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ANALYSIS OF DATA COLLECTED AT CONTROL ROOM FULL SCOPE SIMULATOR AT DUKOVANY NUCLEAR POWER PLANT

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Research article

Abstract: This article describes a computer program that will be used by experts to analyze human factor reliability when analyzing data obtained during the training of operators on a nuclear power plant's control room simulator. The program was applied to data collected during the training of a scenario called Rupture of the Hot Loop of the Primary Circuit (250 t/h). Based on the comparison of charts, temporal passage through the scenario, or by personal participation in the training, analysts evaluate the successful passing of the practice scenario and propose final recommendations. The article also describes the criteria for successfully passing the practiced scenario and its final evaluation.

Keywords: Nuclear power plant, control room, operator, simulators, human performance.

Introduction

One of the most important issues in the operation of nuclear power plants is safety. The Probabilistic Safety Assessment (PSA) is a systematic and comprehensive assessment of nuclear facilities. An important contributor to the overall risk of nuclear power plants is the human factor. To assess human impact on the safety of nuclear facilities, the Human Reliability Analysis (HRA) is used within the PSA. The aim of the HRA analysis is to identify all possible human failures and determine their probability. Based on a detailed analysis, specialists determine the measures that lead to increased safety of the operation of nuclear power plants.

The content of this article is a description of the computer program and its use for the improvement of human factor reliability analysis within the probability assessment of nuclear power plant safety, for feedback in the training of the control room operators, and for the improvement of emergency operating procedures used by control room operators of the nuclear power plant.

There are currently a number of projects in the world that are focused on improving HRA methods and creating databases supporting HRA.

The Nuclear Energy Agency (NEA) is an intergovernmental agency that facilitates cooperation among countries with advanced nuclear technology infrastructures to seek excellence in nuclear safety, technology, science, environment, and law. The NEA, which is under the framework of the Organisation for Economic Co-operation and Development, is headquartered in Paris, France.

The NEA maintains seven specialised standing technical committees representing the major areas of the Agency's programme, each of which oversees various specialised working groups and task groups. These groups are comprised of member country experts who are both contributors to the programme of work and beneficiaries of its results. For example: Committee on the Safety of Nuclear Installations (CSNI), Committee on Nuclear Regulatory Activities (CNRA). (The Nuclear Energy Agency)

The International Atomic Energy Agency is the world's central intergovernmental forum for scientific and technical co-operation in the nuclear field. It works for the safe, secure and peaceful uses of nuclear science and technology, contributing to international peace and security and the United Nations' Sustainable Development Goals. (Overview)

The Scenario Authoring, Characterization, and Debriefing Application (SACADA) database was developed by the U.S. Nuclear Regulatory Commission (NRC) for collecting operator performance data in simulator training for HRA.

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While most of the technical underpinnings (e.g. guidelines and taxonomies) are developed by a bottom-up approach (i.e., the intensive review of existing literature), SACADA taxonomy is constructed on the basis of a cognitive model (i.e., a top-down approach). Certain human performance information that can be provided by SACADA data provided are difficult to be covered by the bottom-up approach. (Park et al., 2017)

U.S. Nuclear Regulatory Commission proposed an approach for collecting human performance data from nuclear power plant (NPP) simulators. The information collected is constrained by the uniqueness of each particular plant and design of each particular simulator study. The process of simulator data collection can be described in four main phases:

- preparation,
- data collection,
- data analysis,
- reporting. (Hallbert et al., 2014)

An important example of international cooperation for the safe and reliable operation of nuclear power plants is the OECD Halden Reactor Project. The Halden Reactor Project is performed and managed by the Institute for Energy Technology in Norway and is the largest NEA joint project. Project is supported by more than 130 organisations in 19 countries. The programme of work is in general split into two areas:

- The Fuel and Materials programme,
- The man, technology and organisation programme. (NEA Halden Reactor Project)

Korea Atomic Energy Research Institute (KAERI) is performed/ing a number of research activities to support an HRA. KAERI developed a standardized HRA method called K-HRA, for the PSAs of NPPs in Korea. A modified K-HRA method, HuRECA (Human Reliability Evaluator for Control Actions), was developed to support the HRA for a new nuclear power plant that has fully digitalized human system interfaces in a main control room.

KAERI also has carried out research to collect data of human performance and reliability from simulators and event reports for HRA in Korea. KAERI's research on HRA database can be divided into two phases:

- collecting and storing data in a OPERA (Operator erformance and Reliability Analysis) database,
- designing framework of data collection for HRA called HuREX (Human Reliability data Extraction).

Another major activity of KAERI is a pilot HRA study for advanced main control room with digital human system interfaces. (Jung et al., 2016)

The Czech Republic is represented in international projects mainly by ÚJV Řež, a.s. (Nuclear Research Institute) and the State Office for Nuclear Safety.

ÚJV Řež, a.s., is a technical-engineering and research organization. ÚJV Řež focuses on research and development, design and engineering services, technical engineering, the manufacturing of special products and equipment, and expert activities in the fields of energy, industry and health. ÚJV Řež is intensively involved in international projects, e.g. within the The International Atomic Energy Agency and OECD/NEA, in projects supported by the European Commission. (Research and Development at ČEZ)

Materials and methods

Nuclear power plant Dukovany

Data collection for analysis was conducted during the training of operators of the control room of Nuclear Power Plant Dukovany (hereinafter Dukovany NPP) (see Fig. 1).

Fig. 1 Nuclear Power Plant Dukovany

Periodic training on a full-scope simulator of the control room was attended by 31 operating crews in the simulator run relevant to the data collection project described in this article. To maintain anonymity, the crew identification number is encrypted. All training participants have a valid license for the given function and mostly consist of the crew of one control room. Each practiced task is assigned a unique one-word code mark and an explanatory text description. (Kubíček and Dedera, 2011)

A full-scope control room replica-type simulator (see Fig. 2) developed by ORGREZ SC, a.s. Brno in co-operation with the American company GSE

Systems is used for the training of operators. (Technology and safety)

Fig. 2 Control room

Data collection

Data is recorded using a collection module in csv files and the separator is a semicolon, which makes it easy to open in Microsoft Excel.

Simulator data is recorded in two ways:

- periodically - the values are archived every second for the entire set of parameters (315 items),
- change - to record the status of actuators, signaling and interventions of the operator that do not change in the long-term. (Kubíček and Dedera, 2011)

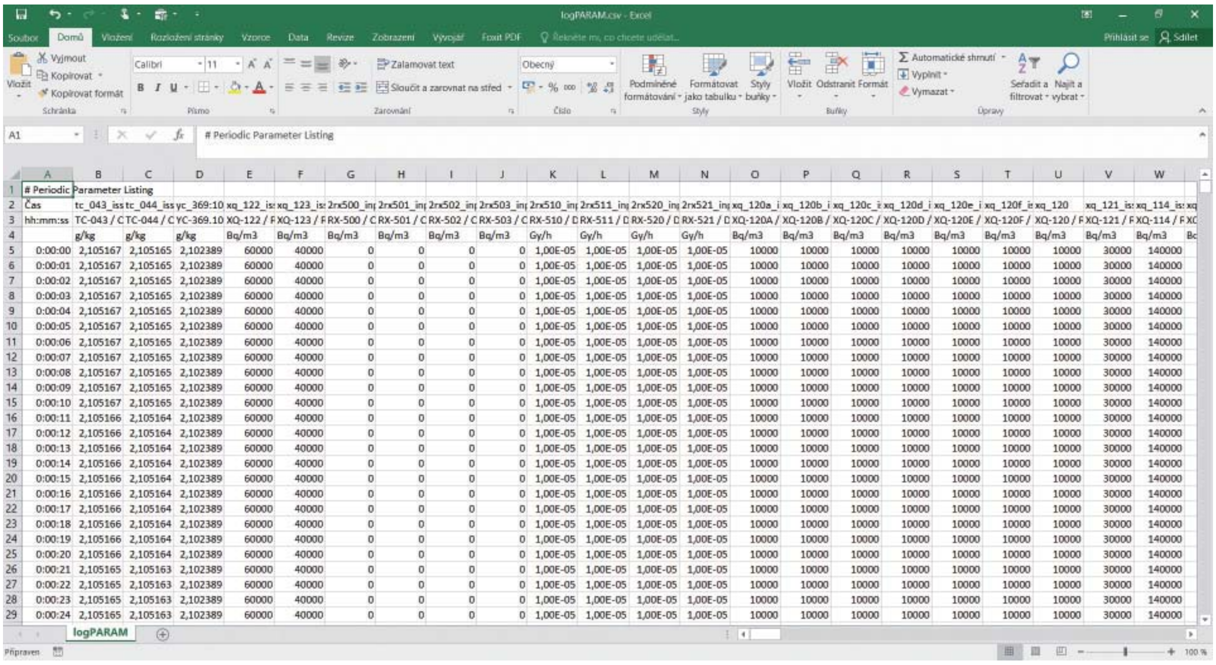
Data files

The time, identifier of the archived variable, and its value at the given time are recorded in the data files. To ensure the comprehensibility of the record, it is supplemented with a textual description of the given variable, and for the discrete values of variables also with the meaning of the given value.

The computer program works with the data stored in the Periodic Parameter Listing. In this file, the selected quantities characterizing the status of the reactor are saved. The header contains the identifier of the archived variable, the meaning of the value, and the physical unit. It is followed by a listing of the values of all the variables at a given time, as shown in Fig. 3. (Kubíček and Dedera, 2011)

Other examples of data files are:

- Task description file - contains a task code, an explanatory text description, encrypted crew identification number.
- Operator intervention file - contains recorded manipulations of the control keys, switches and buttons in the control room, as well as commands entered via the touch screen of the turbine software control system.
- Change of actuator status file - contains moments of valve status changes (Closed-Opening-Paused-Open-Closing), pumps and fans (On-Off).
- Instructor intervention file - records the instructor's actions affecting the course of the task (entering a state simulating the occurrence of a technological failure, executing the requested manipulation on components unavailable from the control room, etc.).
- Fault and technological signaling tableau status changes file.



A1: # Periodic Parameter Listing

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	# Periodic Parameter Listing																							
2	Čas	tc_043_iss	tc_044_iss	yc_369:10	xq_122_is:	xq_123_is:	2rx500_in	2rx501_in	2rx502_in	2rx503_in	2rx510_in	2rx511_in	2rx520_in	2rx521_in	xq_120a_i	xq_120b_i	xq_120c_i	xq_120d_i	xq_120e_i	xq_120f_i	xq_120	xq_121_is:	xq_114_is:	xq
3	hh:mm:ss	TC-043 / C	TC-044 / C	YC-369.10	XQ-122 / F	XQ-123 / F	RX-500 / C	RX-501 / C	RX-502 / C	RX-503 / C	RX-510 / D	RX-511 / D	RX-520 / D	RX-521 / D	XQ-120A /	XQ-120B /	XQ-120C /	XQ-120D /	XQ-120E /	XQ-120F /	XQ-120 / F	XQ-121 / F	XQ-114 / F	XC
4		g/kg	g/kg	g/kg	Bq/m3	Bq/m3	Bq/m3	Bq/m3	Bq/m3	Bq/m3	Gy/h	Gy/h	Gy/h	Gy/h	Bq/m3	Bq/m3	Bq/m3	Bq/m3	Bq/m3	Bq/m3	Bq/m3	Bq/m3	Bq/m3	Bc
5	0:00:00	2,105167	2,105165	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
6	0:00:01	2,105167	2,105165	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
7	0:00:02	2,105167	2,105165	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
8	0:00:03	2,105167	2,105165	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
9	0:00:04	2,105167	2,105165	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
10	0:00:05	2,105167	2,105165	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
11	0:00:06	2,105167	2,105165	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
12	0:00:07	2,105167	2,105165	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
13	0:00:08	2,105167	2,105165	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
14	0:00:09	2,105167	2,105165	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
15	0:00:10	2,105167	2,105165	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
16	0:00:11	2,105166	2,105164	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
17	0:00:12	2,105166	2,105164	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
18	0:00:13	2,105166	2,105164	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
19	0:00:14	2,105166	2,105164	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
20	0:00:15	2,105166	2,105164	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
21	0:00:16	2,105166	2,105164	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
22	0:00:17	2,105166	2,105164	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
23	0:00:18	2,105166	2,105164	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
24	0:00:19	2,105166	2,105164	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
25	0:00:20	2,105166	2,105164	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
26	0:00:21	2,105165	2,105163	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
27	0:00:22	2,105165	2,105163	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
28	0:00:23	2,105165	2,105163	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	
29	0:00:24	2,105165	2,105163	2,102389	60000	40000	0	0	0	0	1,00E-05	1,00E-05	1,00E-05	1,00E-05	10000	10000	10000	10000	10000	10000	10000	30000	140000	

Fig. 3 Periodic Parameter Listing

- Reactor control signaling system status changes file. (Kubíček and Dedera, 2011)

Description of the practiced scenario

To analyze training data on the control room simulator, the task " Rupture of the Hot Loop of the Primary Circuit (250 t/h)" was selected from the task bank. This task is included in thematic unit 3 - abnormal and emergency scenarios. In particular, the use of operating procedure P003a - Emergency Operating Procedures (EOPs) is practiced here. The purpose of this procedure is to provide instructions for restoring a safe status of the unit by means of specific procedures in the event of any situation leading to the need for a quick shutdown of the reactor. These procedures cover a wide range of events, ranging from a simple shutdown of the reactor (by the reactor trip system (RTS)) through project emergencies to some beyond design basis accidents. This part of P003a prescribes to the operators the activity necessary to solve such transition processes during which the RTS system functions automatically or manually or activation of ESFAS (Engineered Safety Features Actuation Systems) occurs. (Task bank)

The general objectives of the training are to acquire or improve the ability of participants to organize and perform activities leading to the removal of an emergency state of the reactor, especially using operating procedure P003. Furthermore, to enhance the ability of participants to communicate correctly, use operational documentation correctly, and observe the operation and equipment control policies in Dukovany NPP in accordance with applicable work practices and methodology. (Task bank)

Basic description of the scenario

The control room crew will initiate the solving of the task according to operating procedure P003. The condition for entering the E-0 procedure is the automatic incorporation of RTS HO-1, that is, the manual shutdown of the reactor with the HO-1 emergency response button.

The important points of the process of solving the task are (transitions between procedures, regulations, or important decision-making steps):

- Assessment of leakage from the Primary Circuit (P.C.) into the steam generator boxes and the incorporation of RTS (using the button) HO-1,
- Incorporation of ESFAS "Small leakage", "Moderate leakage" - activity of emergency systems,
- P003a, E-0 step no. 20 - the possibility of reducing the number of operating high pressure emergency core cooling system (ECCS) pumps,
- E-0 step no. 29 - leaking P.C. - transition to E-1,
- E-1 step no. 10 - need to cool and depressurize the P.C. - transition to ES-1.2,
- ES-1.2 - cooling and depressurization of the P.C., gradual shutdown of high pressure ECCS pumps.

The task ends after cooling the P.C. below 165 °C and the shutdown of the last high pressure ECCS pump. (Task bank)

Objectives of the training and success criteria

The main objective of the training is to enable the crew, in accordance with operating procedures, to:

- diagnose leakage from the primary circuit,
- evaluate its approximate size,
- identify the correct fault resolution procedure according to P003a,
- carry out the necessary manipulations on the technological equipment according to P003a,
- achieve safe reactor status according to P003a. (Task bank)

Achievement of the above training objectives and the success of individual control room operating crews can be assessed using predefined success criteria - in the case of this scenario, the following criteria need to be met:

- timely cooling (through the steam bypass station to condenser) and depressurization of the P.C. (by injection from the make-up system) according to the procedures E-0, E-1 and ES-1.2,
- restore the level in the pressurizer to 6.3 m before commencing the shutdown of the high-pressure pumps,
- gradual shutdown of high pressure ECCS pumps (one or two),
- not to allow for a pressure drop in the P.C. < 8.3 MPa, until the temperature in the hot loops drops < 240 °C,
- when cooling the P.C, according to the foldout conditional information page (hereinafter foldout page), the operating crew must cool the feed water tanks (FWT) so that the feed water is 60-100 °C cooler than the water in the hot loops,
- keeping the pressure in the steam generator boxes as near as possible to atmospheric (overpressure < +10 kPa), when running the containment spray system pumps,

- not to exceed a cooling trend of 60 °C/h due to the risk of pressure thermal shock.

Results

Visual basic for application

The computer program was developed as an analytical tool that will be used in human reliability analysis for a faster and less time-consuming evaluation of a control room operating crews when going through the scenario.

As a suitable tool for creating a computer program designed to analyze collected data, the Visual Basic for Application programming language was chosen, specifically for Microsoft Excel. It is an object-oriented programming language that is part of MS Office.

The VBA program works with Objects, their Properties, Methods, and Events. The properties can be pre-set in the properties window or modified by the program. Methods are operations that can be performed with Objects (functions, commands). An Event can be triggered by a user, a program, or an action. (Benáčanová, 2012)

The entire program will be divided into the following functional units (sub-programs):

- a sub-program for opening a file and for loading data from a file to a worksheet,
- a sub-program for accessing the list of quantities characterizing the status of the reactor,
- a sub-program for creating chart,
- a sub-program for the export of charts to the directory,
- a sub-program for deleting charts,
- a sub-program for help viewing.

A brief description of the sub-programs

The sub-program for opening a file and for loading data from a file to a worksheet will display a dialog window where the user selects the file (or more files) to import. For this purpose we will use the FileDialog object. We save the name of the imported file in the appropriate variable. Use the Add method to add a new sheet to the workbook. The name of the worksheet will be the same as that of the crew for which the data was collected. We load the data from the file in this prepared sheet. (Král, 2010; Laurenčík, 2013)

The sub-program for accessing the list of quantities characterizing the status of the reactor uses the ListBox control element. ListBox is a list of items from which a user can select one or more. To select multiple items, you need to choose the MultiSelect property. The sub-program fills the ListBox with a list of the quantities characterizing the status of the nuclear power plant. (Král, 2010)

The sub-program for creating chart is available in two variants. The first option allows the user to plot a chart for each selected item from the ListBox into a separate image. The second option draws all charts into the same image. When creating charts, we use the Char object. Charts can be placed on a separate worksheet with the chart or in the graphic layer in the worksheet. (Král, 2010)

The sub-program consists of the following steps:

- defining a data area for the chart (using the SetSourceData method),
- adding the chart (Add method) and determining the chart type,
- description of the chart and the axis (e.g. text, location).

For better clarity and fast comparison of charts, it is advisable to save the charts in the appropriate directories. To do so, use the **sub-program for the export of charts.**

If the already plotted charts are saved, or if the user opts for other charts, it is advisable to delete unnecessary charts. To do so, use the **sub-program for deleting charts.**

The sub-program for help viewing serves both to access the user manual and to display the label when move over the object with the mouse (the so-called tooltip).

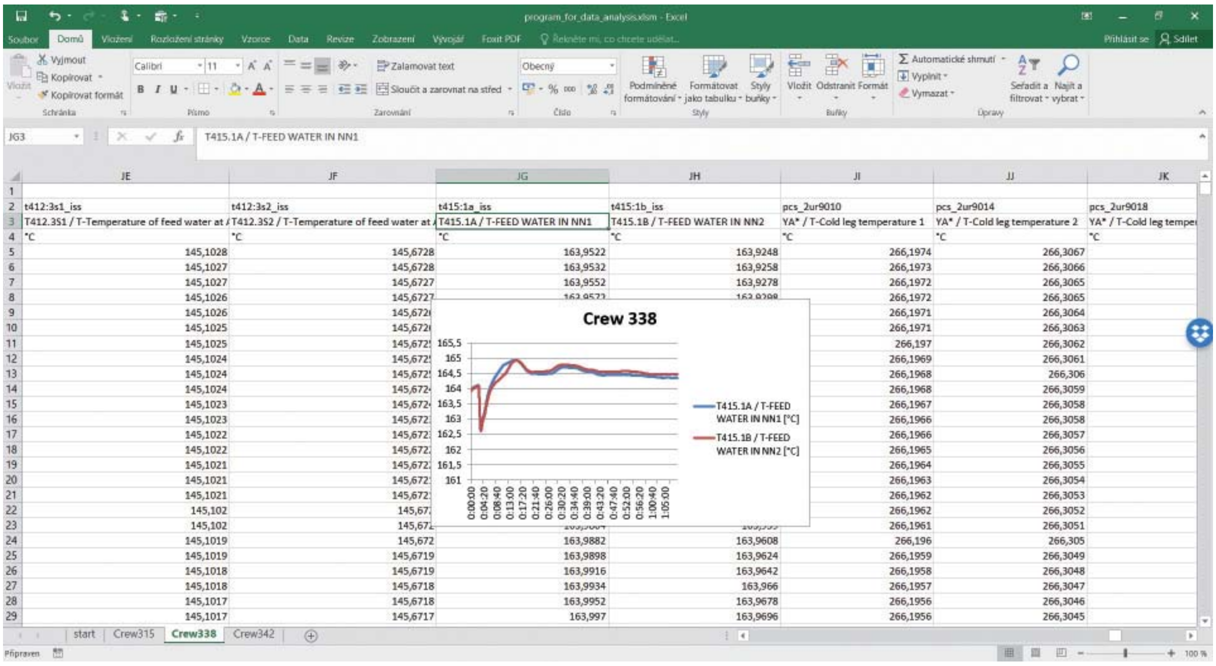
The resulting chart for a randomly selected operating crew of the control room and a randomly selected quantity is shown in Fig. 4.

The user interface

Last but not least, it is necessary to design a suitable user interface (see Figure 5), which is used by the user to control the program. For this purpose, we will use the first sheet of the workbook. This datasheet does not contain data, it is used to insert ActiveX control elements - ListBox, CommandButton, Image, Label. (Benáčanová, 2012)

Discussion

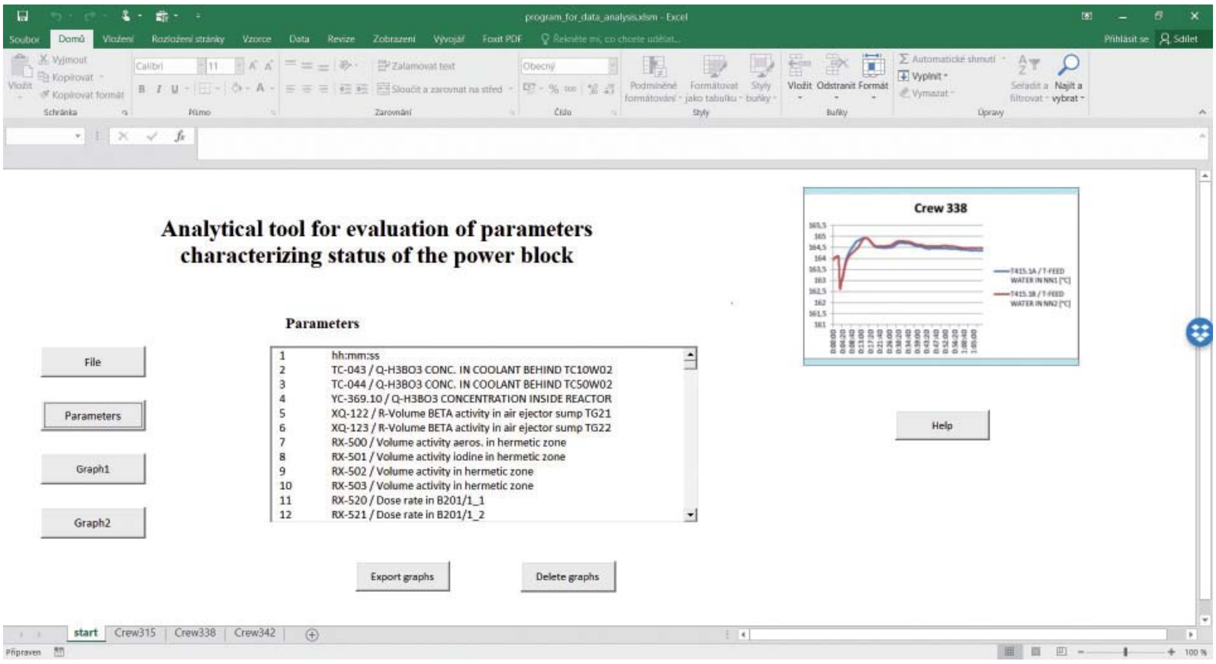
The output of the created program is a set of charts that are used to monitor the development of a parameter characterizing the status of the reactor during a simulated event.



T415.1A / T-FEED WATER IN NN1

	JE	JF	JG	JH	JI	JJ	JK
1							
2	t412:3s1_iss	t412:3s2_iss	t415:1a_iss	t415:1b_iss	pcs_2ur9010	pcs_2ur9014	pcs_2ur9018
3	T412.3S1 / T-Temperature of feed water at	T412.3S2 / T-Temperature of feed water at	T415.1A / T-FEED WATER IN NN1	T415.1B / T-FEED WATER IN NN2	YA* / T-Cold leg temperature 1	YA* / T-Cold leg temperature 2	YA* / T-Cold leg temper
4	°C	°C	°C	°C	°C	°C	°C
5	145,1028	145,6728	163,9522	163,9248	266,1974	266,3067	
6	145,1027	145,6728	163,9532	163,9258	266,1973	266,3066	
7	145,1027	145,6727	163,9552	163,9278	266,1972	266,3065	
8	145,1026	145,6727	163,9572	163,9298	266,1972	266,3065	
9	145,1026	145,672			266,1971	266,3064	
10	145,1025	145,672			266,1971	266,3063	
11	145,1025	145,672			266,197	266,3062	
12	145,1024	145,672			266,1969	266,3061	
13	145,1024	145,672			266,1968	266,306	
14	145,1024	145,672			266,1968	266,3059	
15	145,1023	145,672			266,1967	266,3058	
16	145,1023	145,672			266,1966	266,3058	
17	145,1022	145,672			266,1966	266,3057	
18	145,1022	145,672			266,1965	266,3056	
19	145,1021	145,672			266,1964	266,3055	
20	145,1021	145,672			266,1963	266,3054	
21	145,1021	145,672			266,1962	266,3053	
22	145,102	145,67			266,1962	266,3052	
23	145,102	145,672			266,1961	266,3051	
24	145,1019	145,672	163,9882	163,9608	266,196	266,305	
25	145,1019	145,6719	163,9898	163,9624	266,1959	266,3049	
26	145,1018	145,6719	163,9916	163,9642	266,1958	266,3048	
27	145,1018	145,6718	163,9934	163,966	266,1957	266,3047	
28	145,1017	145,6718	163,9952	163,9678	266,1956	266,3046	
29	145,1017	145,6717	163,997	163,9696	266,1956	266,3045	

Fig. 4 Resulting chart for a randomly selected quantity and operating crew of the control room



Analytical tool for evaluation of parameters characterizing status of the power block

Parameters

1 hh:mm:ss
2 TC-043 / Q-H3BO3 CONC. IN COOLANT BEHIND TC10W02
3 TC-044 / Q-H3BO3 CONC. IN COOLANT BEHIND TC50W02
4 YC-369.10 / Q-H3BO3 CONCENTRATION INSIDE REACTOR
5 XQ-122 / R-Volume BETA activity in air ejector sump TG21
6 XQ-123 / R-Volume BETA activity in air ejector sump TG22
7 RX-500 / Volume activity aeros. in hermetic zone
8 RX-501 / Volume activity Iodine in hermetic zone
9 RX-502 / Volume activity in hermetic zone
10 RX-503 / Volume activity in hermetic zone
11 RX-520 / Dose rate in B201/1_1
12 RX-521 / Dose rate in B201/1_2

Fig. 5 User Interface

To evaluate the scenario Rupture of the Hot Loop of the Primary Circuit (250 t/h), the following parameters were selected:

- Temperature in the P.C. (cooling trend must be < 60 °C/h),
- Pressure in the P.C. (must not drop below 8.3 MPa until the temperature of the P.C. < 240 °C),
- Level in the pressurizer (must be > 6.3 m before high pressure ECCS pumps shutdown),
- Flows of high pressure pumps,
- Pressure in the steam generator boxes,
- Flows of containment spray system pumps,
- The temperature difference between the primary circuit and the FWT (according to the foldout page it should be 60-100 °C),
- Temperatures in FWT,

- Levels in low pressure ECCS tanks (after dropping to 40 cm, according to the foldout page the operator must go to ES-1.3 and check the automatic switch to intake from the steam generator box).

Scenario evaluation

Tab. 1 lists the times of key events and operations of the operating crew from the occurrence of the initiation event or other monitored parameters.

Tab. 1 Times of key operations of the control room operating crews

Operating crew	**HO-1**	**Opening of the steam dump valves to the main condensate**	**Injection into the pressurizer**	**Level in the pressurizer 6,3m**	**Shutdown 1st high pressure pump**	**Shutdown 2nd high pressure pump**	**End of simulation**	**Temp. difference P.C.-FWT**
302 b3KR	0:00:37	0:22:43	0:25:33	0:46:49	0:50:56	-	0:51:04	50-60 °C
305 N2KR	0:01:03	0:23:09	0:26:02	0:53:56	0:48:14	0:57:39	1:26:56	40-50 °C
307 O2KR	0:01:22	0:28:11	-	-	-	-	0:32:36	ok
309 P2KR	0:01:23	0:13:55	0:19:35	0:32:45	0:32:50	0:34:35	0:38:25	40-50 °C
311 J2KR	0:00:48	0:24:24	0:14:31	0:38:34	0:41:44	0:45:47	0:52:35	ok
313 K2KR	0:01:05	0:27:58	0:32:38	-	-	-	0:34:38	ok
315 crKR	0:01:21	0:26:25	0:17:17	-	0:37:41	-	0:42:35	ok
317 drKR	0:00:45	0:18:56	0:22:01	0:42:07	0:43:25	0:45:53	0:50:55	ok
321 ZrKR	0:01:00	0:20:08	0:26:05	0:48:05	0:49:34	0:51:22	1:03:38	40-50 °C
326 VrKR	0:00:56	0:39:35	0:19:17	0:46:42	0:53:26	0:59:50	1:18:23	50-60 °C
328 e_aR	0:00:41	0:25:16	0:14:28	0:49:57	0:50:57	0:54:54	1:04:45	40-50 °C
329 brKR	0:00:57	0:24:40	0:28:31	0:48:44	0:51:38	0:54:05	0:55:44	ok
332 IqKR	0:00:41	0:17:42	0:21:50	0:37:15	0:39:32	0:41:13	0:45:47	ok
334 dvKR	0:00:27	0:19:14	0:22:06	0:39:57	0:41:49	0:44:04	1:01:12	ok
336 evKR	0:01:27	0:17:16	0:21:26	0:39:10	0:41:57	0:43:32	0:47:12	40-50 °C
338 fvKR	0:01:22	0:24:17	0:29:14	0:45:18	0:46:49	0:48:37	1:08:18	30-40 °C
340 ZvKR	0:01:02	0:20:05	0:24:06	0:41:10	0:43:21	0:45:36	0:53:14	ok
342 bvKR	0:01:09	0:23:46	0:15:52	-	0:43:40	-	0:49:01	50-60 °C
344 UvKR	0:01:21	0:22:33	0:24:40	0:44:18	0:45:20	0:50:11	0:55:39	40-50 °C
346 VvKR	0:00:53	0:21:15	0:27:46	0:45:07	0:47:11	0:49:31	0:59:31	40-50 °C
348 PuKR	0:00:45	0:24:34	0:29:58	0:48:22	-	-	0:49:38	50-60 °C
350 IuKR	0:00:38	0:22:59	0:29:55	0:46:50	0:47:11	0:50:10	0:53:29	ok
353 KuKR	0:00:45	0:18:17	0:20:58	0:40:37	0:42:49	0:43:43	0:47:48	>100 °C
355 ejKR	0:00:44	0:18:19	0:19:17	0:41:00	0:41:37	0:43:09	0:57:36	50-60 °C
357 fjKR	0:00:50	0:26:02	0:33:18	0:51:16	0:53:48	0:54:24	0:54:54	40-50 °C
360 ABVQ	0:00:41	0:15:21	0:18:45	0:41:51	0:43:27	0:44:29	0:47:42	ok
361 UjKR	0:01:22	0:27:47	0:35:13	0:57:04	0:58:28	1:03:04	1:09:28	ok
363 UjKR1	0:00:47	0:17:03	0:21:54	0:39:15	0:41:23	0:44:00	0:52:19	ok
365 VjKR	0:01:07	0:20:56	0:15:28	0:41:01	0:42:26	0:45:35	0:50:03	ok
367 OiKR	0:00:51	0:23:14	0:30:39	0:46:22	0:51:00	-	0:51:44	ok
368 NiKR	0:00:58	0:34:49	0:43:10	0:56:46	1:01:42	1:03:42	1:05:42	ok
Average	**0:00:58**	**0:22:56**	**0:24:23**	**0:44:50**	**0:46:13**	**0:49:08**	**0:54:36**	-

Tasks prematurely terminated by the instructor for time reasons are indicated by a gray field in the table. The first column lists all 31 operating crews by their assigned codes to ensure the anonymity of individual operating crews.

Impact of HO-1

In the second column of Tab. 1, the emergency response impact time (HO-1) is plotted after the occurrence of the initiation event. Six cases in which HO-1 was impacted automatically (always at approximately 1:22) are highlighted in yellow. In other cases, the HO-1 was initiated manually by the control room operating crew. From these times, it is clear that most operators were able to correctly evaluate the symptoms of a given IE in an extremely short time.

Initiation of cooling of the P.C. with the steam dump valves to the main condensate

The third column of Tab. 1 shows the start time of cooling initiation of the P.C. (or initiation of the preparation of cooling) by means of the steam dump valves to the main condensate according to step 6 of ES-1.2. This cooling should be performed at a recommended trend of < 60 °C per hour. This point was handled by all operating crews successfully - the average steam dump valves to the main condensate cooling initiation time was 0:22:56.

Initiation of the P.C. depressurization by injection into the pressurizer

The initiation time of P.C. depressurization by means of injection into the pressurizer from the make-up system by opening the 2YP10S28 electro-armature according to step 10 in ES-1.2 is monitored in the fourth column of Tab. 1. In six cases (highlighted in yellow), the operator began to prepare the depressurisation slightly earlier according to procedure E-1, step 5.

Depressurization of the P.C. was not initiated only by operating crew 307 for reasons of premature termination of the task (highlighted in gray). With the exception of the above-mentioned operating crew 307, all operating crews successfully initiated depressurization at an average time of 0:24:23.

When cooling and depressurizing the P.C., the operating crews must meet the criterion set out in warning II in step 10 of ES-1.2: Do not allow a pressure drop of the P.C. < 8,3 MPa until the temperature in the hot loops has dropped < 240 °C. The reason for this warning is to prevent the initiation of the ESFAS "Large Leak" signal. Of the 31 observed operating crews, all fulfilled this condition (except for operating crews 307 and 313, in the case of whom the simulation was terminated prematurely).

Level increase in the pressurizer to 6.3 m

- A necessary condition for initiating the shutdown of the high pressure ECCS pumps is an increase of the level in the pressurizer to 6.3 m, since the pressurizer level may decrease sharply after the high pressure ECCS pump is shut down. This condition was not met by a total of 3 operating crews - 305, 315, 342 (we do not consider operating 307, 313, where the simulation was prematurely terminated), see the fifth column of Tab. 1 (highlighted in red). For example, in Figure 6 we can see that, in the case of operating crew 315, at the moment of the high pressure ECCS pump shutdown at 0:37:41 the pressurizer level was only 1.7 m and in Fig. 7 in the case of operating crew 342, the level at the moment of shutdown of the high pressure ECCS pump (0:43:40) in the pressurizer was 4,5 m.

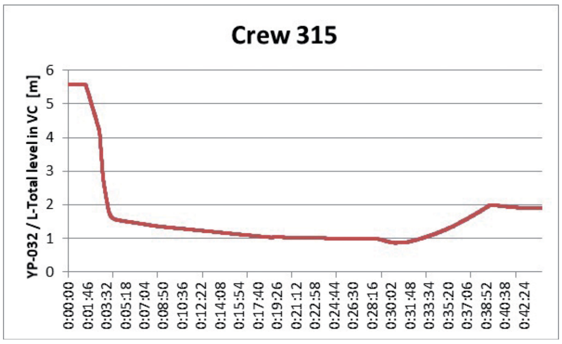


Fig. 6 Total level in the pressurizer of operating crew 315

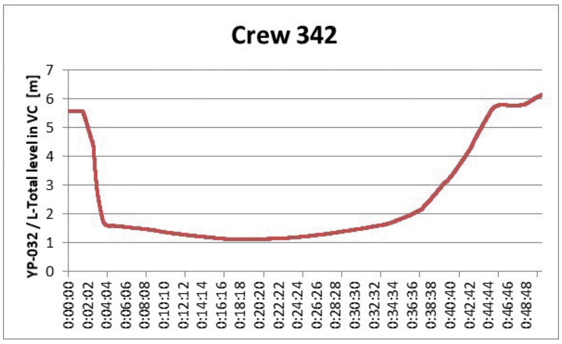


Fig. 7 Total level in the pressurizer of operating crew 342

Gradual shutdown of high pressure ECCS pumps

The main objective of ES-1.2 is the gradual shutdown of high pressure pumps according to step 14 in ES-1.2 - this is the main step of the whole process. The purpose of this step is to reduce the high pressure ECCS pumps flow rate by lowering the pressure in the P.C. and hence the total leakage from the damaged P.C. This step was successfully achieved by all observed operating crews (except for 307, 313, 348, for whom the simulation was terminated prematurely - highlighted in gray), see the sixth and seventh columns of Tab. 1. The average shutdown time of the first high pressure ECCS pump was 0:46:13. The average shutdown time of the second high pressure ECCS pump was 0:49:08. The second high pressure ECCS pump was not shut down by another 4 operating crews (302, 315, 342, 367) because the simulation was terminated when the first high pressure ECCS pump was successfully shut down.

Cooling of the feed water tanks

For an optimal solution to the emergency scenario, the operating crew should adhere to a number of prescribed procedures. One of them is a condition on the foldout conditional information page related to the cooling of the feed water tanks (FWT) so that the feed water is 60-100 °C cooler than the water in the hot loops.

Only operating crew 353 cooled the FWT too fast, so the FWT temperature difference and the mean temperature of the P.C. loops was slightly above 100 °C.

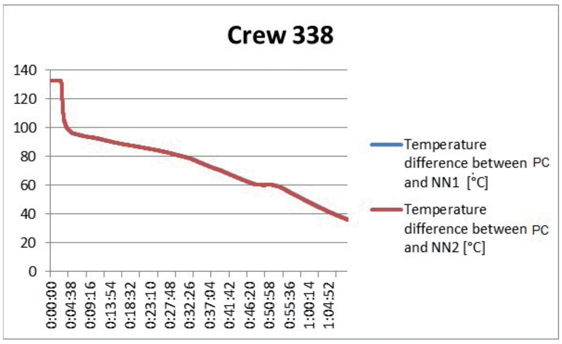


Fig. 8 Temperature difference between the P.C. and feed water tanks of operating crew 338

On the other hand, eight operating crews - 305, 328, 336, 338, 342, 344, 348, 357 - did not begin to cool the FWT before the scenario was terminated (highlighted in orange in the last column in Tab. 1), so the difference between the temperature of the P.C. hot loop and FWT was less than 60 °C. For example, in the case of operator 338, the difference between the temperature of the P.C. hot loop and FWT was about 37 °C (see Fig. 8). The temperature flow in the feed water tanks for operator 338 is shown in Fig. 9.

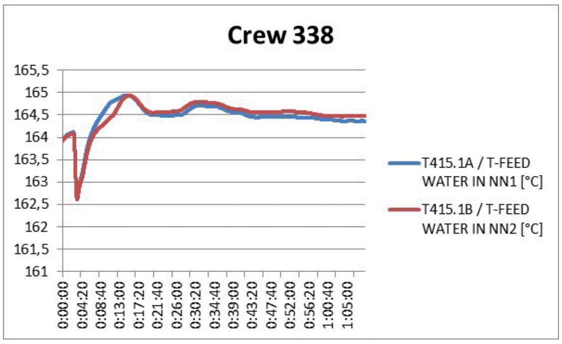


Fig. 9 Temperatures in the feed water tanks of operating crew 338

A total of 16 control room operators maintained the prescribed temperature difference, while the remaining 6 operators deviated from observing this parameter only slightly, or they began cooling a little later.

Cooling the P.C. with a trend of max. 60 °C/h

Cooling of P.C. with a trend of max. 60 °C/h is prescribed in step 6 of ES-1.2. This emergency cooling trend of 60 °C/h was tested by a strength calculation and it was verified to cause neither damage to the reactor pressure vessel nor shorten its service life.

To determine this parameter, the following P.C. limit temperatures were used:

1. temperature of the cold loops of the P.C. when SVD-MC cooling is initiated,
2. temperature of the cold loops of the P.C. at the end of the simulation.

The difference in these temperatures was divided by the difference in time.

However, the 60 °C/h trend does not mean an "instantaneous" cooling rate, but rather a cooling rate over the last 60 minutes. The cooling time was shorter than the required 60 minutes in almost all cases (except operator 305).

At the beginning of the cooling, the trend of 60 °C/h was exceeded by a total of 11 operators, but it is highly probable that during the scenario, the cooling rate would be reduced, as the operators have information regarding the cooling trend directly available to them.

Maintaining pressure in the steam generator box

According to ES-1.2, step 3, the operator must maintain pressure in the steam generator box as close as possible to atmospheric when running the containment spray pumps to minimize any leakage. According to the foldout page, the operator has to ensure the operation of at least 1 containment spray pump when the box pressure increases to +8 kPa. In addition to minimizing possible leakage to the environment, it is intended to prevent the recurring signal "Overpressure in the box +10 kPa".

The requirement for the running of the spray pumps was fulfilled by all operators (i.e. all 3 containment spray pumps were turned on at the beginning of the scenario and then gradually shut down). In two cases (operators 357, 368), however, despite 3 running containment spray pumps, overpressure in the steam generator box increased above +10 kPa and there was an impact of the ESFAS signal (which in practice meant only the lighting of the relevant indicators, since the relevant emergency system was already in operation). The increase in pressure despite the running containment spray pumps was due to insufficient (in the case of operator 357) or no (in the case of operator 368) cooling of the containment spray exchanger from the essentials service water side.

Conclusions and recommendations

A detailed analysis of available data and consultation with training instructors on the full-scope control room simulator show that the control room operating crews who participated in the training of this task successfully met the main training objectives:

1. diagnose leakage from the P.C.,
2. evaluate its approximate size,
3. determine the correct procedure for addressing the fault according to P003a, i.e. go through the procedures:
   - Entry into E-0 "RTS or ESFAS",
   - E-0, step 29 leaking P.C. - transition to E-1 "Loss of Primary Coolant",
   - E-1, step 10 the need to cool and depressurize the P.C - transition to ES-1.2 "Cooling of the P.C. after LOCA (Loss of Coolant Accident)",
   - ES-1.2 cooling and depressurization of e P.C., gradual shutdown of high pressure ECCS pumps,
4. perform the necessary manipulations on technological equipment according to the P003a,
5. achieve a safe reactor status according to P003a.

In general, the operators worked correctly with the procedures, according to the instructions they gradually cooled the P.C. and shut down the high pressure ECCS pumps. However, more detailed analysis has identified some minor deficiencies that are described in the previous section. Typical operator errors identified in this scenario were:

- not restoring the pressurizer level to 6.3 m before switching off the high pressure ECCS pumps (3 crews),
- FWT cooling outside of the recommended difference from the P.C. (60-100 °C),
- increase of overpressure in the steam generator boxes above +10 kPa by insufficient cooling of the containment spray exchanger from the essentials service water side.

Based on these shortcomings, the following recommendations were formulated:

Recommendations for training

- Place emphasis on keeping track of the foldout conditional information page. Observations from previous data collections have confirmed that operators do not always consistently follow the foldout page. Specifically, the lack of cooling of the FWT during the cooling of the P.C was observed in several operators, so the temperature difference between the FWT and the P.C. was outside the recommended range of 60-100 °C.
- Due to the short scenario times, it was not possible to verify the hypothesis that some operators exceeded the maximum permitted cooling trend of 60 °C/h, as cooling through the steam dump valves to the main condensate took an average of only 31 minutes before the scenarios were terminated. It will be possible to test this hypothesis during an analysis of other scenarios in future. In general, it might be advisable to place more emphasis on adhering to the recommended trends, thus avoiding a potential threat of reactor vessel rupture as a result of pressure thermal shock.

Recommendations for procedures

- Add to procedure ES-1.2 of the foldout page (or to the backup only), point "Spray pump flow" the note "Maintain the flow of at least one containment spray pump...including sufficient cooling of the containment spray pumps exchanger from the essentials service water". This will also most likely also be covered in the foldout page of other procedures.

- Add to the backup ES-1.2, step 3, Key operations: Checking the operation of the spray pumps and cooling of the containment spray pumps exchanger from the essentials service water.
- In the case of insufficient cooling of the FWT, the fact that the instruction is the last one on the foldout page may have had an influence. It could help to divide the instructions into two parts - one for the primary circuit operator, the second for the secondary circuit operator, so that each one of them only has to keep track of their own limited number of parameters.
- In the ES-1.2 code backup, in step 6, add to the information about the maximum cooling rate of 60 °C/h that it is the last hour trend, not an instantaneous cooling rate.

Recommendations for PSA and HRA

- Using the Bayesian approach, the probability of failure of the control room operator when cooling and depressurizing the P.C. after a medium LOCA initiating event will be altered - improved quantification is expected.
- Using the Bayesian approach, modify the probability of failure of the control room operators when reloading the intake from the low pressure ECCS reservoirs to intake from the steam generator boxes.
- Some errors were identified in the operator actions records related to so called „group controls“. Thus, in the quantification of operator failure, it is always necessary to take into account whether a component controlled by a dedicated control or a group control.
- Similarly, when quantifying probability of operator error, it is always necessary to take into account whether it is an instruction given directly in the body of the procedure or "only" on the foldout conditional information page (higher probability of failure).

Recommendations for subsequent data collection

- Add information about any simulation failure. Information might have to be entered manually by the instructor.
- In the case of the parameters Total level in the steam generator and Medium level in the steam generator, the units in the data outputs have most likely been switched (cm vs. m).
- Add the following parameters in the list of the collected data:
  - o Trend of cooling of the P.C, (cold loops, e.g. in ES-1.2, k6):
    - 5 min,
    - 30 min,
    - 60 min
  - o Flows through the steam dump valves to the main condensate,
  - o Flows through the steam dump valves to the atmosphere,
  - o Water/steam temperature in the steam generator 1-6,
  - o Steam temperature in the main steam collector,
  - o Pressure in the main feeding collector,
  - o Degree of opening of the pressurizer relief valve, pressurizer safety valve directly in the parameter list,
- Combine collected data with records of observing operators either by an external entity or directly with records from instructors.

Conclusion

The computer program was created on the basis of an analyst request from the Nuclear Research Institute Řež, a.s. as a new analytical tool designed to automate the evaluation of a large amount of data collected during the training of operating crews at a nuclear power plant control room simulator. During the creation of the program, data from the training task Rupture of the Hot Loop of the Primary Circuit (250 t/h) were used. Based on the comparison of charts, temporal passage through the scenario, or by personal participation in the training, analysts evaluate the successful passing of the practice scenario and propose final recommendations.

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