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Restoring the coil pipe thermal insulation layer from the defective fuel system locator. Technological conditions

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Abstract. *A technology for restoring the coil pipe thermal insulation layer from the defective fuel system locator that reduces heat loss inside the moderator tank involves pneumatically transferring the thermal insulation powder inside the confined space between the coil pipe and the inner/outer walls of the equipment. Applying this technology aims to shorten the intervention, and more importantly, without replacing the equipment by cutting and restoring the connection pipes. The article briefly describes the problem generated by thermal insulation aging and establishes the technological conditions for its restauration, followed by a description of the device. It later establishes an operating pressure and presents a solution for the injector design followed by result analysis and conclusions.*

Key words: coil pipe, thermal insulation, aging, grain, pneumatic transfer

1. Introduction

The Defective Fuel System Locator at the CANDU reactor other than supervising the fresh nuclear fuel reload, identifies the primary heat transfer circuit cooling loop into which the case and fuel bundle defect occurred.

The Defective Fuel System Locator sequentially monitors primary cooling agent samples from each reactor fuel channel assembly in order to detect the flow of thermal neutrons. For each of the fuel channels, a sampling route made out of pulse pipe starts from the feeder's exit toward a serpentine pipe (which is a component of an assembly) that is mounted in moderator tank. The coil pipe enter-exit assembly is achieved by applying an approved welding process.

Into each tank filled with cooling water moderator there is a number of flooded coil assemblies mounted vertically in a stable and known geometric configuration, up to the mounting plate. They are fastened with screws to the cover of the tank.

Each coil assembly is composed of an upper and a lower coil, tightly encapsulated between an inner and an outer tube and insulated with mineral powder compacted by a mechanical vibration process. Inside the inner tube a hollow central tube is welded coaxially on a mounting plate to probe using the flow detector. Between the central and the annular ring there is an annular volume of cooling water, demineralized water from the moderator tank.

At the top of each moderator tank, over the sampling routes, a trolley moves carrying the probing mechanism which is equipped with flow detectors. The Defective Fuel System Locator functions (including probing mechanism) are controlled by a process computer.

The process of localizing defective fuel is extremely complex and highly depends on the reactor operating conditions (power, number of circulation pumps in operation, specific flow distribution on each of the channels ...).

Repairing a coil pipe assembly which is mounted inside the moderator tank requires interrupting the heat transport water flow through the sampling pipes that connect two fuel channel assemblies and coil pipes but also the return line connecting the coils to the exit feeders (near an output collector). Applying this technology is difficult considering that besides the problem of obtaining the necessary approvals, it also requires a period of time in order to prepare and make the intervention which must be established after conducting a simulation for the entire operation on a scale model and also a radiation exposure dose received by the working personnel. On the other hand, this intervention would require repairing the damaged thermal insulation and reintegrating the coil pipe assembly to the circuit thus aiming to reduce the environmental impact, activities which extend the planned shutdown time of the plant.

Applying a restoring technology to the thermal insulation directly on the spot shortens the time of the intervention and reduces the dose of radiation exposure for the personnel involved.

The article briefly describes the problem generated by thermal insulation aging and establishes the technological conditions for its restauration, followed by the results and few conclusions.

2. Analysis of the problem posed by thermal insulation aging

Inside the moderator tank chamber and the Defective Fuel System Locator mechanisms, excessive humidity during inactivity periods (between scans) can lead to the humidification of the coil pipe assembly thermal insulation. The damage suffered by the ceramic plugs that close the in/out sampling paths inside the coil pipe assembly due to restricted dilatations favor an increase of the thermal insulation powder humidity.

When scanning, thermal insulation temperature exceeds 100˚C, therefore water infiltrated inside the layer is vaporized. Water vapors on their way out of the mounting plate through the protection tubes inevitably carry particles from the thermal insulation, a mineral powder of mostly extremely fine grain (<< 50 μm).

Mass transfer thus triggered inside the coil pipe assembly thermal insulation during scanning is a proper aging mechanism. Because of the scarcity of water absorbed from the ambient, mass transfer damages the insulation by transporting mineral powder particles from outside the equipment.

Accidental water absorption can accelerate the aging process, inevitably leading to the loss of the thermal insulation in the upper coil. Damage to thermal insulation in the upper coil increases water temperature inside the moderator tank.

In such a situation characterized by accelerated aging damage to the coil assembly thermal protection can embitter the scanning conditions due to higher water temperature inside the moderator tank, much above the alarm level. Note that the waiting period between scans can increase such as a process duration restriction may be necessary or even prevent scanning.

For normal operating conditions we calculated the medium heat flows distributed on a coil pipe (in the two moderator tanks TK1 and TK2): QSTK1 and QSTK2. Assuming that losing the thermal insulation only affects the cooling water inside the moderator tank TK1, the difference between the obtained values is ~ 18 w.

This means that during the scans conducted inside the moderator tank TK1 on cooling water we have a permanent water heating source ~ 3 w greater than the one in TK2.

For a normal scan conducted in normal operating conditions during a period of time (t_s), the cooling water temperature inside the TK1 moderator tank reaches T_2 by applying the formula:

$$T_2 = \frac{P_1 \cdot t_s + m \cdot c \cdot T_1}{m \cdot c} \qquad (1)$$

For the second moderator tank (TK2), in the same conditions we got a temperature T_2 ~ 1˚C lower. Apparently, the difference is extremely low but in order for the cooling water in TK1 to reach initial scanning temperature (Ti) it is necessary to remove heat, which requires a 210 minutes (3h and 30 minutes) waiting period.

In case the ventilated air coolant fails, water temperature inside TK1 would increase by ~ 27˚C surpassing the value set for the security of the neutron flow detectors used during scanning. This involves stopping the scanning process after approximately half of the normal scanning process (½ t_s).

In order to reduce the cooling water temperature by ~ 20˚C, it would be necessary for the additional cooling system in TK1 to work continuously at least 3 times during normal scanning process.

For such a situation, repairing the damaged thermal insulation for each pipe coil is mandatory. Repairing the thermal insulation for a coil assembly involves reintroducing mineral powder used as a thermal insulator through one of the coil assembly protection tubes and filling up the space used for insulation.

3. Technological condition for repairing the thermal insulation

A suitable solution for all geometrical configurations revealed when uncovering the moderator tank requires using a device for injecting mineral powder (used as a thermal insulator) directly through the protection tube. This solution involves transporting mineral powder in a fluidized layer through hot air, which will later be transferred by an injector successively through the protection tubes into the annular space between the coils and the inner walls of the exterior and interior tubes. Access inside the protection tubes would thus be facilitated, and the intervention period would be considerably reduced, [2].

The idea of introducing mineral powder (used as a thermal insulator) through hot air injection is original and suitable for pneumatically transferring powder with a grain size below 50 μm (pneumatic transfer is usually realized for powder with a minimum of 100 μm grain size).

The ceramic powder injector assembly that was initially designed as an experimental model will be comprised of a working chamber that will accommodate a predetermined amount of mineral powder (used as a thermal insulator) and a powder injector. These two basic subassemblies were joined after a number of experiments by a hose used for transporting a mixture of mineral powder and air compatible with the opening between the protection tube and the coil assembly sampling route. In further experiments we attached an electrical heater subassembly mounted directly on the upper enclosure (part of the working chamber) outer wall, and a feeding device provided with a vibrator for discharging the powder mounted on top of the working chamber.

The supply of mineral powder will be achieved in stages when the pneumatically transported volume will not be enough to restore the insulation.

4. Enclosure description. Setting the operating pressure

The work chamber is for streamlining the mineral powder. The working chamber is made out of two chambers (upper and lower) and has a porous plate used as a separation plane. The plate is attached at the upper end of the lower chamber from the upper chamber; its mounting element is a control ring and a sealing gasket.

The lower enclosure is also called pressure chamber because, when the porous plate is charged with extremely fine powder, the pressure in the chamber starts to increase until it reaches the maximum value given by the static pressure of instrument air network. Laterally, near the bottom of the lower enclosure is the instrumental air input zone.

The lower chamber's height is h_1, [m], its interior diameter: D_i, [m] and its pressure chamber volume: V_{cp}, [m3].

The upper chamber's height is h_2, [m], its interior diameter: D_{is}, [m] and its pressure chamber volume: V_{is}, [m3].

The enclosure lid represents the parting plane of between the upper chamber and the powder injector, and between the upper chamber and the filter agent supply device.

As a condition of priming the fluidization process, we can use the granular layer porosity: ε and calculate the packing density ρ_u for the fixed layer of powder initially introduced inside the upper chamber working using the formula, [1]:

$$\rho_u = (1-\varepsilon)\cdot\rho \qquad (2)$$

- ρ - mineral powder density

For the upper chamber volume V_{is}, for the filling density ρ_u, the fixed powder layer volume is reduced to V_S, [dm^3].

The quantity of the powder inserted at the start of the experiment is calculated, [1]:

$$M_i = \frac{\pi\cdot D_i^2}{4}\cdot h_3\cdot\rho \qquad (3)$$

- h_3 - height of the fixed mineral powder layer which was initially inserted inside the chamber

After inserting the instrumental air and priming the fluidized bed, the amount of powder M_S remaining in the fixed layer from the upper chamber is calculated (for an ε granular porosity), [1].

$$M_S = V_S' \cdot \rho_u \qquad (4)$$

The amount of powder driven by the air flow, M_a, [1]:

$$M_a = M_i - M_S \qquad (5)$$

The fixed layer height becomes h_3’ [dm].

The working pressure of the instrumental air entering inside is established early in the process to value that exceeds the critical pressure, a value that should provide porosity on the fixed layer in order to prime the fluidized bed. From this moment on, it is considered that the instrumental air speed velocity reaches the value required by the upward solid particles movement inside the layer.

The technological fluidization process uses a poly-dispersed system and will face inevitable problems of multiphase fluid dynamics, which include [1]:

- Volume elements’ layer movement;
- Energy transfer from the insufflated air towards the solid particles;
- Transfer of impulses between the particles through impact;
- Mass transfer (upward particle transfer inside the layer).

The fluidized bed that we want to obtain is a non-adiabatic heterogeneous system formed by turbulent pulsation blast air through continuous solid particles entrained in a lurching.

One issue would be to find the optimum speed onto which the air flow does not cause granules separation inside the layer according to their weight, but to lead them directly, either individual or in compound on an ascension, so that when discharging the air through the injector and later through the flexible line, the air-solid particles is kept in a continuous column, without solid particles clusters.

5. Operating mode elements of calculation

Research regarding the flow of a fluid environment through a fixed granular layer have shown the existence of mixture currents, upward currents intersected by solids particles free falling back inside the layer in freefall, currents of fluid that surround the particles infiltrating their pores. For the calculation, we are assuming that we are only dealing with spherical particles of an average diameter, d [mm]. In this case, the particle volume is V [mm^3], and the area surface is A [mm^2]. The equivalent diameter of the porous channel, dec:

$$d_{ec} = 4 \cdot \frac{V}{A} \text{ , [mm]} \quad (6)$$

The specific area, a_0:

$$a_0 = \frac{A}{V} \text{ , [m}^{-1}\text{]} \qquad (7)$$

The working area specific surface:

$$A_{in} = \frac{\pi D_i^2}{4} \text{ , [m2]} \quad (8)$$

For an air flow of Q_1, [m^3/s], we can calculate the average velocity, w_1:

$$w_1 = \frac{Q_1}{A_{in}} \text{ , [m/s]} \qquad (9)$$

With these known elements, we can calculate the Reynolds number value:

$$\mathrm{Re}_1 = \frac{w_1 \cdot d}{\nu_{g100}} \quad (10)$$

ν_g is the kinematic viscosity of the preheated dry air at t = 100˚C, [3]

For $Re_1<0.1$ there is no drive flow of solid particles, so it is not necessary to calculate the slipping velocity inside the layer, wec. For Reynolds numbers lower than 0.1, the flow near the surface of the sphere is different than the symmetrical flow around it [1]. For a Q_2 air flow we obtain the medium particle velocity:

$$w_2 = \frac{Q_2}{A_{in}} \text{ , [m/s]} \qquad (11)$$

We continue by calculating Re_2. For the average equivalent velocity:

$$w_{ec} = \frac{w}{\varepsilon_{ec}} c \text{ , [m/s]} \quad (12)$$

For $Re=Re_{ec}/2>0.1$, the inertial terms start to deform the flow symmetry through the porous channels and a boundary layer detachment takes place behind the solid particle so that the air flow drives upswing particles. Airflow and particle ascension inside the layer are related to a laminar flow into which particles float, raise and descend inside the layer on short distances.

In the event that we have no airflow, the scope will fall freely in a fluid (air + solids) estate viscous. The criterion of Archimedes (the solid phase) for this situation, is calculated by formula, [1]:

$$Ar_S = \frac{g \cdot d^3}{\nu_{100}^2} \cdot \frac{\rho_S - \rho_{g100}}{\rho_{g100}} \qquad (13)$$

For $Re<0.2$ there is laminar flow at a drag coefficient $Cx = 24 / Re$, Archimedes criterion is calculated using the equation:

$$Ar = \frac{3}{4} \cdot \mathrm{Re}^2 \cdot C_x(\mathrm{Re}) \qquad (14)$$

In order for the sphere to float without falling or ascending inside the layer, a turbulent regime is required that is characterized by $Re \geq 20$. The minimum critical fluidization speed in the laminar domain ($Re < 10$) is calculated using the equation (M. Leva):

$$w_{cr} = \frac{0{,}005 \cdot d^2 \cdot g\left(\rho_S - \rho_{g100}\right) \cdot \varepsilon_{cr}^2}{\mu_{g100} \varphi^2 \left(1 - \varepsilon_{cr}\right)} \text{, [1]}$$

$d = d_{ec}$, for polydisperse systems;

ε_{cr}, macroscopic porosity at the critical expansion of the granular layer;

μ_g, gas dynamic viscosity at 100°C, Ns / m^2, [3];

φ, solid particle geometrical form factor; $\varphi = \frac{d_{ec}}{d}$.

The critical Reynolds number is calculated using the critical interpolation formula (15) which applies for both the laminar and the turbulent regimes.

$$\mathrm{Re}_{cr} = \frac{Ar_S}{150\frac{1-\varepsilon_{cr}}{\varepsilon_{cr}^3} + \frac{1{,}75}{\varepsilon_{cr}^3} \cdot Ar_S} \qquad (15)$$

The floating speed is an important gas dynamic characteristic of a mass of solid particle, located in a stream of air:

$$w_{pl} = \sqrt{\frac{4}{3}\frac{g \cdot d_{ec}}{\rho_{g100} \cdot C_f}\left(\rho_S - \rho_{g100}\right)} \qquad (16)$$

C_f - solid particle coefficient of dynamic gas resistance

for $10^{-4} < \mathrm{Re} \leq 0.4 \ldots 2$, $C_f = C_x = \frac{24}{\mathrm{Re}}$, [1].

Reynolds number for flotation:

$$\mathrm{Re}_{pl} = \frac{w_{pl} \cdot d_{ec}}{\nu_{g_{100}}} \qquad (17)$$

From the graph Li = f (A_rS) for polydisperse systems whose granules have regular (>1mm) dimensions and high densities (fig.1), we note that the number of Archimedes (for the solid phase) should vary between 17 and $5 \cdot 10^5$. In conclusion, in our case, for pneumatic transport it is preferable to test the model and to obtain real dynamic gas data for the desired regime using powder with granulation between 0.003 and 0.050 and a reduced density (ρ_S, [Kg/m^3]) as a thermal insulator.

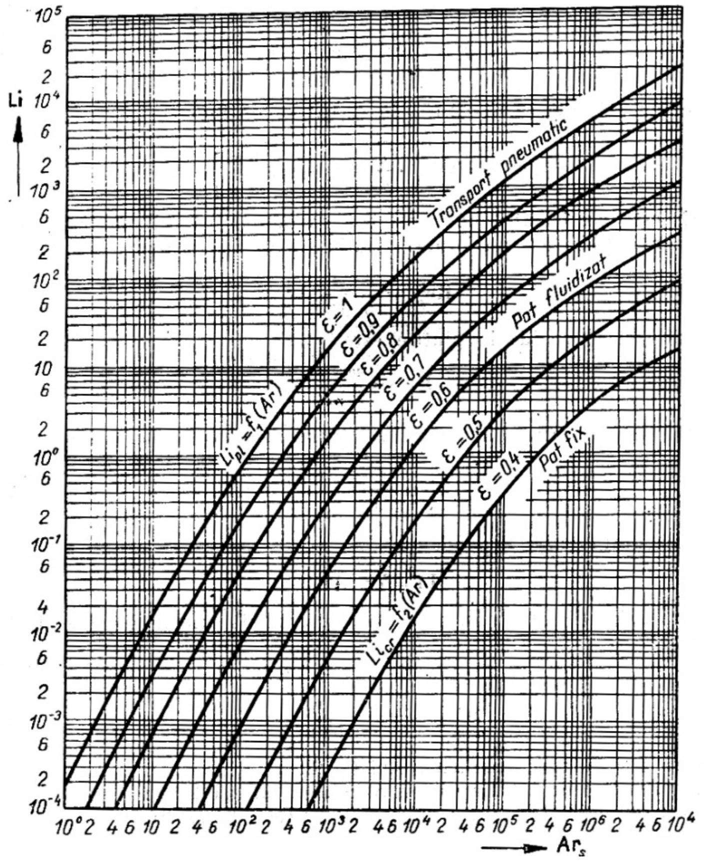

Fig. 1. Li = f (ArS)

6. The chosen solution for the design and production of the injector

The injector, an experimental model was designed in a constructive version into which we can change the sequential expansion nozzle geometry and the geometry of the mixing chamber.

For the dimensional computation of the experimental model, we used a simplified calculation model used for wet steam into which we have replaced the sizes characteristic to wet steam with parameters characteristic to the powder - hot air mixture.

The injector, an experimental model was designed and built so as within the test program it would be possible to:
- replace the nozzle;
- modify the nozzle position relative to the mixing chamber entrance;
- modify the mixing chamber length;
- modify the rate of the air flow entering the mixing chamber.

7. Results

Excessive humidity inside the moderator tank chamber and the damage that occurs to the ceramic plugs used for closing the input and output of the sampling routes inside the coil assembly, due to the prevented expansions, favors a water absorption increase inside the thermal insulation of the coil (upper and lower).

The temperature inside the coil assembly thermal insulation when scanning the fuel bundles reaches the temperature of the primary heat transport agent that crosses the coil (upper and lower). Water absorbed inside the coil thermal insulation boils instantly and the resulted vapors also inevitably drive extremely fine-grained mineral powder particles (<< 50 μm) spreading them inside the chamber.

Insulation deterioration leads to a water temperature increase inside the moderator tank while scanning fuel channels which finally reaches alarm threshold.

Normally in such a context, between scans, additional water cooling inside the moderator tank would be enough that later during the scanning process, the water temperature should not reach the alarm threshold. In case of ventilated air coolers failure, the situation gets complicated because during scanning, moderator tank water temperature rather quickly exceeds the value set for the security of the neutron flux detectors, thus imposing to stop the scanning process. In order to resume the scanning process, reducing the temperature value for the water temperature inside the moderator tank requires too much time for it to be considered.

In such a case, it is necessary that the coil assembly thermal insulation is rebuilt. Applying this rebuilding technology directly on site (on the moderator tank) would shorten the time of intervention and accordingly, reduce the dose of radiation exposure received by the personnel involved.

We presented the technological restoring condition for the thermal insulation. Such a technique involves using a mineral powder injection device (which will be used as a thermal insulator) directly through the coil assembly protection tube. The idea of injecting mineral powder through hot air is original and suitable for the pneumatic transport of powder with a grain size below 50 μm.

The ceramic powder injector assembly was designed as an experimental model. Its components are a working chamber, an injector and a hose compatible with the space between the sampling route ant the protection tube of the coil assembly.

The working chamber is strictly used for the technological mineral powder fluidization process. It consists of two stacked enclosures (upper and lower) separated by a porous plate. Instrumental air enters the lower chamber (also called pressure chamber) through its side.

The two chambers were sized through calculus so that for a certain instrumental air working pressure, a big part of the powder layer originally introduced inside the upper chamber will be found in the fluidized bed. From there on the air airflow velocity must not cause grain separation inside the layer according to their weight, instead, it must lead them directly, either individual or in compound on an ascension movement towards the injector. It must be a continuous process so that an air discharge through the injector will maintain the air and solid particles mixture in a continuous column without solid particles clusters throughout the entire length of the hose to the inside of the coil assembly. We presented the computing elements of the working regime necessary to ensure the continuity during the experiment.

Priming the fluidized bed and the process continuity was achieved by heating the instrumental air passing through the fixed bed of powder above the porous plate.

The solution for the design and production of the injector was based on the simplified calculations used for wet steam and corresponded to the demands resulted from the experiments.

The experimental ceramic powder injector assembly (fig. 2) was developed and used during few experimental campaigns and was improved accordingly in order to achieve the requirements, [4].

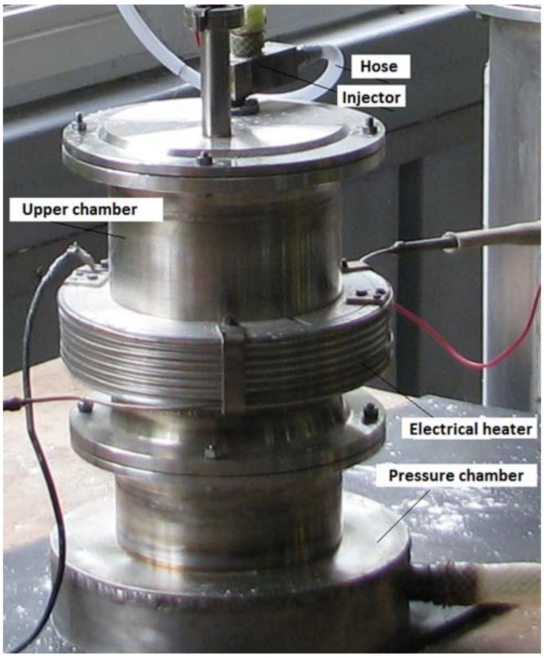

Fig. 2. Experimental ceramic powder injector assembly

8. Conclusions

- damage to the coil assembly thermal insulation during the fuel channels scanning process increases the water temperature inside the moderator tank until it nearly reaches alarm threshold;
- in case of accidental damage to the ventilated air coolers, the situation gets complicated because during scanning, moderator tank water temperature would exceed the value set for the security of the neutron flux detectors, thus imposing a stop to the scanning process;
- such a case would require a coil assembly thermal insulation repair;
- applying a technology to restore the damaged insulation for the coil assembly directly on site (on the moderator tank) would shorten the time of intervention thus reducing the radiation exposure dose for the personnel;
- the technological conditions for rebuilding the thermal insulation led to designing and building a ceramic powder injection assembly based on the idea of introducing mineral powder (as a thermal insulator) through hot air injection (given that the powder grain is less than 50 μm);
- priming the fluidized bed and the pneumatic transport continuity was achieved by heating the instrumental air passing through the fixed bed of powder above the porous plate;
- the experimental ceramic powder injector assembly was developed and used during few experimental campaigns and was improved accordingly in order to achieve the requirements

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