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Thermal Test of the DN30 Package for the Transport of UF6

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Abstract

The DN30 package was developed by DAHER NUCLEAR TECHNOLOGIES GmbH (DAHER NT) for the transport of enriched commercial grade and reprocessed UF_6 up to an enrichment of 5 %. It consists of a standard 30B cylinder and the DN30 Protective Structural Packaging (PSP) and shall be licensed as type AF, IF and B(U)F package. The basic design was already presented at PATRAM 2010 [1] and 2013 [2]. This presentation will concentrate on the thermal test simulating ACT.

For the thermal test a single DN30 package fully loaded with surrogate UF_6 was subjected to twice the drop tests required by the Regulations: first, the regulatory drop test sequence onto the valve corner followed, with the same specimen, by the regulatory drop test sequence onto the plug corner. Results of our computer analyses show an excellent match with the real world drop tests.

In the next step, the numerical model for the thermal analysis of ACT was developed based on the damaged DN30 package. The simulation takes into account the regulatory boundary conditions. Furthermore, all mechanical deformations and gaps resulting from the doubled regulatory tests are modelled. In deviation from the package used for the drop tests the model used for the thermal analysis does not contain any surrogate UF_6 to minimize thermal capacity and thereby maximize the temperature of the cylinder and its components.

The real world thermal test requires a considerable amount of preparation to comply with the requirements of the Regulations. First, the deformations of the prototype used for the drop test, especially the gaps between upper and lower shell, were documented. Then, the DN30 PSP was opened and the 30B cylinder filled with surrogate material was replaced with an empty 30B cylinder. A tailor made heating blanket was manufactured to heat up the specimen to the initial temperatures resulting from NCT and the surface of the specimen was painted to ensure the “sooty” surface. Last but not least, the environmental conditions, especially the ambient temperature and missing insolation during the cooling phase, had to be taken into account by adjusting the exposure period.

The thermal test showed that polyurethane foams produce a huge amount of decomposition gases

which could flow into the cavity of the PSP and result in an additional heat source for the 30B cylinder and its components. The admissible temperature of the sealing of the valve and plug against the cylinder could be exceeded considerably. DAHER NT improved the design of the DN30 package by adding an additional layer of thermal protection between DN30 PSP and 30B cylinder consisting of intumescent material. Preliminary tests show a dramatic improvement of the thermal protection properties of the DN30 PSP. The regulatory thermal test will be performed early September and the results will be presented at PATRAM 2016.

Introduction

The transport of enriched uranium hexafluoride (UF_6) is performed worldwide since decades in 30B cylinders using an additional PSP for mechanical and thermal protection under normal (NCT) and accident conditions of transport (ACT). There are several PSP designs in use today; however some time ago it became apparent that a new state-of-technique design was required to answer the evolving requirements of the Regulations. DAHER NT presented the new PSP design and its safety analysis at PATRAM 2010 [1] and first results of the extensive drop test program at PATRAM 2013 [2]. Further papers are presented during this PATRAM of advanced safety features [3] and drop testing [4].

The package DN30 is going to be licensed in France as type AF, IF and B(U)F package for commercial grade and enriched reprocessed uranium up to an enrichment of 5 wt.% in U-235.

Valve and plug are part of the containment and confinement system. They are each fitted to the 30B cylinder with a NPT thread and sealed against the cylinder by a layer of tin-lead solder between the valve thread and the thread in the cylinder. The DN30 PSP must ensure that the valve and plug of the 30B cylinder are not affected by the thermal test simulating ACT. The melting temperature of the tin-lead solder is about 183°C. This temperature must not be exceeded during the thermal test to ensure that the 30B cylinder remains leak tight (see para. 680 of the Regulations).

The following presentation contains a description of the thermal test simulations and real world tests with a prototype of the DN30 package.

Design of the DN30 PSP

The DN30 PSP is a right circular horizontal loading container which consists of a top and bottom half which are connected with six closure systems. A gasket is fitted on the step-joint part between both halves to prevent water inleakage.

The DN30 PSP is shown in Figure 1.

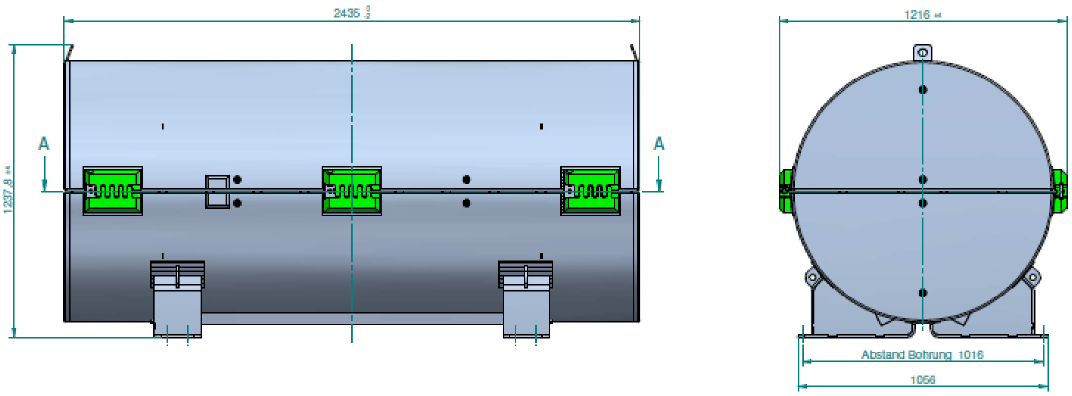

Figure 1: DN30 PSP

The halves consist of an inner and outer stainless steel shell and energy-absorbing and insulating closed-cell PIR foam of different densities filling the space in between as shown in Figure 2. The qualification of this type of foam was presented at PATRAM 2013 [5].

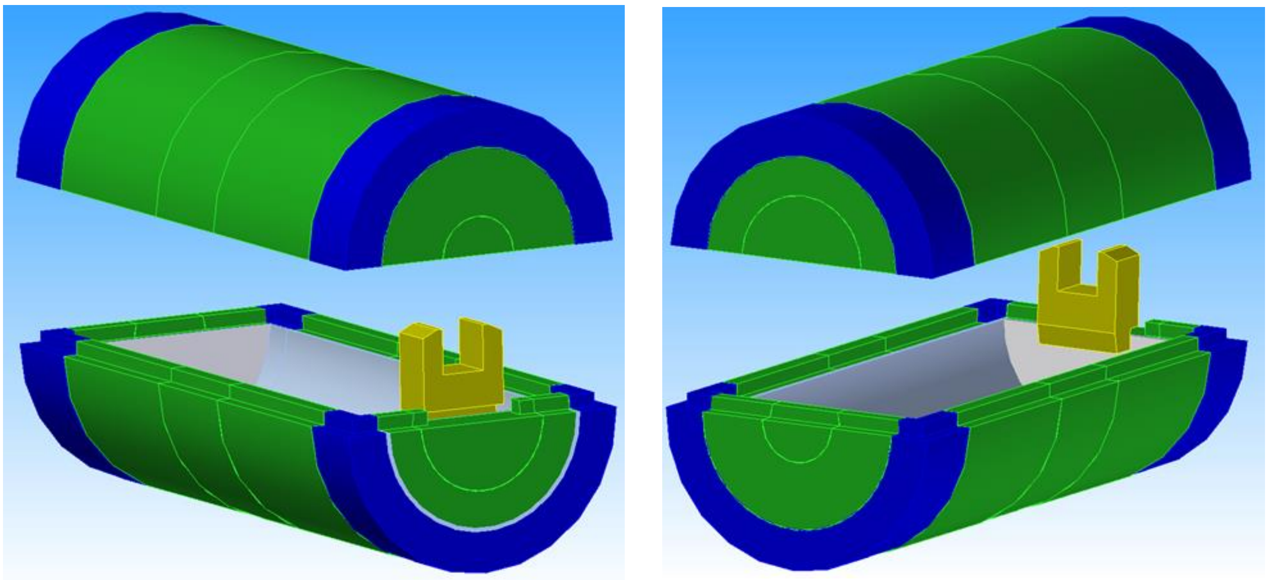

Figure 2: Distribution of PIR foam

Selection of the fire test prototype

The free drop test as specified in para. 722 (a) of the regulations followed by the mechanical tests specified in para. 727 (a) and 727 (b) were carried out with 4 prototypes of the DN30 package in 5 drop test sequences. After these tests one of the prototypes was selected for the thermal test. The criteria for this selection were:

- The prototype with the largest deformation (minimal remaining foam thickness) on the valve side.
- The prototype with the largest deformation (minimal remaining foam thickness) on the plug side.

As the prototype had to be opened after the drop tests to remove the 30B cylinder simulating a filled cylinder and replace it by an empty cylinder another point for consideration was, that there should be only minor damage added by opening the prototype after the drop test sequence(s) and that it should be possible to return the prototype to the same condition documented after the drop test sequence before the fire test. The prototypes used for the drop flat onto the valve side and flat onto the closure line could only be opened by cutting the deformed areas; the prototype used for the slap-down drop tests had only minor deformations in the valve and plug area. The prototype used for the drop test onto the valve corner and plug corner had the largest deformations in the valve respectively plug area and could be opened rather easily. Hence, this prototype was selected for the thermal test (see Figure 3).

Figure 3: DN30 prototype used for the thermal test

Thermal test simulations

Prior to the performance of thermal tests simulations for NCT and ACT were performed with the computer code ANSYS.

In a first analysis the temperature of the DN30 package under NCT was calculated. For that several cycles of 12 hour with solar insolation complying with the Regulations and 12 hours cycles without insolation and constantly 38°C ambient temperature were repeated until the daily change of the temperatures reached a constant pattern. The maximum temperature of the 30B cylinder, its components and the content was calculated to be approx. 60°C.

In a second analysis the expected temperatures during the fire phase and the cooling phase of the thermal test were analyzed. In the cooling phase solar insolation and an ambient temperature of 38°C were assumed to comply with the regulations.

As neither the solar insolation conditions nor the ambient temperature at the test site (real world conditions) complied with the requirements of the Regulations the impact of the deviating ambient conditions on the results of the thermal test were analyzed.

Two simulations were performed to determine the influence of the ambient conditions:

- Case 1: Regulatory thermal test simulation (38°C ambient temperature, solar insolation)
- Case 2: Real world thermal test (approx. 5°C ambient temperature, no solar insolation).

Based on the results of these simulations DAHER NT assessed that the thermal test duration has to be increased by 2 minutes to compensate for the deviating ambient conditions.

Finally, to be able to compare the results of the simulations with the results of the thermal test a third simulation was performed with the real world test conditions on the day of the thermal test.

In the simulation the maximal temperature recorded was located at the valve and was about 122°C which is far below the tin-lead solder melting temperature of 183°C.

Thermal test

The performance of a fully complying thermal test as required by the Regulations is not feasible for following reasons:

1. The thermal test cannot be performed with a kerosene fire but with a propane gas fire (environmental issues).
2. Several solar insolation cycles to reach a constant temperature pattern with the insolation defined in the Regulations cannot be reached under natural conditions.
3. The ambient temperature of 38°C cannot be reached under natural conditions.

To compensate the fact that a thermal test cannot be performed as specified in the Regulations some measures are required:

1. The compliance of a propane gas fire has to be demonstrated.
2. The DN30 prototype has to be artificially pre-heated before the thermal test to reach NCT conditions.

3. The duration of the fire of the thermal test has to be increased to compensate that during the cooling phase of the thermal test the ambient conditions differ from the ambient conditions stipulated in the Regulations.

Compliance of the fire

The compliance of a propane gas fire with the Regulations was shown in a paper presented at PATRAM 1992 [6]. Here it was shown that the thermal flux of both fires are identical and the thermal load is for the propane gas fire the same as for a kerosene fire.

However, an important difference between a kerosene fire and a propane gas fire is the soot produced by the kerosene fire. This soot increases the surface absorptivity of the specimen considerably. The Regulations require a coefficient not less than 0.8. Hence the outer surface of the DN30 prototype was painted with a black coating satisfying this requirement (see Figure 4).

Figure 4: DN30 prototype coated for the thermal test

Pre-heating

The thermal simulations for NCT show that the temperature inside the DN30 package reaches an average temperature of 60°C. The Regulations specifies that the thermal test should start at NCT conditions; therefore the DN30 prototype was pre-heated with a heating jacket (see Figure 5). The temperature at the 30B cylinder as well as the temperature at the valve and plug were approximately 63°C at the beginning of the thermal test.

Figure 5: DN30 prototype in heating jacket

The thermal test and the duration of the fire

The propane gas fire test was performed at the BAM test facility as required by the Regulations, meaning a full engulfment of the specimen by the flames, a duration of at least 30 min (32 min to take into account the deviating ambient conditions) and a flame temperature of at least 800°C. Figure 6 shows the fire test and proves that the DN30 prototype is fully engulfed by the flames.

Figure 6: Picture of the fire test showing the full flame engulfment of the DN30 prototype

After the fire, the DN30 PSP was naturally cooled down. During the cooling phase there was no rain which could have accelerated cooling-down.

During the cooling phase gases escaped through cable holes (see Figure 7). This indicates self-contained decomposition of the foam, independent of the fire as an external heat source.

Figure 7: Gases escaping from the DN30 prototype during the cooling phase

Results of the thermal test

After the drop tests there was a crack at the inner front side of the DN30 PSP as shown in Figure 8. The gases from the decomposition of the foam escaped from the PSP directly into the valve area, transporting heat into the PSP. The hot gases increased the temperature at the valve considerably and produced a layer of soot and black crust at the valve protector and the valve (see Figure 9).

Unfortunately, the production of decomposition gases cannot be avoided. The production of decomposition gases is an intrinsic part of the chemical decomposition of organic substances like PIR foam. The production of decomposition gases cannot be further reduced because the foam used in the DN30 PSP is already an optimized fire retardant foam type.

Figure 8: Fracture of the inner shell of the DN30 PSP

Figure 9: Valve and valve area covered with a black crust (condensation of the decomposition gases of the foam)

The main consequence of the flow of these gases into the cavity of the PSP was an increase of the temperature inside the DN30 PSP. The production of decomposition gases started early in the thermal test and consequently the temperature increase started early as shown in Figure 13. After only 5 min of the thermal test the temperature at the valve seat was about 150°C and after 15 min about 190°C.

The same phenomenon can be observed at the plug side, but not as strong as at the valve side because the plug was better protected from the hot gases than the valve. The temperature at the plug seat was about 90°C after 5 minutes and 160°C after 15 minutes.

The self-contained burning of the foam also caused a further increase of the temperature inside the DN30 prototype in the cooling phase. The maximal temperature at the valve and the plug is reached approximately 30 min after the end of the fire for the valve and after 100 min for the plug. The temperatures reached are about 344°C at the valve thread and 244°C at the plug thread. These temperatures are far above the melting point of the tin-lead solder which is 183°C. As expected, the helium leak tightness test performed after the thermal test did show that the 30B cylinder did not remain leak tight in the thermal test.

Conclusion for the thermal test of the DN30 prototype

The thermal test with a DN30 prototype has demonstrated that polyurethane foams (e. g. PIR foam) have some deficiencies as thermal protection in contrary to their excellent mechanical properties. At high temperatures such foams produce decomposition gases as a part of the chemical decomposition of the organic substance. The gases transport heat into the cavity of the DN30 PSP via unavoidable cracks and fractures which leads to a considerable increase of the temperatures at the valve and plug threads.

Consequently the thermal protection properties of the DN30 PSP have to be improved. The improved design must be focused on avoiding gas inflow to the critical areas around the valve and the plug. The free space around the valve and plug allowing heat transfer by convection and radiation should be reduced.

Design improvements

Analysis of possible technical solutions

Based on the results of the thermal tests described so far design improvements were investigated. Following principal solutions were identified:

- Improvement of the thermal properties of the PIR foam
  The foam type used in the DN30 prototype is already fire retardant and an improvement of the thermal properties could not be achieved.
- Replacement of the PIR foam with another foam type
  In the early development phase of the DN30 package phenolic foam has been investigated and tested. Based on the tests this foam was excluded from further designs. Other foam materials than polyurethane and phenolic foams are not available for such purposes like the DN30 package.
- Additional thermal protection by replacing PIR foam with high performance insulating materials
  The mechanical tests carried out with DN30 prototypes showed that the PIR foam thickness is adequate for the mechanical loads experienced during NCT and ACT. A reduction of the shock absorber thickness was not feasible. An increase of the outer dimensions of the DN30 PSP was also not possible, as this would have affected the whole logistics chain considerably (2 packages instead of 4 packages on a flat-rack).
- Additional thermal protection by intumescent material on the outer surface of the DN30 PSP
  This solution was not considered feasible as the international use of the package and the variety of transport conditions would render any protection ineffective by wear and tear.
- Additional thermal protection by intumescent material inside the DN30 PSP
  This solution was selected for further analysis as
    - The mechanical properties of the DN30 PSP are not affected
    - The thin layer of intumescent material does not affect handling of the DN30 PSP and 30B cylinder
    - The intumescent material is protected from the environment during transport
    - The intumescent material has the potential to minimize the decomposition gas flow into

the cavity or even reduce it to zero

Description of the design improvement

The first design improvement is the use of a thin layer of intumescent material on all inner surfaces of the DN30 PSP as shown in Figure 10. The thin layer does not affect the loading of the 30B cylinder into the DN30 PSP nor the unloading of the 30B cylinder from the DN30 PSP. In case of a fire the material will start to expand and fill up the gap between 30B cylinder and DN30 PSP thus adding an additional layer of thermal insulation and preventing the circulation of decomposition gases.

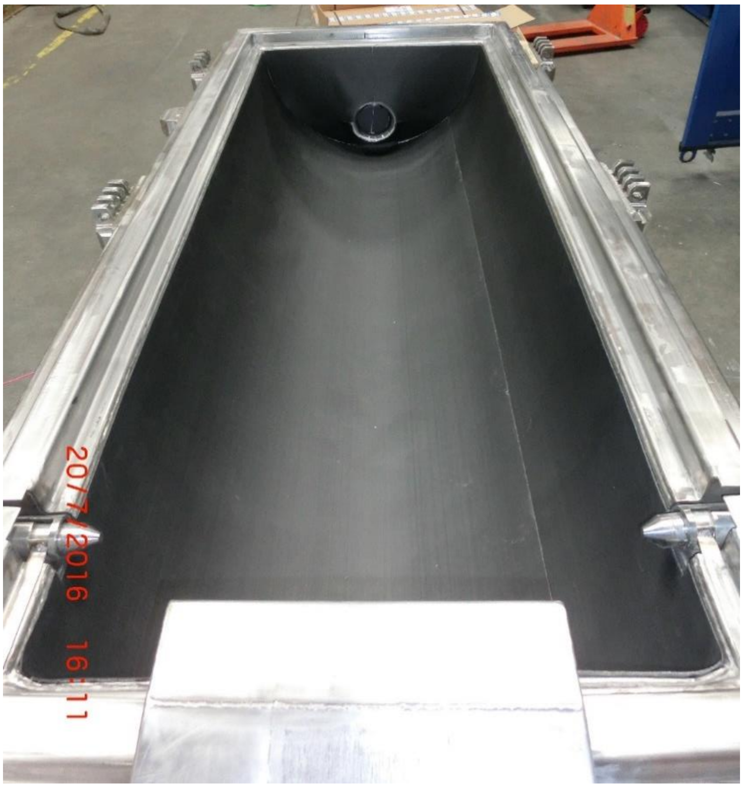

Figure 10: Inside of the DN30 PSP covered with intumescent material

The second design improvement is to close the valve protecting device at the outer and upper sides and apply intumescent material to all sides of the valve protecting device facing the valve as shown in Figure 11. During a fire the temperature at the external surfaces of this housing will increase and the intumescent material will expand and enclose the valve thus adding an additional layer of thermal insulation and preventing the direct flow of decomposition gas onto the valve.

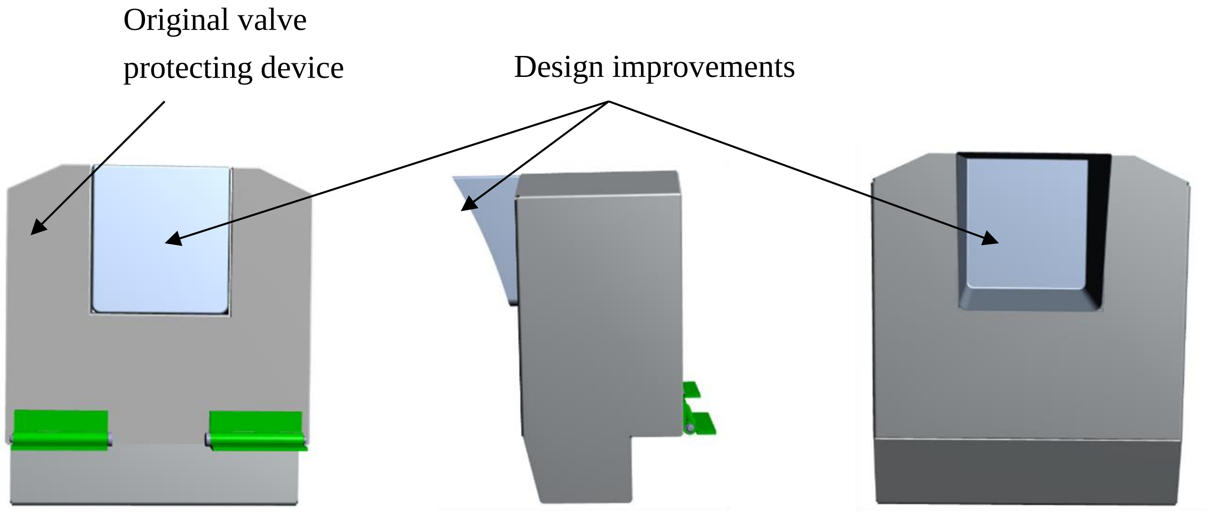

Figure 11: Improved design of valve protecting device

The third improvement is to use the intumescent material also for the plug protecting device where it has the same function as in the valve protecting device.

Verification of the design improvements

To verify the design improvements a DN30 prototype with installed improvements was tested in an oven. The prototype was damaged by a drop test sequence onto the valve corner and a drop test sequence onto the plug corner. It was not pre-heated for this preliminary test. Instead, the duration of the thermal exposure in the oven was prolonged to more than 1 hour. The temperature in the oven was 800°C.

The intumescent material behaved as expected during this preliminary oven test. The gaps between the 30B cylinder and the inner shell of the DN30 PSP were sealed with expanded intumescent material (see Figure 12, left picture). The intumescent material in the valve protecting device expanded considerably and enclosed the valve completely (see Figure 12, right picture). The intumescent material in the plug protecting device expanded as well considerably and enclosed the plug completely.

Figure 12: Expanded intumescent material inside the DN30 PSP after the oven test

The temperature measurements showed that the intumescent material improves dramatically the thermal protection properties of the DN30 PSP. The expanded material closes gaps and cracks and prevents the inflow of decomposition gases into the cavity of the DN30 package.

Figure 13 shows the temperature of the valve as function of time for the original design and for the improved design. For the original design there is a sharp increase of the temperature of the valve after a few minutes thermal exposure time. For the improved design there is a very slight and steady increase over the thermal exposure time. The maximal temperature reached for the improved design are well below the acceptable temperature level for the tin-lead solder.

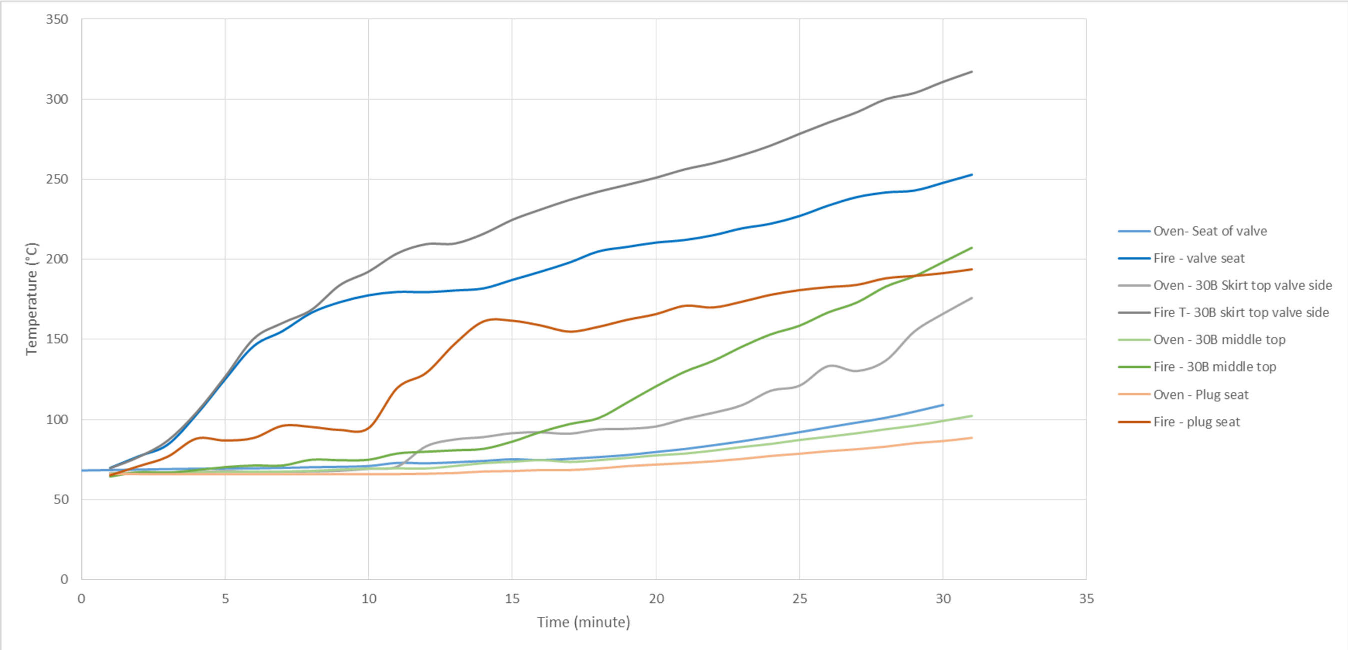

Figure 13: Temperature as function of time

<u>Thermal test of the improved design of the DN30 package</u>

For the thermal test of the improved design of the DN30 package a further prototype was manufactured and the intumescent material applied to the inside of the DN30 PSP, the valve protecting device and the plug protecting device. Then the prototype loaded with a 30B cylinder filled with surrogate material was dropped from a height of 10.2 m onto the valve corner, followed by a bar drop from 1 m height onto the valve area, followed by a 10.2 m drop onto the plug corner, followed by a bar drop from 1 m height onto the plug area.

For preparation of the thermal test the DN30 PSP was opened and the filled 30B cylinder replaced with an empty 30B cylinder. The thermal test is scheduled for early September 2016 and first results will be presented at PATRAM 2016.

Conclusions

The thermal test of the DN30 prototype showed that polyurethane type foams like PIR foam might not offer enough thermal protection for the 30B cylinder and its components in ACT. The decomposition gases of the foam might be driven through cracks or fractures resulting from the mechanical tests into the cavity of the PSP. These hot gases might cause a sharp increase of the temperature by transporting heat directly onto the valve and the plug of the 30B cylinder which could result in melting of the tin-lead solder in the thread and finally a loss of leak tightness.

DAHER NT developed a solution based on intumescent material which does not affect the excellent mechanical behavior of the DN30 PSP in NCT and ACT. PIR foam in a stainless casing is an excellent shock absorber with reliable mechanical properties under all conditions specified in the Regulations. The use of intumescent material between DN30 PSP and 30B cylinder and around valve and plug improve the thermal behavior of the DN30 PSP dramatically.

The modified design of the DN30 package will fulfill the requirements of the Regulations in full.

References

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