H. Schwalbe***: The engineering flaw assessment method (EFAM)—Document EFAM 96, GKSS Report 98/E/40. Geesthacht, 1998*

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CABLE-AGING MANAGEMENT PROGRAM IMPLEMENTATION IN NUCLEAR POWER PLANTS

NADZOR STARANJA ELEKTRIČNIH KABLOV V JEDRSKIH ELEKTRARNAH

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Keywords: nuclear cable aging, diagnostic testing criteria, residual life prediction model, risk ranking

Abstract

As a requirement for nuclear power plant life extension beyond 40 years, some additional Aging Management Programs (AMP) for passive equipment have to be implemented. This article presents an overview of Cable-Aging Management Program (CAMP) activities. The program defines basic rules and initial activities for the identification of adverse operation environment parameters that could lead to the accelerated aging of specific materials. Samples of cables are selected based on nuclear safety and electrical equipment criticality for inspection and testing, to check functionality and prevent unexpected failure during normal operation. Acceptance criteria for environment parameters and diagnostic testing have been set. Initial visual inspection of cable conditions in an adverse environment and testing of sampled cables and environment yield results for on-time preventive measures. The first cable aging management program in Slovenia has been operating since 2010, and its experience could be adapted to other companies for which cables are key components.

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Povzetek

Podaljšanje življenjske dobe jedrske elektrarne nad 40 let zahteva vzpostavitev dodatnih programov nadzora stanja pasivnih komponent. Program nadzora staranja električnih kablov je vzpostavljen z namenom pravočasnega odkrivanja učinkov staranja in preprečevanja nepričakovanih odpovedi pri normalnem obratovanju. Program postavlja osnovna pravila in določa aktivnosti razpoznave vgrajenih materialov, obratovalnih pogojev in specifičnih parametrov, ki vplivajo na pospešeno staranje kablov. Vzorčenje kablov je izvedeno na osnovi zahtev po delovanju kritične varnostne opreme. Program določa kriterije sprejemljivosti ključnih parametrov okolice ter rezultatov nekaterih uporabnih merilnih metod. Začetna vizualna kontrola stanja izpostavljenih lokacij in izvedena diagnostična testiranja dajejo po šestih letih rezultate na osnovi katerih je mogoče pravočasno načrtovanje nadaljnjih preventivnih ukrepov. Prvi vzdrževalni program nadzora staranja električnih kablov v Sloveniji je koristen in se lahko prilagodi uporabi v drugih podjetjih, kjer je ta oprema ključna.

1 INTRODUCTION

The purpose of the Cable-Ageing Management Program (CAMP), *[1]*, is to provide reasonable assurance of functionality of the electrical cables with connections exposed to localized adverse environments. Identification of potential adverse localized environments or adverse service conditions and management of cable insulation and connections are its main concern. The main goal is to confirm the functionality of cables for planned extended life operation for beyond 40 years.

CAMP defines activities on low voltage power, control, instrument and medium voltage cables with associated connections to safety-related equipment (1E), critical equipment and cables identified in the operating experience of the plant as exposed to adverse localized environments.

The Aging Management Program for cables uses two approaches. The first is a visual inspection of cable areas, to search for potential local adverse environments (harsh environments or "hot spots"), such as high temperature, humidity or submergence, chemical or mechanical wear. The second approach is to perform diagnostic testing of selected cables in specific local adverse environments. In a typical nuclear power plant, there are more than 1000 km of installed cables in more than 20,000 circuits and hundreds of different cable types, with regard to construction, material, and manufacturer. Obviously, all cables cannot be inspected or tested, though the sampling approach of the most critical cables in adverse environments was conducted, as shown in Figure 1. CAMP is a continuing process, which concludes when all inspected and tested cables in a harsh environment meet the acceptance criteria; the whole population of cables is deemed functional until the next period of inspection.

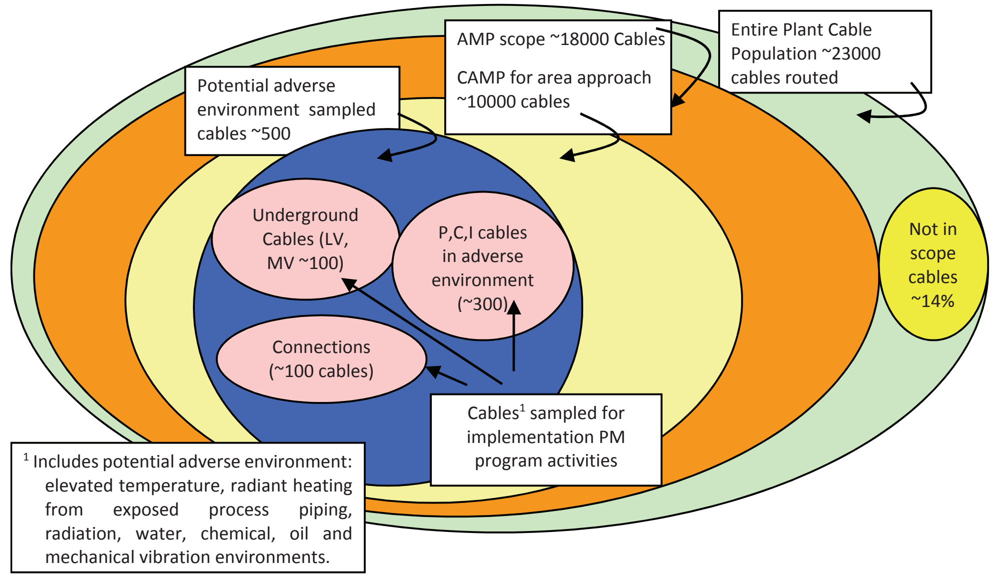

Figure 1: *Cable scoping and sampling process, [1]*

Most of the cables sampled in program scope are recognized as qualified safety-related class SR (1E). LOCA-qualified cables could be considered with a spaces approach, assuming all cables are installed in environmentally benign areas with all five of the following characteristics will remain operational for 40 years. If these environment conditions are met, there is no appreciable aging of cables for 60 years:

- room ambient temperature never exceeds 40°C,
- no close, hot process lines,
- no radiation sources,
- no connections frequently manipulated,
- the area is always dry.

The program applies to different cable groups in adverse environments: qualified safety-related cables (1E) purchased in accordance with technical specifications, operationally important cables (N1E), critical equipment and Operating Experience.

Different cable types are grouped based on voltage or type:

- Medium Voltage (MV) Power Cables (5 bills of material-BOM types, ~1%),
- Low Voltage (LV) Power Cables (42 BOM types, ~10% of cable),
- Control Cables (23 BOM types, 70% of cables),
- Instrumentation Cables (45 BOM, 19% of cables).

Several different manufacturers were identified. Three of them were recognized during construction time as the main producers of installed cables for SR (1E) circuits: Okonite for MV, Boston Insulated Wire (BIW) and Rockbestos for (LV). Most of the cable materials identified for insulation used in safety-related 1E qualified cables are ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE) with CSPE (Hypalone®) for the jacket. All materials have good thermal, radiation and moisture resistance for long-term operation of more than 40 years under normal designed temperature and radiation. The jacket material (Hypalone®) as the most vulnerable material, used for mechanical and fire protection, is a good indicating material for adverse environment effects.

2 LICENSING REQUIREMENTS AND PROGRAM OVERVIEW

NUREG-1801 Generic Aging Lessons Learned (GALL) 0 requires an aging management program to detect possible aging effects on electrical cables with appropriate consideration for low-voltage power, control, instrument and medium voltage cables with connections in a period of plant lifetime. Other licensing sources were considered: Maintenance Rule (10 CFR 50.65), License Renewal Rule (10 CFR 54) and Critical Components-reliability (INPO AP-913). Their additional requirements to be in scope are cables used to mitigate accidents or transients or support emergency operating procedures, cables whose failure could cause a reactor scram or actuation of a safety-related system, station blackout, fire protection, and reliability, i.e. cables supporting the function of critical components. The CAMP is conservative and specific in activities to identify adverse environments and requires the assessment of exposed and sampled cables by:

- Identification of locations and parameters where environments are more severe than the plant design environment for those areas and could cause premature aging effects;
- Visual inspection of sampled accessible cables located in adverse environments;
- Evaluation of calibration and surveillance testing results to identify deviations leading to direct testing of the circuits with involved cables and connections;
- Inspection for water collection in power cable manholes and draining water;
- Electrical test samples of inaccessible cables in identified adverse environments;
- Testing samples of power cable connections (i.e. IR camera, resistance testing, or other);
- If an unacceptable condition is identified at inspection or testing, a determination is made as to whether the same condition or situation applies to other (in) accessible cables;
- Estimating life prediction for exposed cables with site testing, theoretical calculations or laboratory testing to predict residual life of cable insulation.
- Corrective actions with repairing and replacing cables are planned to eliminate and prevent aging effects on cables (rerouting, thermal insulation, shielding, water pumping, etc.).

CAMP is a coordinated effort between different existing programs and organization departments of Technical Operation (TO), Engineering Support Division (ESD), Quality Assurance (QA), and Training. Responsibilities are defined with roles of personnel in specific departments.

3 CABLE-AGING DIAGNOSTIC TESTING METHODS

The focus of Cable Aging Management Program is to implement the best available inspection and testing method with predefined acceptance criteria to detect cable aging on time with appropriate action based on a risk-ranking model or remaining-life prediction. An overview of the concept is shown in Figure 2.

In the first place, visual inspection of the cable area was conducted to search for adverse environments and install environment monitors to measure specific parameters.

In the second phase, detailed in-service-inspection with diagnostic testing evaluation of electrical and mechanical properties was conducted to confirm cable functionality.

In the third phase, aged samples will be taken for a laboratory test to determine the actual scale of different properties change. Laboratories testing could be used for detailed modelling of remaining life prediction.

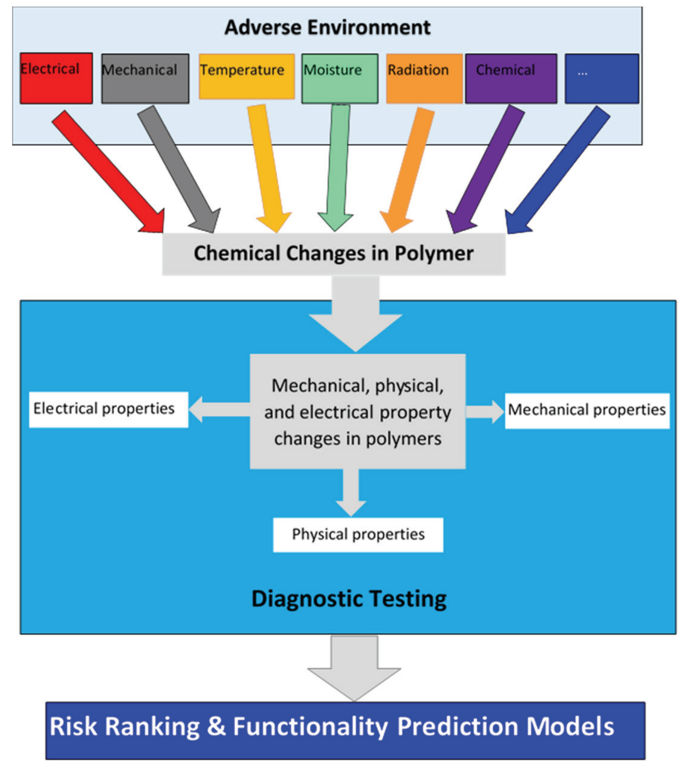

Figure 2: *Cable Aging Detection and Remaining Life Prediction, [4]*

3.1 Visual Inspection

Visual inspection is started with an area approach to look for adverse environment and service conditions looking for hot spots observable on the cable surface (colour change, hardening, cracking).

Basic adverse environment conditions are defined for an initial "hot spot":

- High Local Temperature: $T_{ambient}$>50 °C.
- High Radiation: >200 mSv/h.
- Long-term wetting: 75%-100% relative humidity.
- Mechanical: no hardening, cracking, no indentations, no cuts.
- Chemical: no softening, swallowing, swelling, no oil, acid, or base contamination.

Adverse service conditions for power cables are:

- High conductor temperature from ohmic heating.
- High resistance connections.

3.2 Temperature Monitoring

Elevated temperature is the most common cause of long-term aging of cable insulations and jackets in dry areas. For most insulation types and jackets identified in NEK, thermal aging causes the materials to harden, lose elongation properties, and eventually tensile properties. For low voltage power cables, operational ratings are based on a maximum conductor temperature of an assumed 40 °C ambient environment. Power cables have 90 °C conductor temperature ratings. Accordingly, power cables in areas with high ambient temperature (> 40 °C) will tend to thermally age more rapidly if operated close to ampacity if the elevated ambient temperature was not considered in the derating process. As the ambient temperature increases above 50 °C, the jacket materials of some power cables will begin to thermally age. Finding a hardened cable jacket would indicate that assessment of the aging of the cable is desirable to determine if the insulation has hardened and may be susceptible to cracking and failure. Table 1 provides approximate time to the point at which jacket aging would be detectable via tactile assessment for various ambient temperatures. The values are given to show that elevated temperatures significantly reduce lifespan. The table gives a rough indication of temperature sensitivity for identifying areas where cable condition should be assessed.

Table 1: *Approximate Time When Jacket Aging Would Be Detectable (hardened), [1]*

Jacket Material [1] \ Temperature	50° C	60° C	70° C
Neoprene	16–20 years	2–3 years	Very short
CSPE (Hypalon)	Very long life	25–30 years	9–11 years
PVC	14–22 years	5–8 years	2–3 years

[1] Generic material data used (not NEK-specific)

Appropriate tools for local temperature harsh environment finding are infrared camera, data logger and irreversible label memory sticker for one-time use in Figure 3-c for temperature range 37°C-65°C in 8 stages.

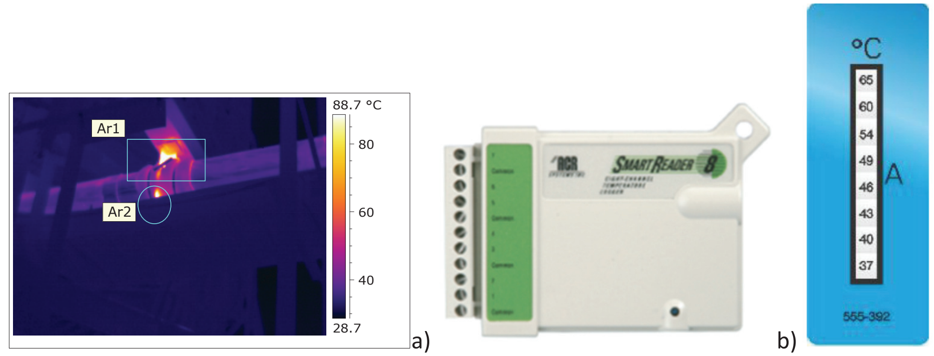

Figure 3: *Different temperature monitors: a) IR camera, b) data logger, c) irreversible label, [9]*

3.3 Radiation Monitoring

With respect to radiation effects, most cables will be in low-dose areas of the plant. However, some cables may be located in areas with appreciable doses. Some early Sandia research showed that effects on physical properties are not observable at 1-5 Mrad (10-50 kGy). The effects of radiation and temperature are to change the physical properties (loss of elongation and tensile properties) of the insulation and, after very severe aging, the electrical properties are eventually affected.

Radiation zone maps and environmental reports were reviewed and dose rates >200mSv/h were set for hot spot evaluation in the scope of CAMP. To determine if there are any additional zones where high radiation may exist, additional alanine pellets were set at 50 locations for gamma radiation and 5 neutron detectors. Conservative estimation suggested that the maximum radiation that cables would "see" in 60 years at selected hot spots would not reach more than 60-80 Mrad. Cables are qualified for 200 Mrad total dose. In general, high radiation conditions are expected to be accompanied by elevated thermal conditions and a few additional areas needing assessment should be identified by additional research about simultaneous effects of radiation and actual temperatures.

3.4 Humidity

There are two concerns associated with wet conditions. One is moisture in the vicinity of connections where conditions for corrosion of terminations is possible. Damp terminal blocks may also be subject to surface tracking that can lead to the failure of connections in damp areas. The second concern is long-term wetting of cables as could occur in underground applications. The duct/manhole system containing low and medium voltage power cables was reviewed, and long-term wetting of cable in adverse condition was determined. A conservative approach assumed that underground cables are wet. Underground systems have been designed to be drained naturally, with sloped ducts towards manholes structures, assuring cables are not submerged most of the operating time. Cables mounted on the trays and walls and not subject to wetting along their length are considered dry. Man holes are checked monthly, and water is pumped as needed to prevent the submergence of cables. Periodic exposures to moisture lasting less than a few days (i.e. normal rain and drain) are not significant. Significant voltage exposure is defined as exposed to system voltage for more than 25% of the time. Potentially wet cables are not energized for more than 25% of the time have a low likelihood of sustaining water-related degradation. As long as the continuously energized cables remain healthy, there is little concern that the normally de-energized cables have degraded. Conservatively, more than 75% relative humidity is calculated in the risk-ranking contribution.

3.5 Chemical

Most cables are not subject to contamination with oil or chemicals. Areas containing borates or other chemicals are inspected for being in touch with cables. With respect to borates, deterioration of exposed terminations is more of a concern than jacket/insulation deterioration.

Contamination with oil, in general, is more related to a spill. Cables subjected to oil contamination should be cleaned and evaluated for any effects on longevity around the turbine and large, oiled pumps.

Some traces of mineral oils were found in special sealants on a tray to a conduit that might affect the Hypalone jacket with softening and swallowing effects. Tests were conducted at different laboratories with no evidence on primary insulation confirmed. Visual inspection is planned for specific locations with repair and replacement as needed.

3.6 Ohmic Heating

Current in the conductor of power cable causes raised temperatures due to ohmic heating, mainly at connections. The power circuits loading current are checked. If the normal conservatism measures were applied during design, cables were applied with no more than 80% ampacity. The given temperature rise is proportional to the square of the current, 80% ampacity should result in 64% of the allowed temperature rise. In the case of a 90 °C cable in a 40 °C environment, the rise at 80% ampacity should be approximately 32 °C; the conductor temperature would thus be 72 °C.

Ohmic heating should be considered in conjunction with identified adverse thermal conditions in rooms especially if the ambient temperature coupled with the conductor rise results in temperatures approaching the rated temperature of the cable.

There are more approaches to evaluate the ohmic heating-induced aging of polymers or connections:

- Tests were conducted for different materials and resulting in a realistic calculated additional 14 °C to 17 °C temperature rise due to ohmic heating depending on material type, *[9]*.
- MV cables high electrical fields could impact impurities and voids in insulation, resulting in partial discharge as microscopic arcs leading to electrical trees resulting in dielectric failure or insulation breakdown. We start to use partial discharge testing.
- Infrared camera - Any temperature difference above reference (dT) is a concern. Table 2 provides suggested severity ranges for evaluating electrical power connections.

***Table 2:** Suggested Severity Ranges for Indoor Electrical Power Connections, [1]*

Status	Range
Advisory	0.5 °C to 8°C Rise Above Reference
Intermediate	9 °C to 28 °C Rise Above Reference
Serious	29 °C to 56 °C Rise Above Reference
Critical	> 56 °C Rise Above Reference

3.7 On-Site Mechanical Test of Tensile Strength - Indenter Modulus

For the on-site mechanical test, evaluation of tensile strength (hardness), the Indenter Modulus (IM) testing method was implemented, and acceptance criteria developed[6]. This method, shown in Figure 4-a), uses a small-diameter probe (anvil) to press against a cable. The force needed to compress the polymer jacket to a limited, defined extent is measured. The force F used and the displacement X are plotted against each other as shown in Figure 4-b). The indenter modulus of the material is the slope of the line relating the change in force ΔF to the change in deformation ΔX.

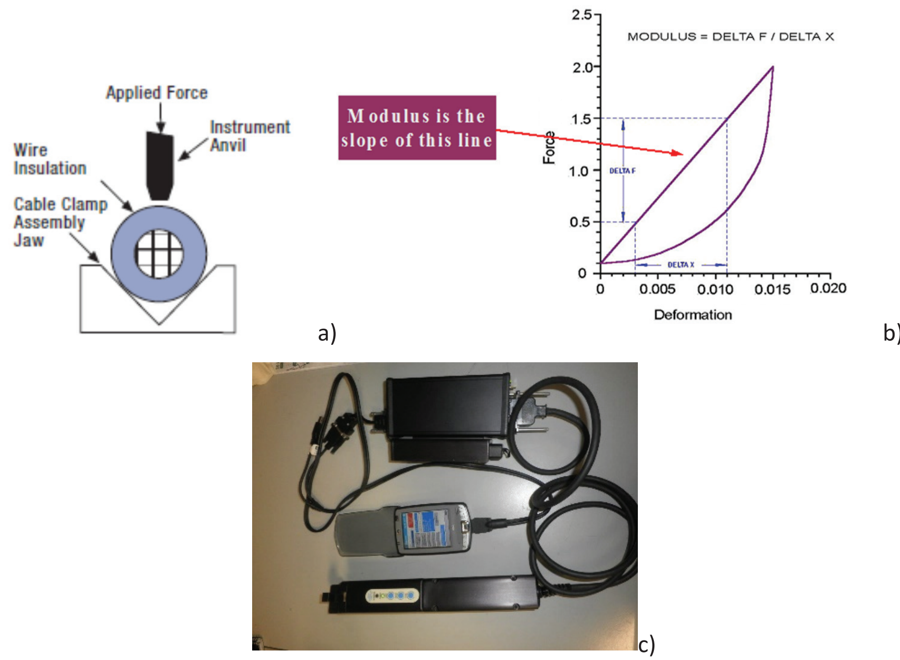

***Figure 4:** Indenter Modulus Testing Equipment and functionality description, [6]*

Criteria were developed on 21 samples of cables from a warehouse and aged in an oven at 120°C for 9 different time stages; some visual aging results are shown in Figure 5, *[6]*:

- Sample #1 new cable: Indenter modulus measured from 10 to 13 N/mm NEW
- Sample #2 (72 h) and #3 (144 h): Modulus: 10-13 N/mm; no aging effects: OK
- Sample #4 (240 h) and #5 (360 h): 11-17 N/mm and 14-20 N/mm TRENDING

- Sample #6 (528 h): 85-118N/mm and #7 (1032 h): 151-206 /mm End of Life (EOL)-R&R
- Sample #8 (1872 h): 170-250N/mm and #9 (3264 h): 227-283N/mm EOL- Replace

Samples are used for training for visual inspection and acceptance criteria development for the IM of different materials. For jacket material CSPE (in all SR cables) three stages: up to 15 N/mm NEW material; from 16-80 N/mm initial degradation of jacket, insulation OK; 3 year – TRENDING; more than 80 N/mm End Of Life reached: Repair or Replace (R&R): Cable Jacket hardened and can crack; insulation possibly damaged.

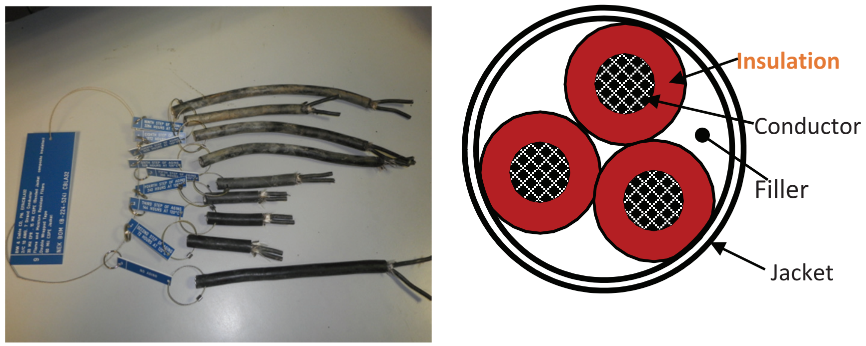

***Figure 5**: Samples of 9 stages Owen Aged Control Cable (BIW 7C#14 AWG), [6], and description of cable jacket and insulation layers*

3.8 On-Site Electrical Tests

Evaluation of electrical properties is done using different testing methods depending on cable type and voltage (LV/MV). Some of the most useful techniques, with comparison in Table 3:

- Insulation resistance IR (R_{iz} > 2-100 MΩ) and polarisation index (PI=IR10'/IR1'<1,5)
- Connection Resistance (R<0,1 Ω); voltage drop at 100A (dU>0.1V deviation, asymmetry)
- Capacity (nF-pF)
- Dielectric Losses, tan δ using Power Frequency-50Hz or Very Low-Frequency VLF-0,1Hz (Acceptance criteria for EPR: tan δ<0,015 and XLPE: tan δ < 0,0015; Constant At Voltage Rise). Figure 6 compares both testing equipment.
- Partial Discharges, PD (as low as possible PD LAB<5pC and PD industry<500 pC for EPR)
- Time/Frequency Domain Reflectometry (TDR/FDR)
- Impedance, line impedance resonance analyse (LIRA)

***Table 3:** Comparison of available cable inspection technique, [4]*

Inspection Method	Advantages	Disadvantages
Time-Frequency Domain Reflectometry (TDR and FDR)	Commonly used for the condition of inaccessible instrumentation, control and power cables.	Currently intrusive, requires disconnecting the cables to install instrumentation.
Insulation Resistance	Commonly performed in industry to determine the condition of the cable insulation.	Currently intrusive, requires disconnecting the cables to install instrumentation.
Inductance/Capacitance/ Resistance (LCR)	Good for detecting changes in cable and terminations by trending changes in inductance, capacitance and resistance.	Currently intrusive, requires disconnecting the cable at one end. Does not indicate location or cause of change in measurement.
Tan Delta (Tan δ)	Determines changes in insulation (dielectric) properties by measuring change in dielectric loss angle. Can measure aging effects over entire cable length.	Intrusive, requires disconnecting the cables at both ends. Single number from long cable makes isolating location of aging section difficult. Loss angle may be trended but single test insufficient to estimate remaining life.
Partial Discharge	Good in determining voids and defects in insulators of medium voltage cables.	Test can damage insulator with localized heating that causes degradation.
Line Impedance Resonance Analyse (LIRA)	Indicate location of change in measurement.	A lot of data setup and interpretation knowledge.

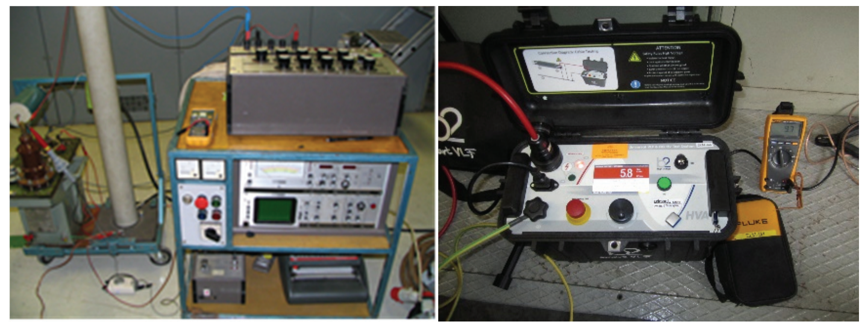

***Figure 6:** Tan δ testing equipment with 50Hz (left) and 0.1Hz frequency*

3.9 Laboratory Testing Methods

Different methods are available for the laboratory testing of mechanical or chemical properties. The basic difference between methods is in the size of samples needed for the test (large=few m of cable insulation/small=few mg). This chapter gives a short overview of a few basic laboratory tests.

3.9.1 Elongation at Break (EaB)

Elongation at break is the ratio between changed length and initial length after breakage of the test specimen. The elongation at break defined by the EN ISO 527 standardized method for tensile mechanical properties of the polymer, used for End of Life (EoL) prediction, with known and predefined acceptance criteria for different materials (i.e. 300% for new cable and 50% for EoL).

Figure 7: *Testing equipment for EaB*

3.9.2 DSC Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry (DSC) is a technique that is especially useful for the characterization of semi-crystalline polymer systems. DSC measures the flow of heat in and out of test samples over time as a function of sample temperature. Features in a DSC curve include phase change transitions. As illustrated in the DSC curve of different polymer materials in Figures 8, 9 and 10, [9], heat flows into a sample with rising temperature to effect endothermic transitions including the transition from solid to a glassy state, the glass transition, and from a glassy solid to a melted liquid. Heat is also consumed in the evaporation of volatile compounds, such as added processing aids. In a semi-crystalline polymer, it is the material in the crystalline regions that undergoes a distinct melting transition. The integral of the melting peak in the DSC curve is thus a direct measure of the crystalline content of the system. The shape of the DSC curve, including the location of glass transition, is also related to chain scission and cross-linking that the polymer may have experienced.

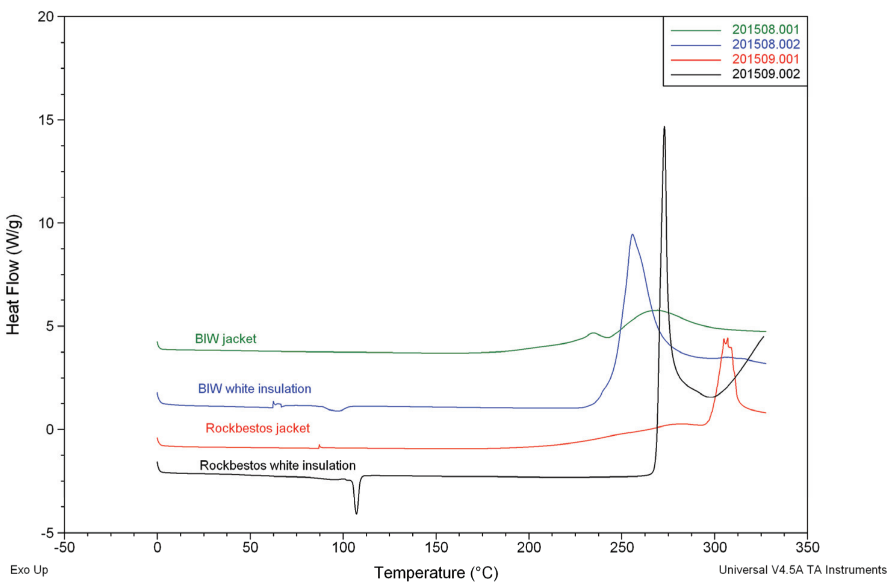

Figure 8: Dynamic method specific signature for insulation and jacket materials [9]

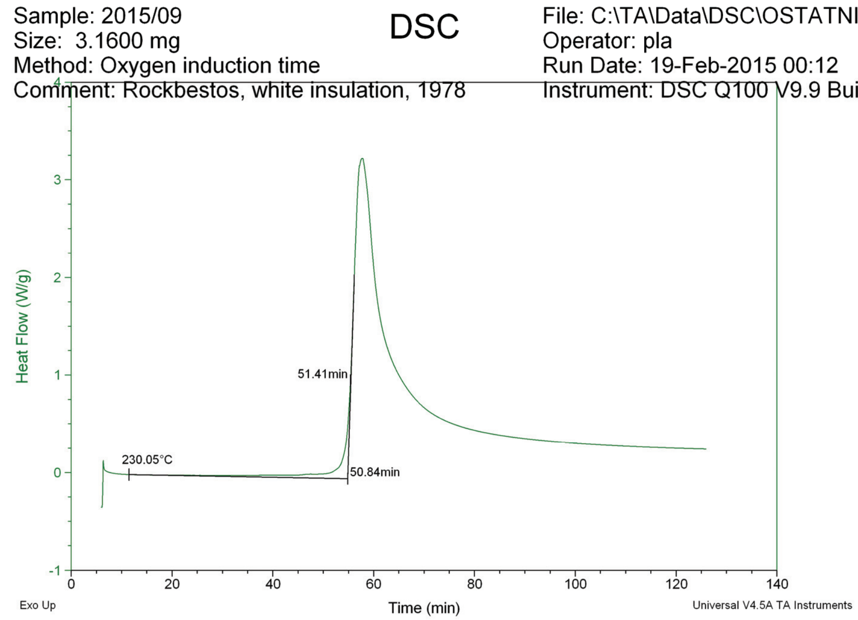

Figure 9: *Detailed analysis of results static method T=constant, [9]*

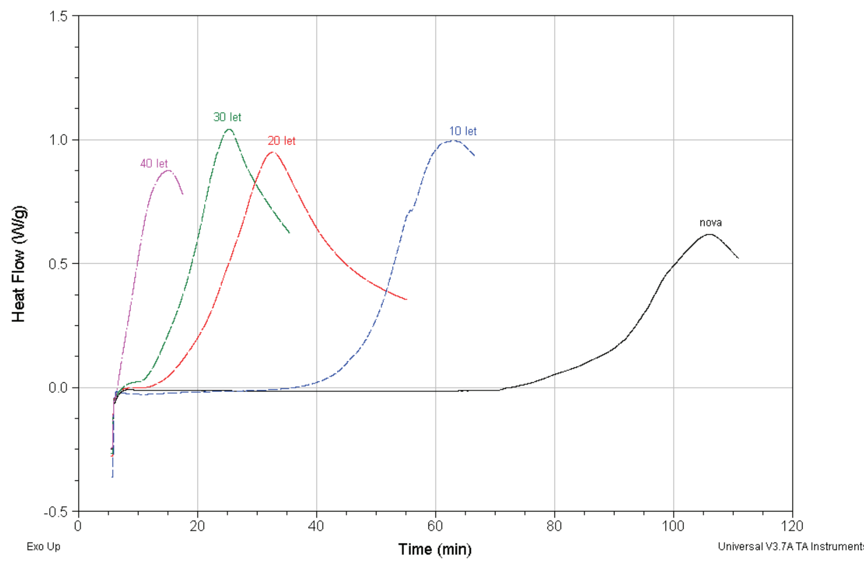

Figure 10: *DSC Heat Flow of different aged cables [9]*

3.9.3 Fourier Transform Infrared Spectroscopy (FTIR)

Oxidation and crosslinking of cable insulation polymers, such as EPR and XLPE, inherently introduce new chemical bonds within the material, including C=O carbonyl and C=C carbon bonds that have unique vibrational frequencies. A convenient method, therefore, for characterization of related polymer degradation is FTIR spectroscopy. The FTIR spectrum is shown in absolute values for different wavenumbers.

3.9.4 Thermogravimetric Analysis (TGA)

In thermogravimetric analysis (TGA), the mass of a sample is monitored as a function of temperature and time. The experiment may be performed under inert, reactive, or oxidizing atmospheres, and the TGA may be combined with a mass spectrometer to detect mass fragments of species volatilized during sample heating. Mass loss with heating can reveal copolymer ratio, moisture content, volatile additive content, and inorganic filler content. The decomposition behaviour of polymer samples at higher temperatures can also reveal information regarding the extent of chain scission and cross-linking in the polymer. Thermal decomposition in the TGA experiment may be a useful measure of the relative degradation and history of polymer samples.

4. DIAGNOSTIC TESTING RESULTS

Using all of the described onsite diagnostic methods, different tests were conducted and many results collected. After 6 years of CAMP implementation, we can summarize the results in Table 4 as follows *[5]*, *[7]*, *[8]*. We can summarize the most valuable techniques in visual inspection with temperature monitoring and IM hardness test. Among the electrical tests, tan δ and new LIRA give the best results with most deficiencies found.

Table 4: *Number of tests/findings/deficiencies (red) by diagnostic method [10]*

Diagnostic method / Cable type	Insulation resistance (IR)	Dielectric loss (tan δ)	LIRA	Partial discharge (PD)	Visual inspection	Humidity	Temperature (T)	Radiation	Indenter (IM)
MV(10 kV)	55/2	55/5	2/2	30/3	55/7	55/25/5	55/3	8/4/2	8/0
LV-P,C,I (<1000 V)	130/4	0	6/6	0	240/60/15	120/25/2	240/45/12	120/15/4	45/12

All cable areas were reviewed in buildings, and more than 45 temperature hot spots were considered and actions taken. Actions with rerouting cable from the hot spot and repair or replace as needed. More than 60 cables were rerouted and not in one had insulation failed but only the outer jacket; 12 cables were replaced due to jacket hardening/cracking.

In a 2015 outage, containment temperature and radiation adverse environment identification was finished after three years. Temperature data loggers (55) and alanine pellets for gamma radiation (50) and neutron detectors (5) near cable routes were analysed. Six hot spots were identified: 2 for temperature and 4 for radiation will be considered in the future.

As a standardized test, insulation resistance (IR) or the Megger test does not give very useful results, finding mainly severely damaged, failed cables: 3 LV power cables failure found dueto mechanical damage in the tray (all triplex power cables without jacket) shown on Figure 11 and c) one N1E underground failure in the splice.

a) 2005 b) 2015 c) 2016

Figure 11: *Failures of LV power cables found with IR test*

A total of 55 MV cables were tested with 5 findings in trending criteria for tan δ results (all underground with accessories – connections and splices).

The only qualified cable trending results for the last three tests conducted in 2012, 2013 and 2015 on Figure 12 do not show significant changes from lower trending limits (same for both testing methods: power frequency and VLF). Tape splices are most contributing factor of higher tan δ results.

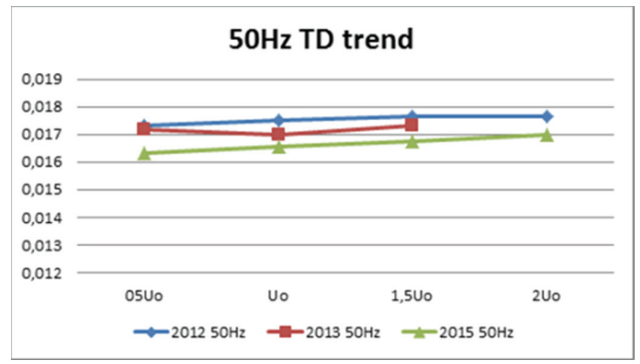

Figure 12: Trending results for tan δ at power frequency 50Hz

The explanation of lowering trend results in recent years, was a fact, the underground trenches (manholes) are keeping dry all the time for the last 6 years as much is possible. Preventive maintenance activities are conducted regularly, twice per month inspections and water pumping as needed before water reaches level of 0,2m. Trended cable with splice connections are in trays, raised from manhole floor for more than 1m.

Non-qualified Medium voltage (MV) cable N1E with XLPE insulation found bad connection at termination on Figure 13.

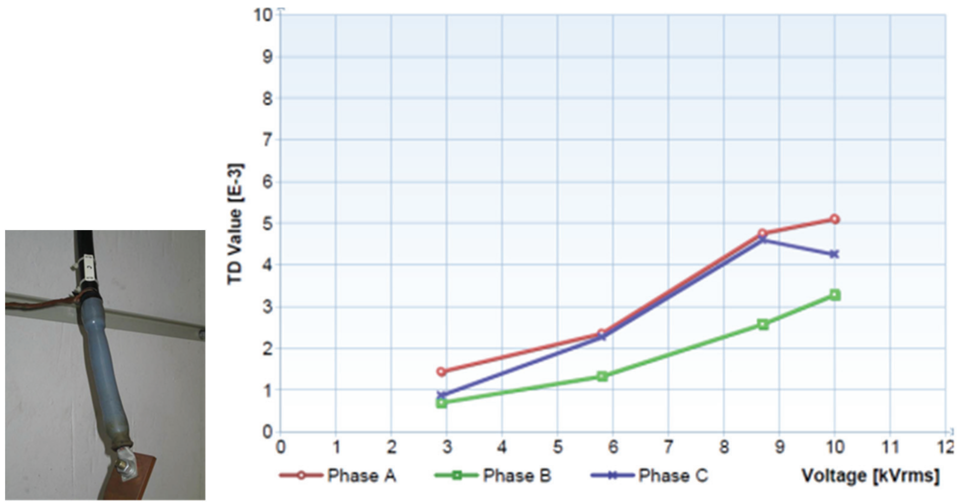

Figure 13: *Found deficiency on XLPE cable connection with diagnostic test*

Time Domain Reflectometry (TDR) signature results of primary cycle temperature detector cables in Figure 14..

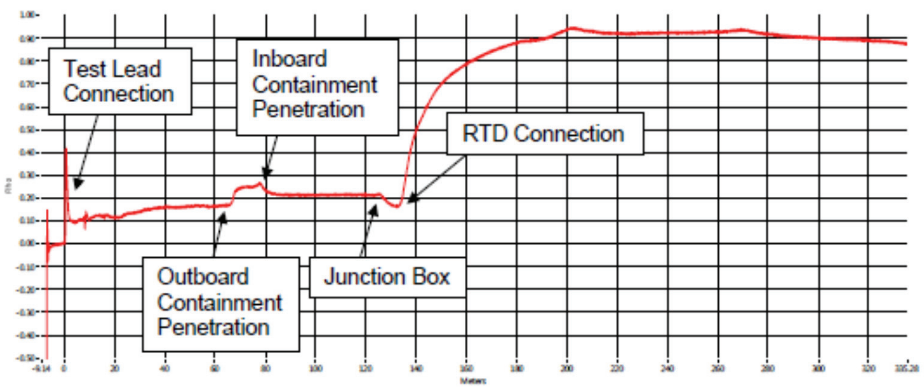

Figure 14: *TDR test plot with route configuration description, [9]*

Method is usable mainly as comparison signatures of aged cable with same new cable plot. Other possibility is to compare same type of cables routed in exact same configuration (conduit or tray). In any case, initial tests of new routed cables have to be plotted to have baseline for comparison to track any age related deviation in insulation or connection

MV cable partial discharge test results in Figure 15.

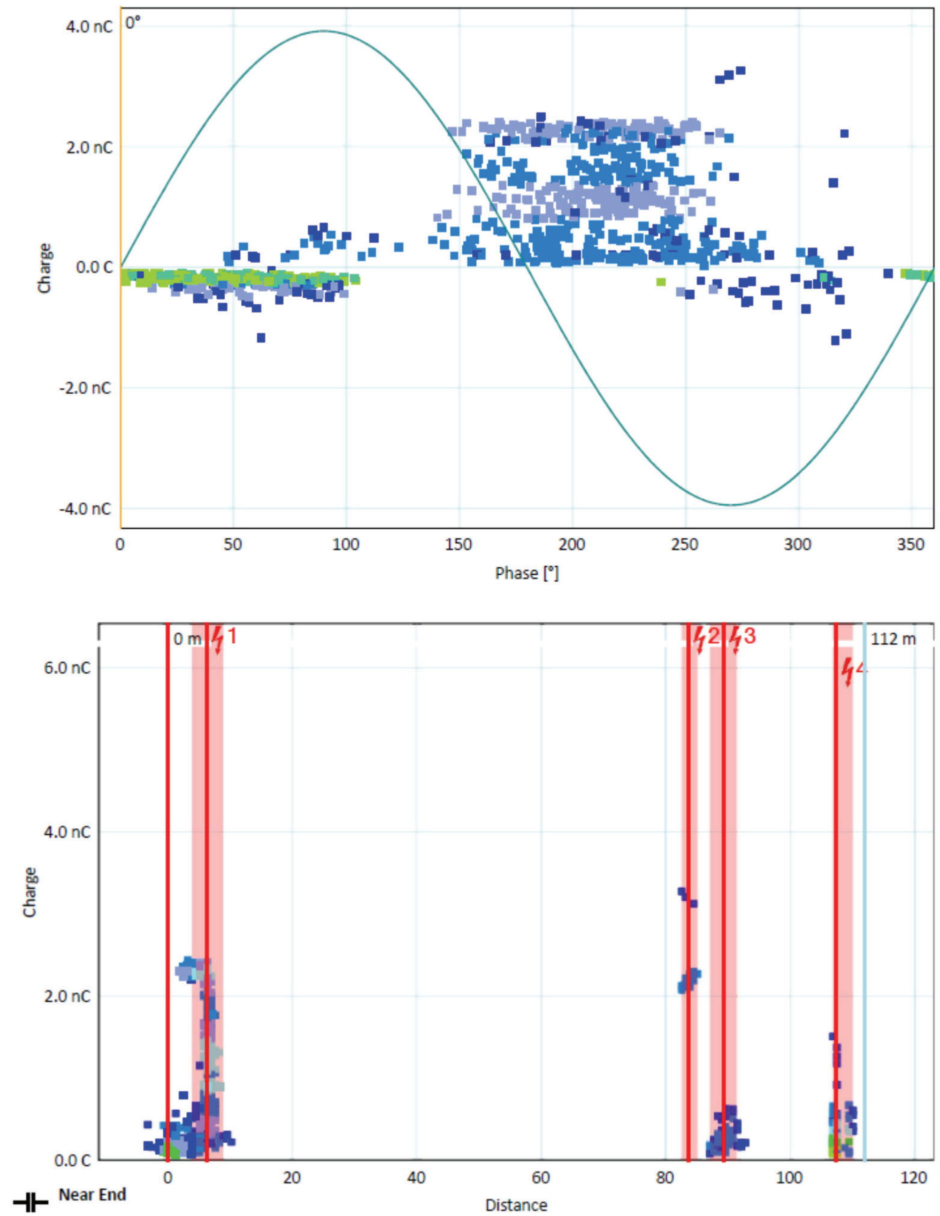

Figure 15: Significant PD events: XLPE cable failure at 5 m from cable near end

Line Impedance Resonance Analysis (LIRA) testing of 8 cables resulted in 8 findings and deviations: 3 on field cables and 5 at the instrument testing with the known location of cable damage (short circuit, bad connection, cut in insulation, local burned insulation). In Figure 16, a Spot Signature (dB) is shown with deficiencies at two locations. The short circuit in Figure 11-c) was found 30 m from cable end that is marked in left peak on Figure 16, second was indentation.

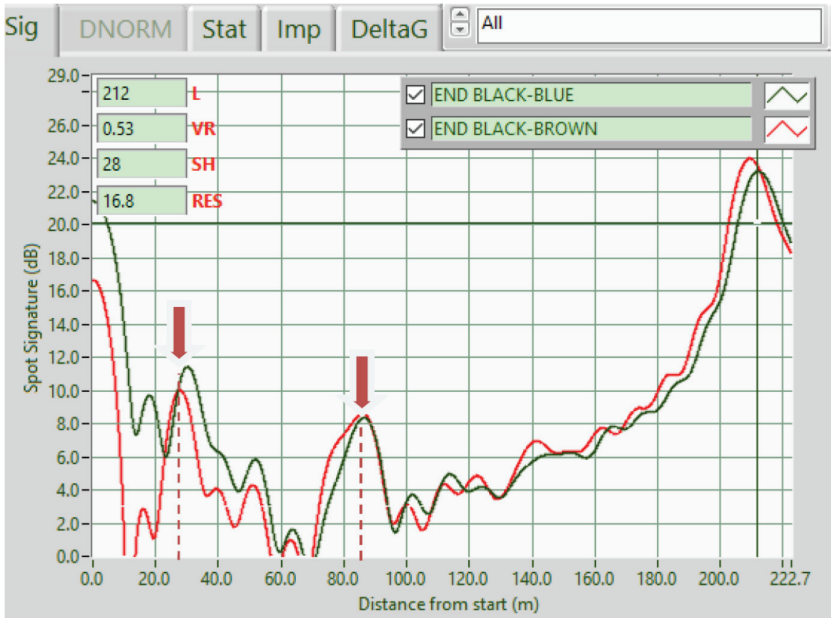

Figure 16: LIRA located two deviations on LV cable insulation, [10]

5 CONCLUSION

CAMP has been in the implementation phase for the last 6 years. Diagnostic testing results are promising and trending with immediate actions taken as needed. The most useful and promising on-site testing methods in NEK are an infrared camera, hardness test-Indenter Modulus, dielectric Losses- tan δ and LIRA.

Laboratory testing has not been required nor implemented at a larger scale. It will be used only in some specific examples for additional evaluation of specific effects that might be found in the future.

Additional diagnostic on site and laboratory tests will aid in residual life-time prediction and risk ranking according to deviations between qualification test methods and real environmental conditions including simultaneous aging effects of radiation, temperature, humidity, chemical environment, and mechanical load. Additional testing would also help to control functionality and possible different failure mechanisms, such as LOCA testing condition in a low oxygen atmosphere or inverse temperature effect including Arrhenius calculation for temperature calculation with activation energy (E_a) as temperature dependant, where a small difference in material constant yields significant change (10% change results in double residual life-time), [3].

Program health report and risk-ranking tools are in the development phase and are planned to be implemented after a testing period in 2016.

References

[1] **M. Pirc**, *Cable Aging Management Program*, TD-2D, rev.1, NEK, 2011

[2] NUREG-1801, *Generic Aging Lessons Learned (GALL)*, rev.2, U.S. NRC, 2010

[3] NP-T-3.6, *Assessing and Managing Cable Ageing in Nuclear Power Plants*, IAEA, 2012

[4] **K. L. Simmons,** *Determining Remaining Useful Life of Aging Cables in Nuclear Power Plants – Interim Study FY13*, PNNL for US DOE, September 2013

[5] **M. Pirc**, *Vzpostavljanje programa nadzora staranja električnih kablov NEK*, CIGRE, 2011

[6] **M. Pirc**, HS-2011-02-T-IM: *Development of acceptance criteria for Indenter Modulus*, NEK, 2011

[7] **M. Pirc**, *Diagnostična testiranja električnih kablov v NEK*, CIGRE, 2013

[8] **M. Pirc**, *Rezultati diagnostičnih testiranj kablov v NEK*, CIGRE, 2015

[9] *Testing reports in scope of work orders and internal NEK database*

[10] **M. Pirc**, *Cable Aging Management Program Implementation in NEK*, HND, 2016

Nomenclature

(Symbols)	(Symbol meaning)
NEK	Nuklearna elekrarna Krško
CAMP	Cable Aging Management Program
SR	Safety Related, Nuclear Qualified (1E)
LOCA	Loss Of Coolant Accident
MV	Medium Voltage (6,3kV or 10kV)
LV	Low Voltage (up to 1000 V); P - power; C - control; I - instrument
EPR	Ethylene Propylene Rubber (EPDM)
XLPE	Cross-Linked Polyethylene
CSPE	Chlorosulfonated Polyethylene (Hypalone®)
TD	Tan δ, Dielectric Losses
PD	Partial Discharge
IR	Insulation Resistance
LIRA	Line Impedance Resonance Analyse
TDR	Time Domain Reflectometry
E_a	Activation Energy
IM	Indenter Modulus
EoL	End Of Life

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Chapter examples:

1 MAIN CHAPTER

(Arial bold, 12pt, after paragraph 6pt space)

1.1 Section

(Arial bold, 11pt, after paragraph 6pt space)

1.1.1 Sub-section

(Arial bold, 10pt, after paragraph 6pt space)

Example of Equation (lined 2 cm from left margin, equation number in normal brackets (section. equation number), lined right margin, paragraph space 6pt before in after line):

Equation (1.1)

Tables should have a legend that includes the title of the table at the top of the table. Each table should be cited in the text.

Table legend example:

Table 1: *Name of the table (centred, on top of the table)*

Figures and images should be labelled sequentially numbered (Arabic numbers) and cited in the text – Fig.1 or Figure 1. The legend should be below the image, picture, photo or drawing.

Figure legend example:

Figure 1: *Name of the figure (centred, on bottom of figure, photo, or drawing)*

References

[1] **N. Surname:** Title, Publisher or Journal Title, Vol., Iss., p.p., Year of Publication

Examples:

[2] **J. Usenik:** Mathematical model of the power supply system control, Journal of Energy Technology, Vol. 2, Iss. 3, p.p. 29 – 46, 2009

[3] **J.J. DiStefano, A.R. Stubberud, I.J.Williams:** Theory and Problems of Feedback and Control Systems, McGraw-Hill Book Company, 1987

Example of reference-1 citation: In text [1], text continue.

Nomenclature

(Symbols)	(Symbol meaning)
t	time

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