Complex investigation of Fire PSA dominant scenario related to direct flame contact with safety related pipes

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Abstract: Fire risk is one of the complex problems and potentially serious challenges to the safety of Nuclear Power Plants (NPPs). Fire PSA is a powerful and systematic tool which can reveal critical safety issues from the point of view of fire. A detailed fire PSA study performed for Unit 2 of the Armenian NPP (ANPP) shows that overall fire risk is driven by several fire scenarios. However before applying the results in a safety-related decision making process, it is important to verify the robustness of conclusions related to the identified risk contributing factors. Observation shows that the results received for the confinement oil fire scenario imply a need to implement substantial modernization activities. On the other hand, the approach used for oil fire modeling in confinement is considered conservative and the results obtained are considered to have considerable associated uncertainty. The aim of the current paper is to present a more accurate complex investigation of the oil fire scenario in the ANPP confinement building in order to create an adequate basis for further plant modernization decisions. The aim of the current paper is to present a more accurate complex investigation of the oil fire scenario in the ANPP confinement building in order to create an adequate basis for further plant modernization decisions.

Keywords: PSA, Fire, flame, pipe rupture, direct contact

1. INTRODUCTION

Fire risk is one of the complex problems and potentially serious challenges to the safety of Nuclear Power Plants (NPPs). Probabilistic safety analysis (PSA) performed for VVER reactors shows that fire could contribute up to 50% of overall core damage frequency (CDF) [1]. Armenian NPP Unit 2 is not an exceptional case, fire risk contributes about 20% of overall CDF for full power operational modes. Fire PSA performed for Armenian NPP Unit 2 allowed to reveal several specific fire safety issues for first generation VVER-440 reactors [2]. According to Fire PSA results, the most dominant contributor is large oil fire scenario in confinement area (more than 30% of overall fire-induced CDF).

Oil located in main coolant pumps (MCP) oil system's pipelines is considered as a source for large fire. It was assumed that fire could start in case of oil leakage from MCP oil system and its contact with hot surfaces. Fire scenario analysis evaluated possible impact on discharge pipes of emergency make-up system (EMS) which are passing through A-013/2 compartment in confinement area (see Figure 1). According to state of the art fire PSA approach fire induced pipe ruptures are typically could be neglected from the analysis [3]. However it was decided to considered mentioned scenario due to the following factors:

- existence of water stagnation zones at the closed valves on the pipes (see Figure 1)
- high pressure inside the pipe (P=125atm)
- direct flame contact with pipes and potentially large amount of combustible material (oil from MCP system)
- direct core damage in case of EMS pipes failure (due to LOCA through the pipes breaks and simultaneous unavailability of EMS system)

Analysis of mentioned scenarios was performed by fire simulation using CFAST two-zone code. It was concluded that pipeline metal temperature reaches critical temperature when integrity of the pipe could not be credited. Meanwhile CFAST has several limitations which does not allow to fully address

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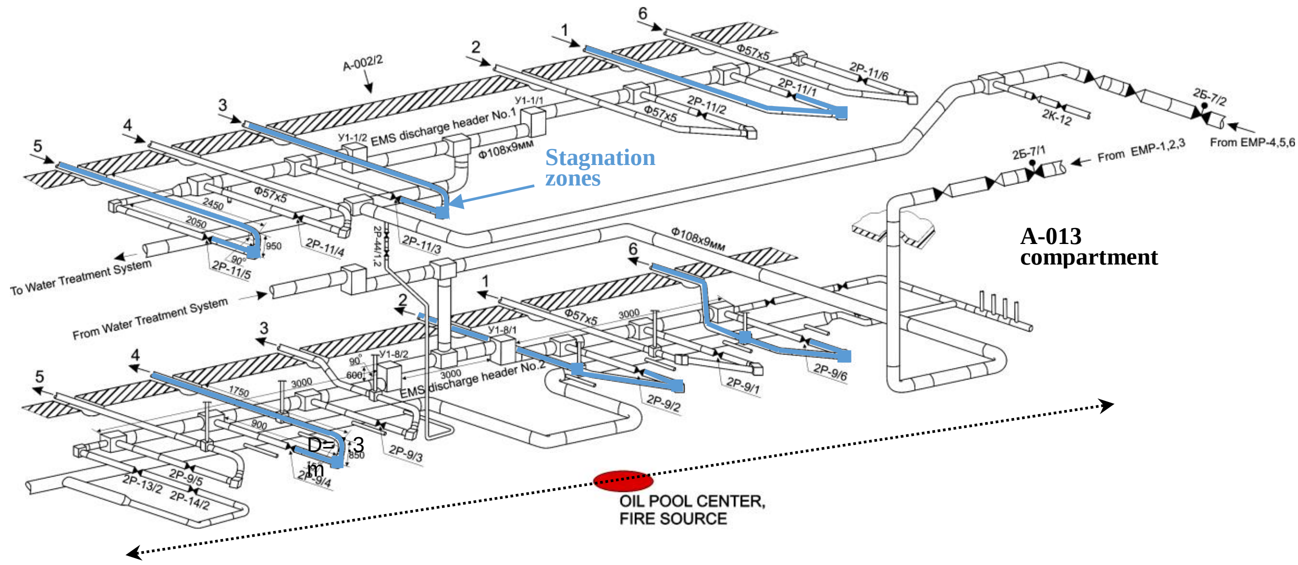
mentioned fire scenario. Particularly CFAST does not allow to correctly model direct flame contact effect taking into account radiation heat transfer. In addition performed analysis considered pipelines as a thermally thick target neglecting existence of water inside the pipe.

Figure 1: EMS discharge pipeline geometry in compartment A-013/2



Results received for the confinement oil fire scenario require implementation of substantial modernization activities. On the other hand, the approach used for oil fire modeling is considered to be conservative and the results obtained are considered to have considerable associated uncertainty. Basically, following aspects considered to be questionable:

- Heat transfer from fire to the pipe
- Strength analysis for given pipe metal temperature

The aim of the current paper is to present more accurate complex investigation of the oil fire scenario in the ANPP confinement building taking into account overall heat flux from the fire flame, geometrical characteristics of the pipe and pressure in the pipeline in order to create an adequate basis for further plant modernization decisions.

2. ANALYSIS OF HEAT TRANSFER FROM FIRE TO THE PIPE

RELAP5 was used for analyzing of heat transfer phenomena from fire flame to EMS pipeline. EMS pipeline was modeled in RELAP5, and integrated into plant-specific RELAP5 model. Geometrical characteristics of modeled EMS pipeline segment are introduced in the table 1.

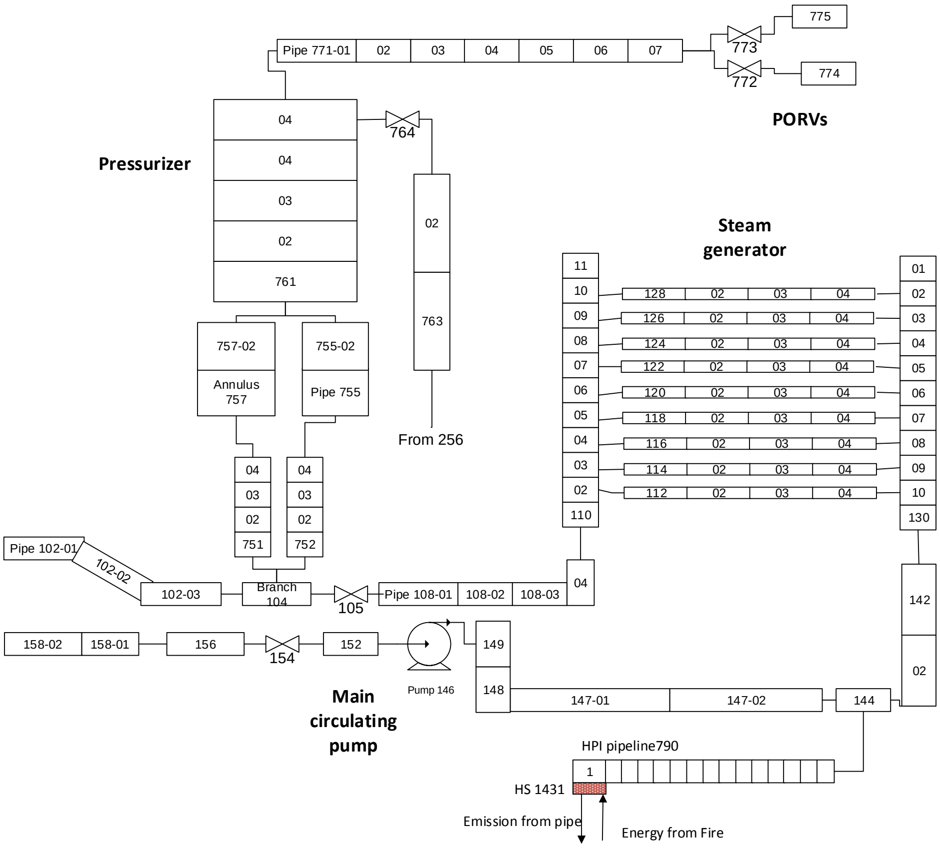
Table 1: Geometrical characteristics

Parameter	Size in mm
Total length of EMS pipeline	68000
HPI pipeline length covered by fire	5000
Inner diameter	47
Outer diameter	57

Taking into account that EMS pipeline is connected to cold leg of main circulation loop, the temperature of coolant was obtained based on steady-state calculation of integral ANPP model. The results of steady-state calculation showed that initial temperature of coolant equals 268 ^{o}C.

EMS pipeline were modeled as “pipe” element consisting of 15 volume elements with 1.7E-3m^2 cross-sectional area (see Figure 2). Each of 13 volume elements has length of 5m; remaining two volume elements have correspondingly 2 and 1 meter of length.

Figure 2: RELAP5/MOD3.3 nodalization of ANPP Unit 2 primary circuit



Maximum time-average heat fluxes from the flame to an object (size of the object was small relative to flame size), located in the flame, was taken 120kWt/m^2 [4] which includes radiation and convective heat fluxes.

Radiant flux emitted from pipe was modeled with Stephan-Boltzmann equation:

$$q_r = \varepsilon\sigma T^4 \quad (1)$$

where ε is the emission coefficient of steal, σ is Stephan-Boltzmann constant, T is the temperature of pipe.

In order to calculate the emission from the pipe specific metal characteristics were used. The material of the pipeline is 0X18H10T for which ε=0.85 emission coefficient is taken from [5]. Heat transfer from pipe wall to water was modeled by “Heat Structure” component (see Figure 2), element HS1431 simulates pipe wall. Duration of simulation was taken 1000 seconds.

From the calculation results, it can be noticed that at the volume which interacts with fire water temperature reaches saturation point in 43 second after fire initiation (see Figure 3 and 4). Due to continuous heat flux from fire to the pipe the water in mentioned volume starts to evaporate and fully transfers to the steam on 52nd second after fire initiation.

Starting from this time point, temperature of steam rapidly increases and reaches value of 707°C by 400th second. After 400th second radiant flux emitted from pipe becomes comparable with fire heat transfer to the pipe (see Figure 3 and 4). This effect is conditioned by the fact that pipe metal temperature increase rate starts to reduce.

At the end of calculation, temperature of considered steam reached 807°C (see Figure 3). As it could be seen from Figure 5 temperature of pipe wall has the same behavior as steam temperature and at the end of calculation the considered pipe segment walls temperature reaches 949°C.

Figure 3. Water and steam temperatures behaviour in time

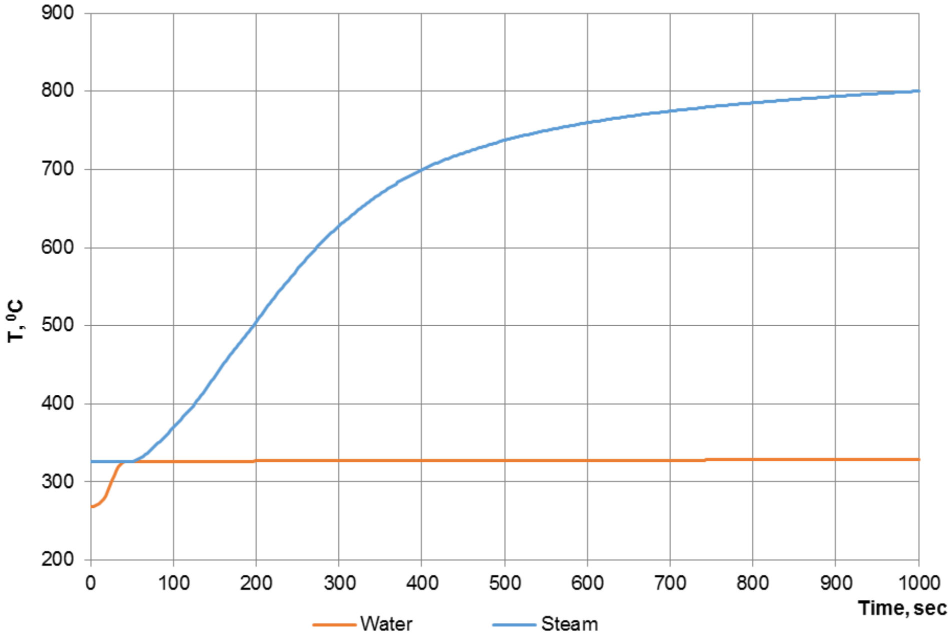


Figure 4. Radiant flux emitted from pipe and fire energy flux in time

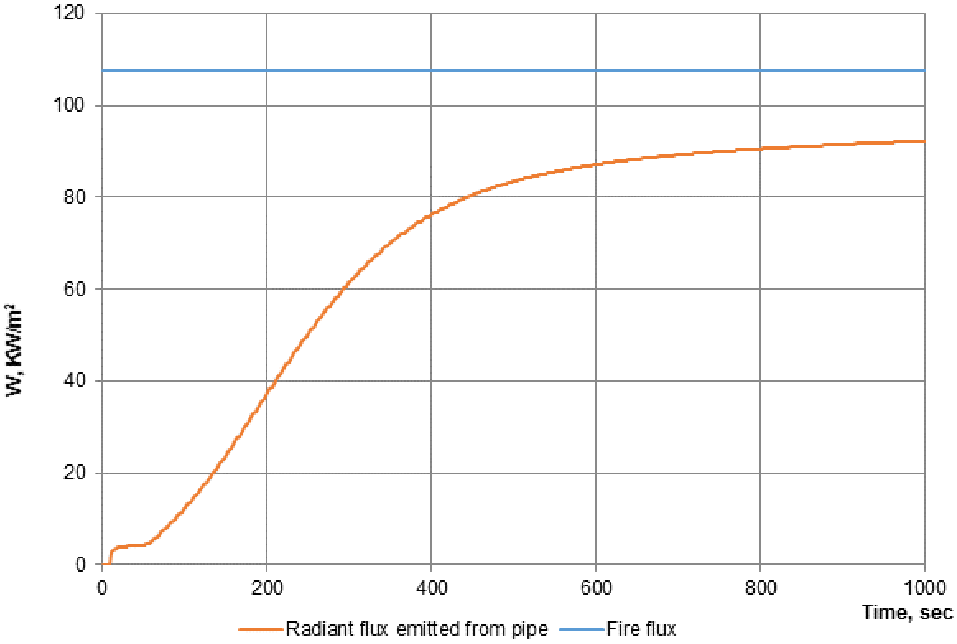
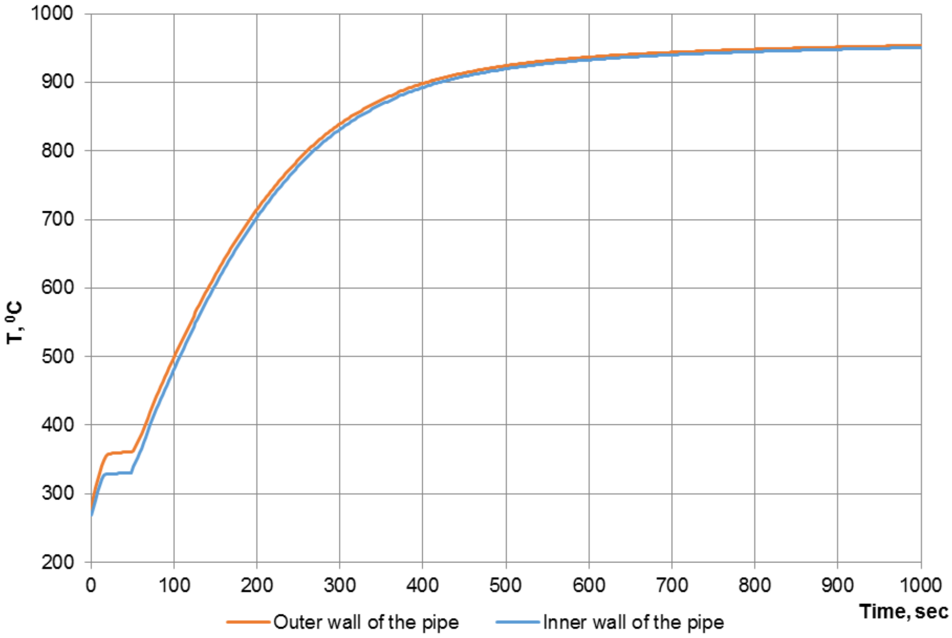


Figure 5. Pipe wall temperatures behaviour in time



3. PIPE STRENGTH EVALUATION

Pipe strength evaluation was implemented using PNAE G-002-86 standards [6] applicable for pipe metal type (0X18H10T). According to [6] allowable stress (σ) is calculated using following equation:

$$\sigma = \frac{p(Dm_3 + Sm_2)}{Sm_1} \quad (2)$$

where p – pressure inside the pipe (MPa), D – inner diameter of the pipe (mm), S – wall thickness (mm), m_1, m_2 and m_3 are parameters which depends on the pipe geometry. According to [6] for cylindrical pipe m_1=2, m_2=m_3=1. By putting in the equation all of the pipe characteristics presented in Table 1 and corresponding pipe pressure once could obtain allowable stress– σ=71.3MPa.

Following equation was used in order to calculate critical temperature of the pipe metal when σ=71.3MPa is reached from temporary resistance point of view

$$R_m = n_m \sigma \quad (3)$$

where R_m is allowable for particular temperature, n_m–strength margin coefficient which equals 2.6 for temporary resistance limit [7]. Taking into account that for considered EMS pipes allowable stress equals σ=71.3MPa, obtained R_m is 185.38 MPa. According to [7] R_m=185.38 MPa corresponds to 750^{O}C of pipe metal temperature (see Figure 6).

Following equation was used in order to calculate critical temperature of the pipe metal when σ=71.3MPa is reached from elasticity limit point of view

$$R_{p0.2}^{T} = n_{0.2} \sigma \quad (3)$$

where $R_{p0.2}^T$ is elasticity limit for particular temperature, $n_{0.2}$ – strength margin coefficient which equals 1.5 for elasticity limit [7]. Taking into account that for considered EMS pipes allowable stress equals σ=71.3MPa, obtained $R_{p0.2}^{T}$ is 106.95 MPa. According to [7] R_m=106.95 MPa corresponds to pipe metal temperature close to 1000^{O}C (see Figure 7).

As it is presented on Figure 6 pipe metal temperature reaches 750^{O}C value approximately in 223 seconds after fire initiation. Therefore it could be concluded that for considered fire scenario pipe integrity could not be credited. For elasticity limit pipe metal temperature does not reach the critical $R_{p0.2}^{T}$ value.

Figure 6. R_m dependency on pipe metal temperature

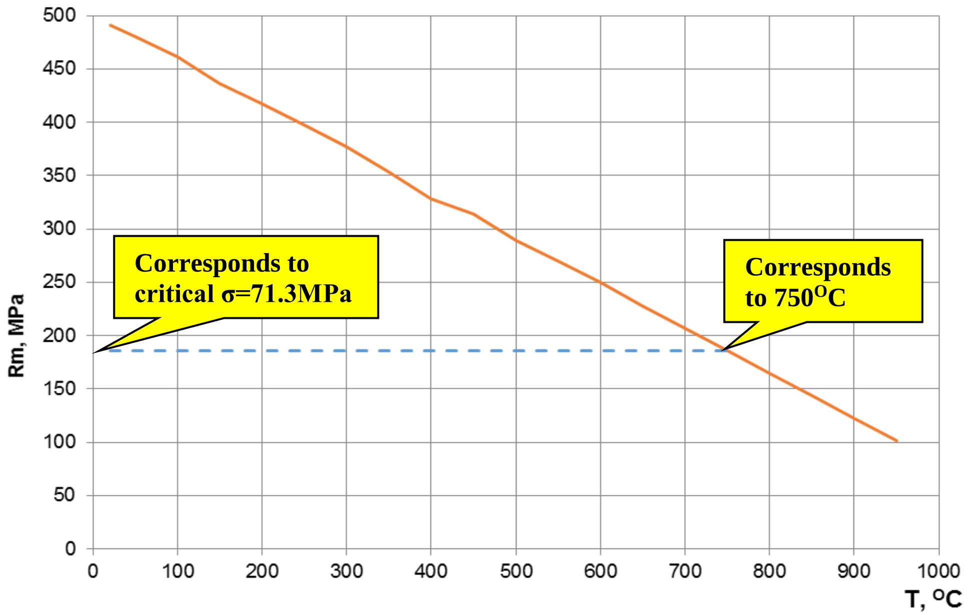
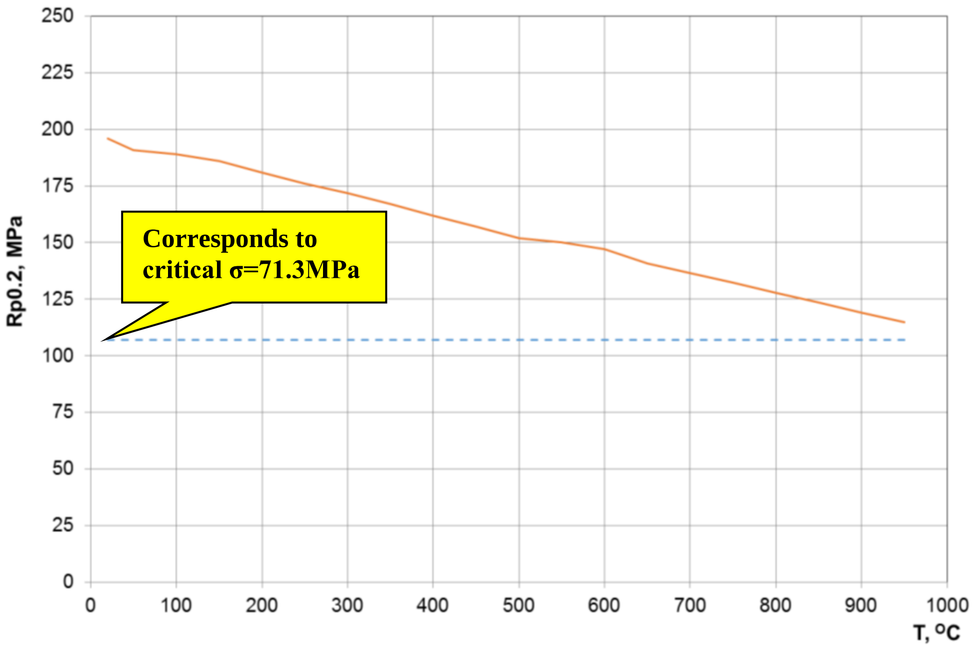


Figure 7. $R_{p0.2}^{T}$ dependency on pipe metal temperature



4. CONCLUSION

Fire PSA performed for Armenian NPP Unit 2 revealed that the most dominant contributor is large oil fire scenario in confinement area. The risk of dominant fire scenario is conditioned by impact on discharge pipes of emergency make-up system (EMS). Previous analysis of this fire scenario was performed by fire simulation using CFAST two-zone code that has several limitations which does not allow to fully trust obtained results. The main problems of CFAST: limitation in modelling of direct flame contact effect and neglecting of pipe water effect. Since elimination of considered fire scenario requires implementation of substantial modernizations, it was decided to spend efforts for more accurate investigation of the scenario in order to assure credibility of obtained results.

Investigation implies analysis of heat transfer from fire to the pipe and evaluation of pipe metal temperature. In addition strength analysis for given pipe metal temperature was provided. Heat transfer analysis from fire to the pipe was done taking into account both radiation and convective heat fluxes. Analysis shows that pipe temperature exceeds 949^{O}C in 1000 seconds after fire initiation.

Pipe strength evaluation was implemented using PNAE G-002-86 standards [6] applicable for pipe metal type (0X18H10T). Calculation shows that EMS pipe's maximal allowable tension– σ=71.3MPa is reached in 223 seconds after fire initiation.

The overall conclusion is that pipe integrity could not be credited for considered oil fire scenario. Therefore it was recommended to develop and introduce measures to decrease risk of fires in confinement room A-013/2. Particularly following actions could be suggested:

- increase reliability of MCP oil pumps disconnecting electrical scheme in order to decrease amount of oil spill in the compartment
- create possibility for fire detection in A-013/2 compartment
- decrease likelihood of oil pipe rupture (i.e. pipe cover installation)

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