Validation of VessFire

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Summary:

Some example on calculations performed by use of *VessFire* has been listed. The results show reasonable good agreement with the experiments and calculations performed by use of other calculation tools.

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1 Introduction and conclusion

VessFire is a computer program dedicated for time-dependent non-linear analysis of thermo-mechanical response during blowdown of process segments and process equipment exposed and unexposed to fire.

Brilliant is an object based, multi-physic simulation system, containing Computational Fluid Dynamic (CFD) solver and Finite Element Method (FEM) solver. Brilliant is developed for simulation of industrial problems containing complex time-dependent physics. Brilliant solves models of different physics simultaneously and for that reason ensure true interaction between physical phenomena. Brilliant is using an unique gridding technology that allow a span in grid size from tenth of a mm to size of km within the same case and with a limited number of control volumes.

VessFire is built on Brilliant. The program is a coupled solution of problems using a combined numerical and analytical approach to simulate:

- Heat transfer from the fire onto the vessel, flow line, heat exchanger or pipe work ("object") surface, the surface of fire protective coating, thermal insulation or a protective shield
- Heat transfer through the fire protective coating, thermal insulation or protective shield
- Heat conduction through the object shell
- Heat transfer from the inner object surface to the object contents
- Thermodynamics of the object contents
- Variation of pressure in the object due to depressurization counter-acted by the increase of the pressure due to evaporation, boiling and expansion of object contents
- Stress in the object shell
- Temperature in the depressurization pipe work for material selection
- Time to object failure.

VessFire may be used for simulation of vessels with no flow or flow lines / pipe work or heat exchangers with flow, where in the latter case; the flow removes heat transferred from the fire. Any time variation of the heat input from the fire may be simulated.

VessFire was developed in 1998 in response to the requirements in the petrochemical industry for a computer tool that would rapidly simulate the thermo-mechanical response of pressurized systems to accidental fires in the petrochemical industry, offshore and onshore. Since its inception, the program has been applied in the design and analysis of great number of pressurized objects and depressurizing systems in the oil & gas, refinery and chemical industries to prevent object explosions, escalation and "domino effect". The program follows the requirements outlined in *Guidelines for the Design and Protection of Pressure Systems to Withstand Severe Fires* (Ref. 1) and the *Guidance for the Design and Analysis of Fire Response of Pressurized Systems* (Ref. 2).

VessFire is under continuous development. Petrell AS, who supplies *VessFire*, works in process safety and system integrity engineering, and associated research. New capabilities are developed in *VessFire* as new requirements are identified and research findings are obtained. *VessFire* users may also require their own specific capabilities to be included in the program.

VessFire is documented in two manuals, ref. 6 and 7. The two manuals are respective the User Manual and the Technical reference Manual.

2 The purpose of the document

This is a collection of verification examples performed with *VessFire*. The collection is made to document the validness of *VessFire*. Most of the cases shown here are compared to experiments, but some are also compared to other calculation methods that have been performed on special cases.

The results are in reasonable good agreement with the measurements and other simulation system.

In chapter 9 a case with long-term exposure is presented. The case is not compared to any experiments, but is included to visualise the effect of long-term exposure. Even if the pressure is lowered rapidly during the first blowdown period, there is a pressure rise later when the inventory begins to boil.

3 Cold Blowdown

This cold blowdown experiments was performed in 1992 by M.A. Haque et all, ref. 1. The data and compared results are copied from M. Mahgerefteh and S.M.A. Wong, ref. 2.

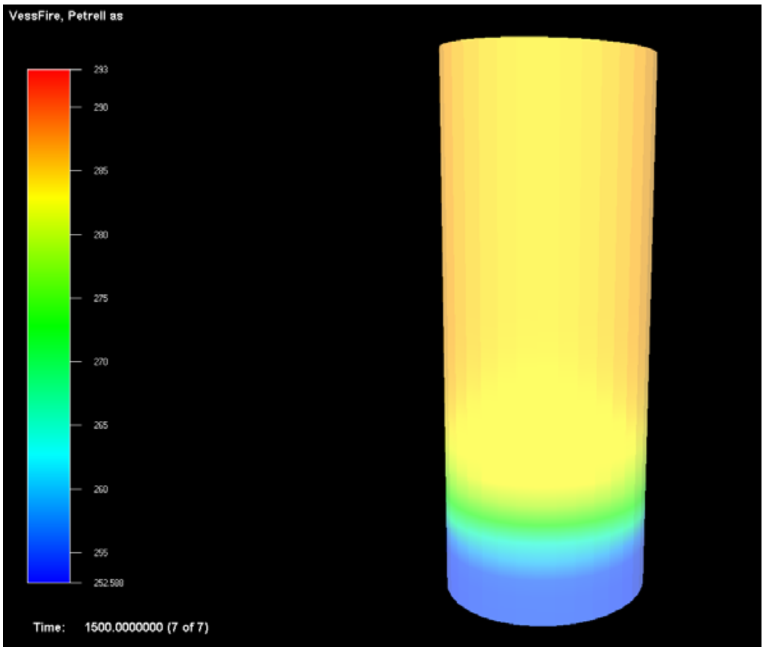

Figure 1 **Temperature plot of the 3-dimenional model of the vessel applied in calculations. The temperature variation is after 1500 secounds.**

According to ref. 2 the experiment is performed on a vertical full-size suction scrubber with given inside diameter of 1.130 m and length 3.240 m (2.75 m tanto-tan). The wall thickness was 0.059 m. The inside composition was a gas mixture with molfraction C1 0.64, C1 0.06, n-

C3 0,28, n-C4 0,02. The initial conditions where: pressure 116 atm and temperature 293 K. The equivalent choke diameter was 10 mm. The results are described below. The figures includes comparisons between experiments, VessFire version 1.2, ref. 6 and 7 and Blowdown by M.A. Haque et al. ref. 3.

The experiment is not to well documentet, but it is assumed that the wall temperature of the sucrubber initially has the same temperature as the gas and that the environmetal conditions are calm air with a temperature similar to the scrubber shell temperature. As seen from Figure 1 there is a variation of temperature in the shell dependent on location. There is minor information where the shell temperature is measured.

VessFire calculates 3-dimensional temperature profiles for the shell. The steel temperatures presented here by VessFire is the average with respect to the wall thickness. VessFire seek the lowest and the highest average temperatures in the shell. The highest will be located in the gas zone and the lowest is located in the liquid zone.

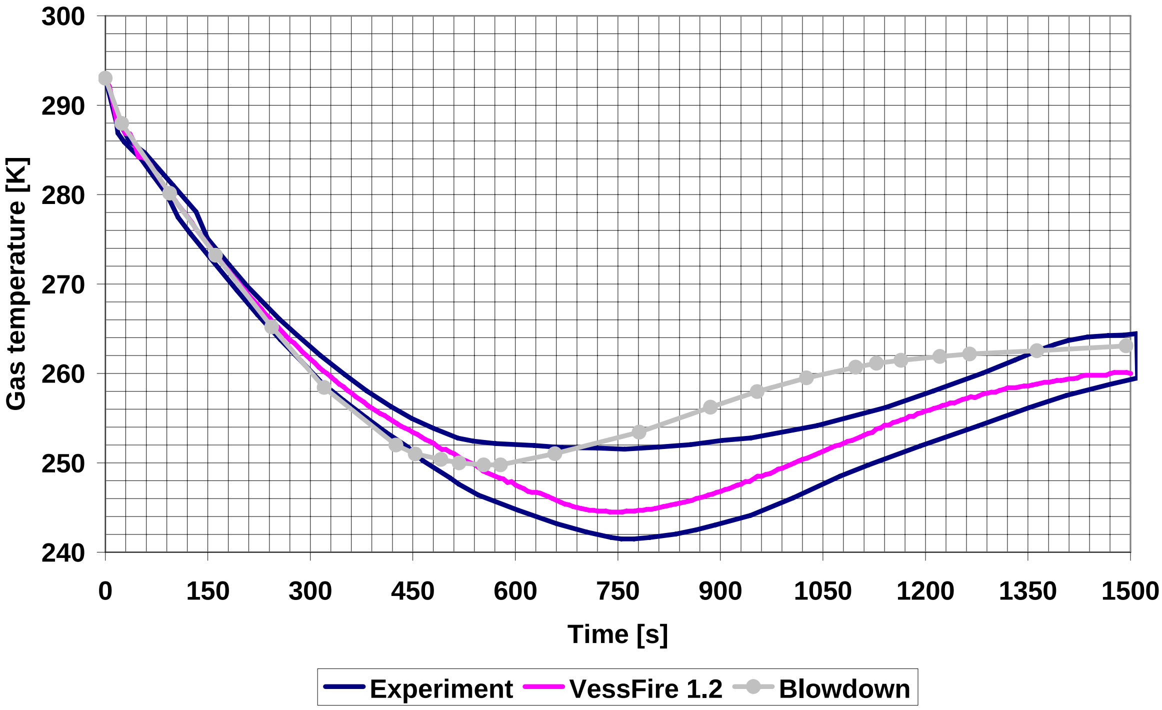

Figure 2 **Gas temperature as function of time during cold blowdovn of gas. The blue lines indicate the span of the measured temperature.**

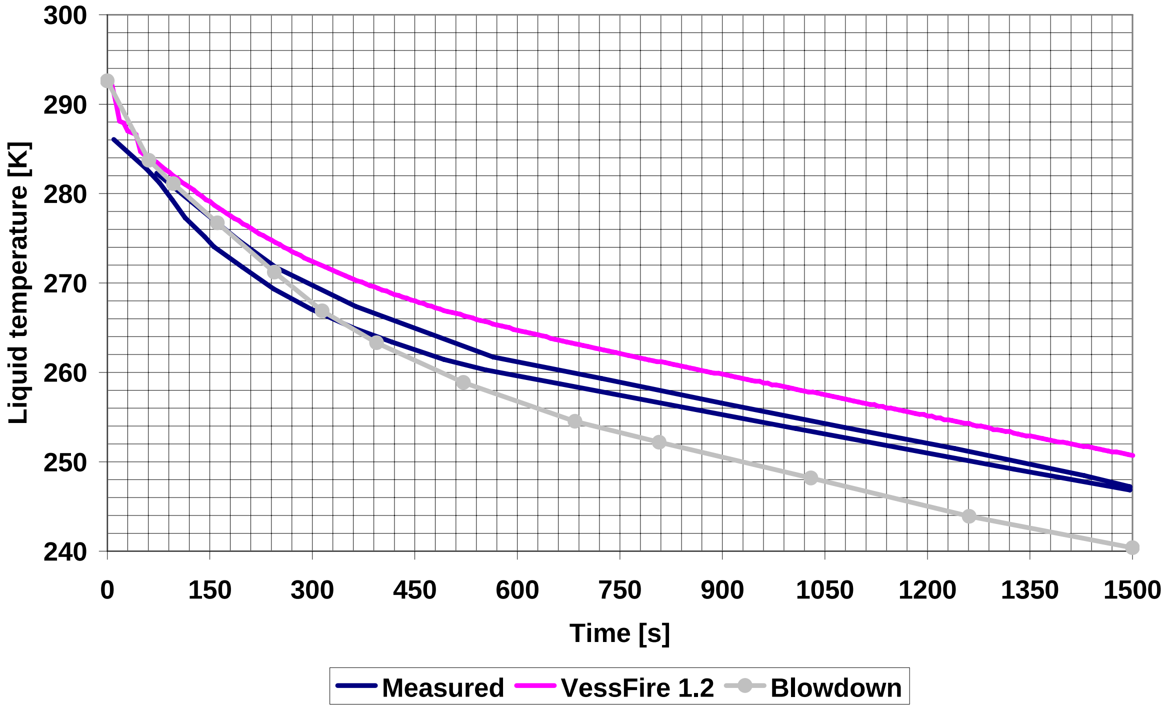

Figure 3 **Liquid temperature as function of time. Comparison between measurements and calculations.**

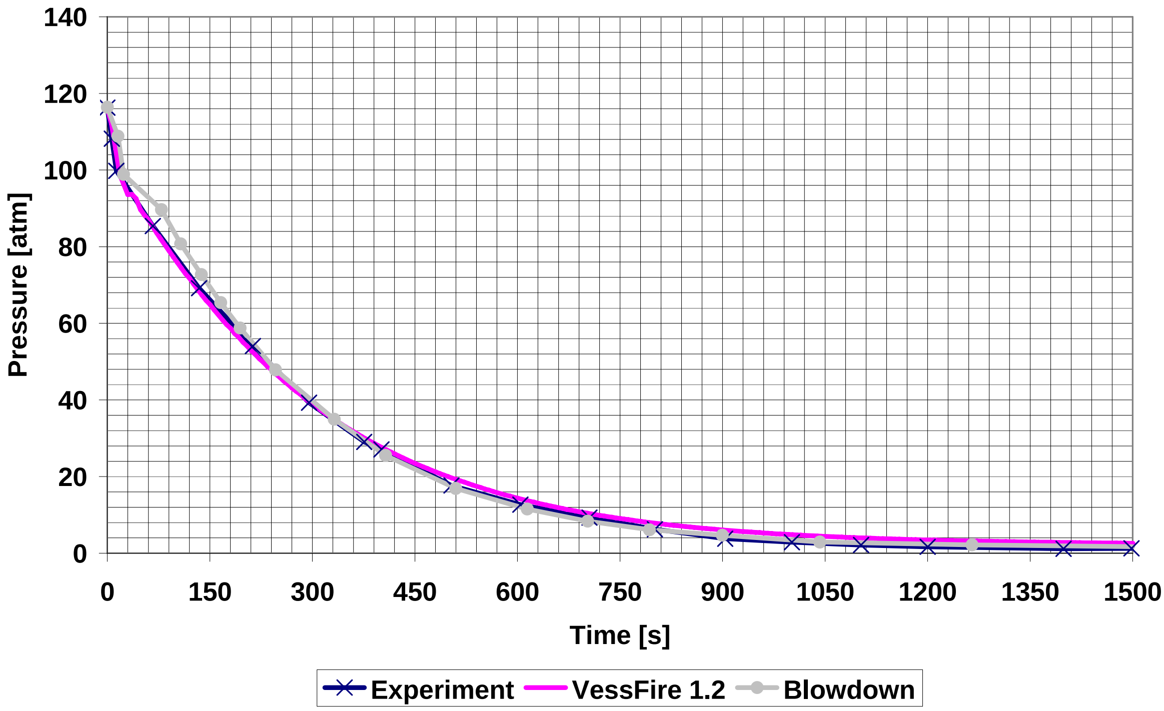

Figure 4 **Pressure as function of time for the cold blowdown. Comparison between measurements and calculations.**

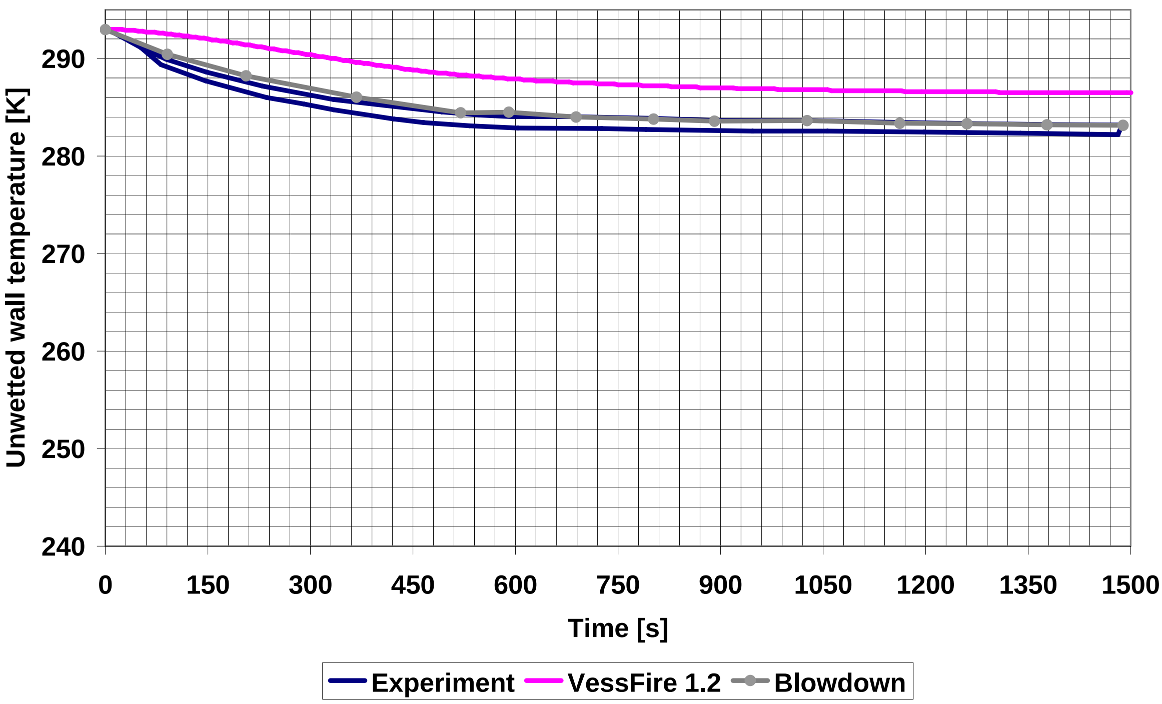

Figure 5 **Unwetted wall temperature as function of time. Comparison between measurements and calculations.**

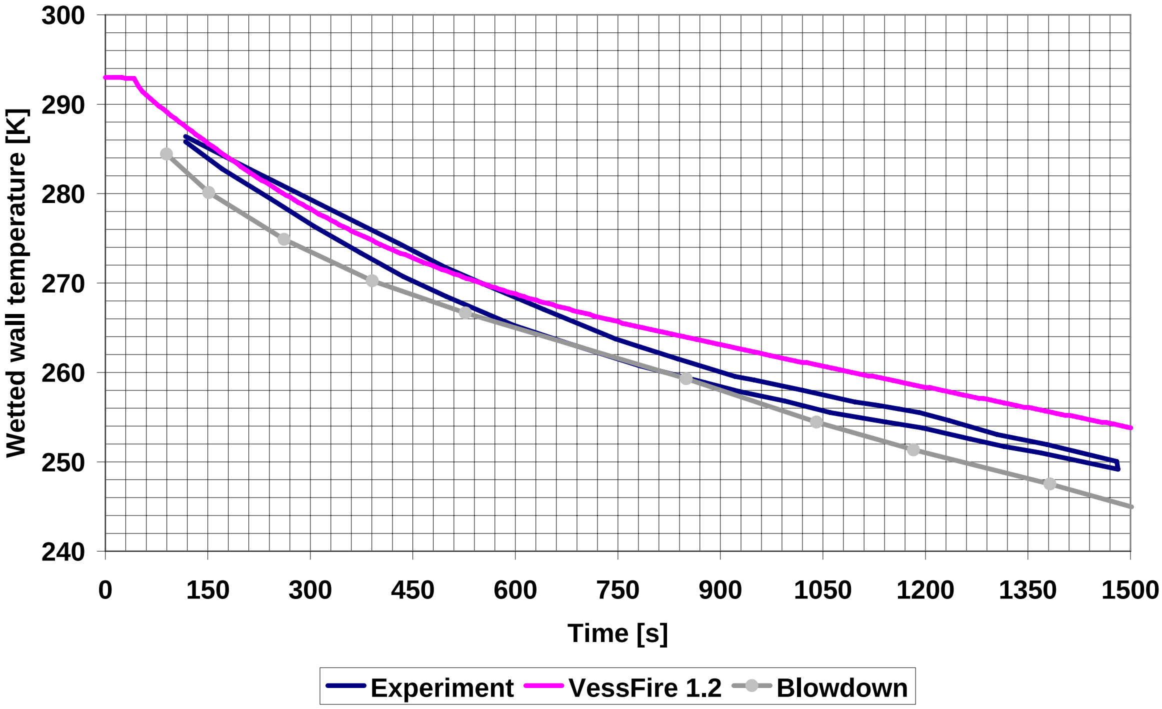

Figure 6 **Wetted wall temperature as function of time. Comparison between measurements and calculations.**

4 Pipe insulation in bulkhead

This is a calculation of a penetration of a bulkhead. On the exposed side of the bulkhead (steel plate) the pipe is closed with a steel plate welded to the pipe. The pipe and the insulation inside the furnace are exposed to the standard temperature curve (ISO 834). Temperature is measured on the insulation and the steel as shown in Figure 7. This case is special in that radiation inside the pipe is essential to the results.

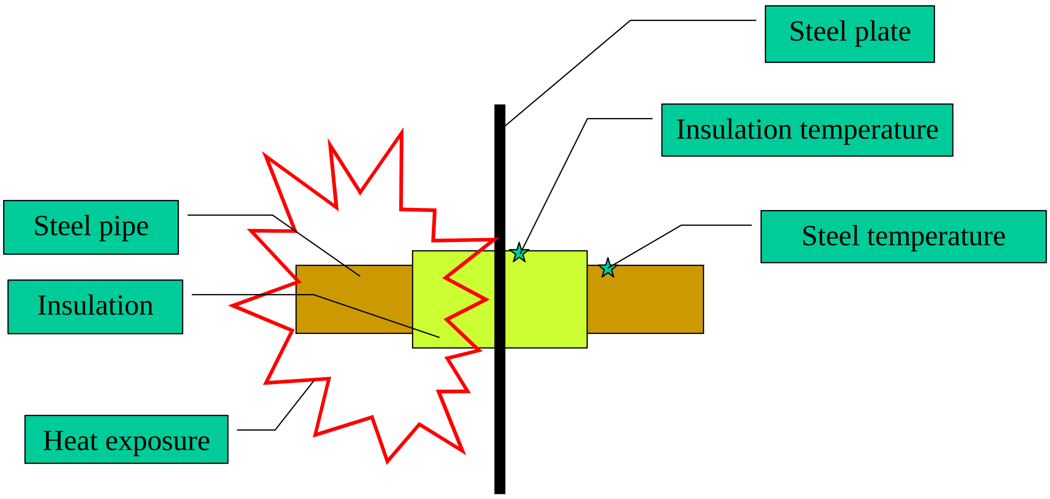

Figure 7 **The figure shows a principle drawing of a test. A specimen is exposed to fire on one side of a bulkhead. Temperatures are measured as shown on the figure at the opposite side of the bulkhead.**

Figure 8 shows the results of the calculations compared to the measured temperature. The calculations where only made for 60 minutes.

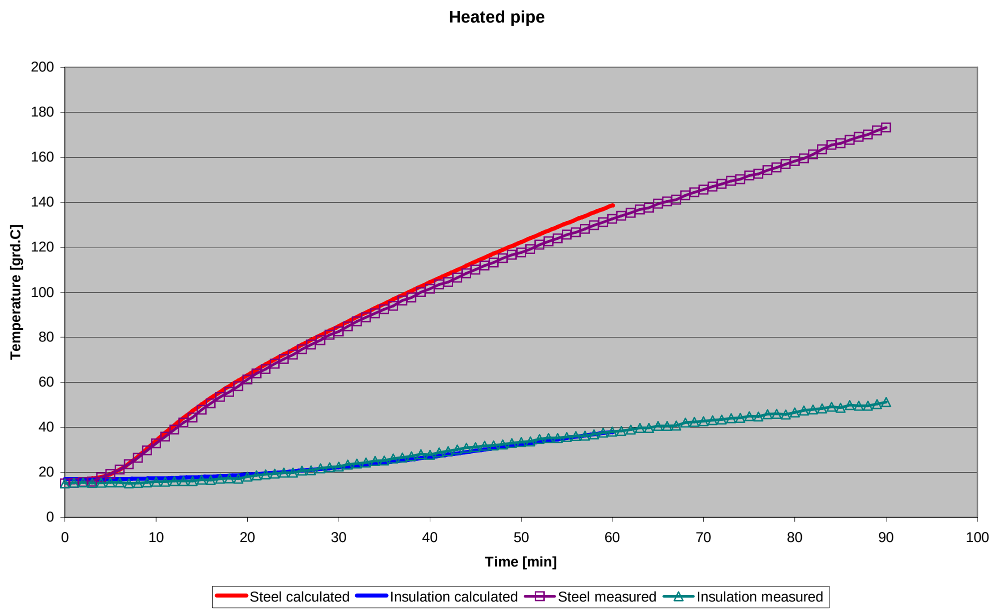

Figure 8 **Simulation results performed with *VessFire* are compared to measurements performed in a test furnace at the Norwegian Fire Laboratory for the test case shown in Figure 7.**

5 Comparison with PRO II

VessFire has been compared with other calculation systems. Neither of the system represents the "ultimate" solution, but indicate the range of expectation. The results indicate that *VessFire* give predictions in the expected range compared to other methods. The comparison is done for three different cases are shown below.

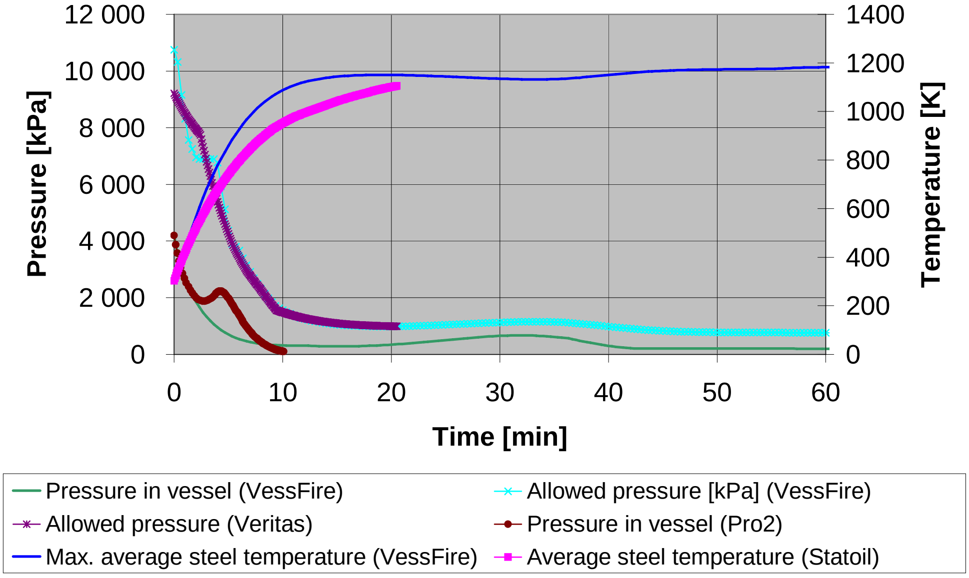

Figure 9 **Vessel exposed to flame. The results from *VessFire* are compared with results from PRO/II and calculations performed by Statoil and Det norske Veritas (DnV). The deviation between PRO/II and *VessFire* (the top after 5 minutes) is due to a difference in heat load. PRO/II had not the ability to implement the heat load properly.**

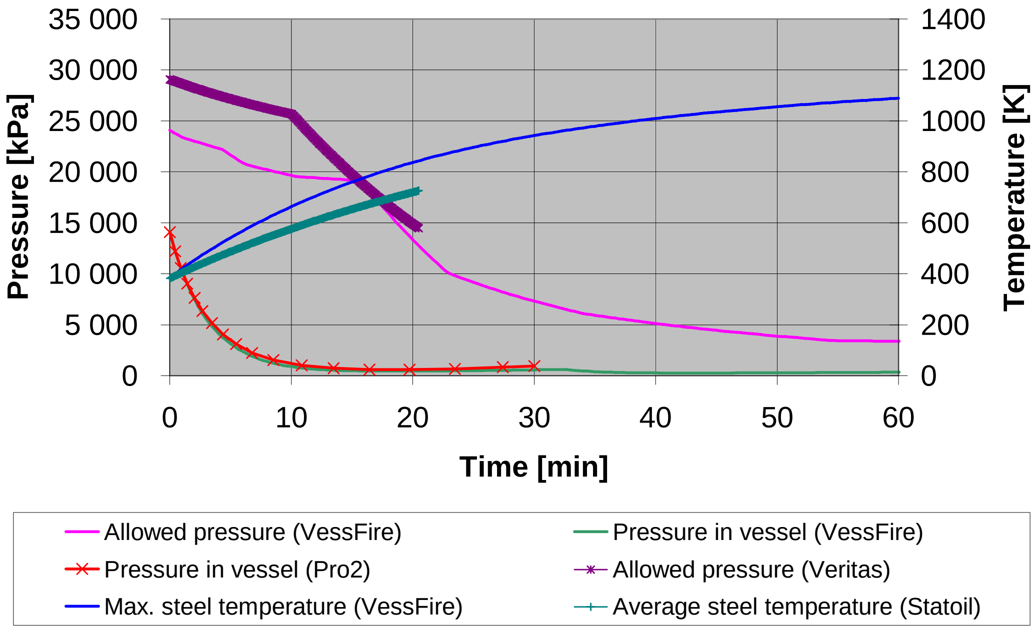

Figure 10 **Result from blowdown of a first stage separator under exposure of heat load. The results from *VessFire* are compared with results from PRO/II and calculations performed by Statoil and Det norske Veritas (DnV).**

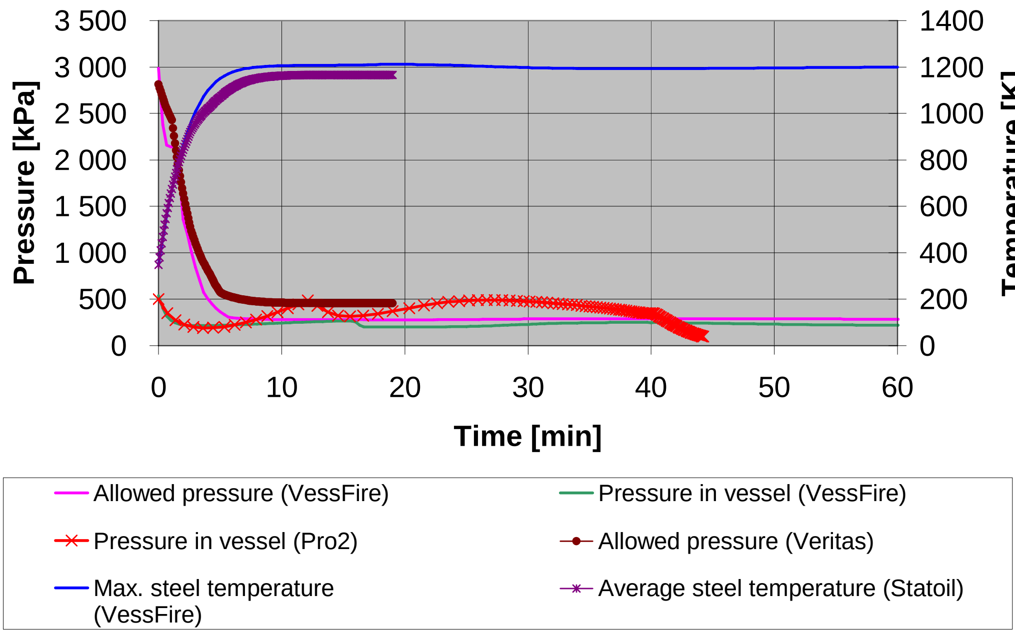

Figure 11 **Vessel exposed to fire. The results from *VessFire* are compared with results from PRO/II and calculations performed by Statoil and Det norske Veritas (DnV). The deviation between PRO/II and *VessFire* (the top after 12 minutes) is due to a difference in heat load. PRO/II had not the ability to implement the heat load properly.**

6 Exposure of a spool piece (cylinder)

Some small-scale experiment was performed on a 1060 mm long cylinder with inner diameter 177 mm and material thickness of 12 mm. The cylinder was exposed to heat load varying from 20 to 260 kW/m^2. The exposure was done by an element heated by electricity. The experiments are documented in ref. 1. The cylinder was completely closed in one end. At the other end there was a 50 mm opening to the atmosphere, see Figure 12.

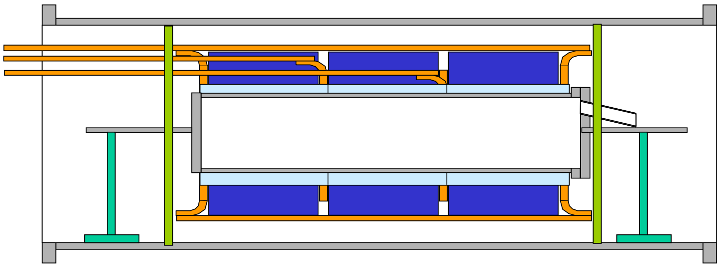

Figure 12 Experimental upset. The cylinder is surrounded by heat element consisting of a thin nickel foil.

Two cases where calculated with *VessFire*. On case (case 5) where the dry cylinder is exposed to heat and another case (case 7) where the cylinder is partly filled with water and exposed to heat.

6.1 Dry cylinder exposed to heat

This calculation correspond to the experiment no. 5 in ref. 1. The radial emissivity for the cylinder surface was 0.8 and the heat element emissivity was 0.9. The emissivity for the heat element was estimated based on measurements.

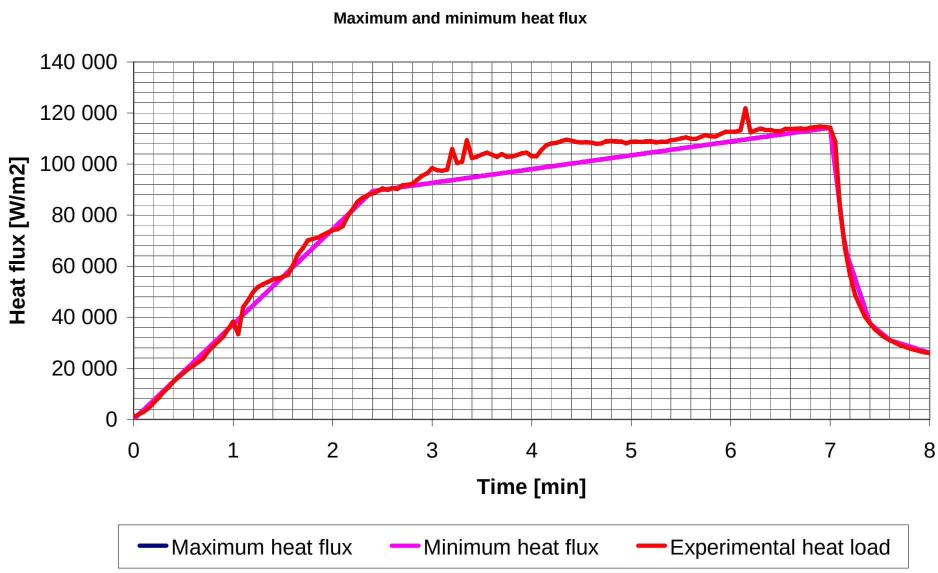

Figure 13 The figure shows the heat load from the experiment compared to the heat load used in the calculations as function of time. Here the maximum and minimum heat load is the same.

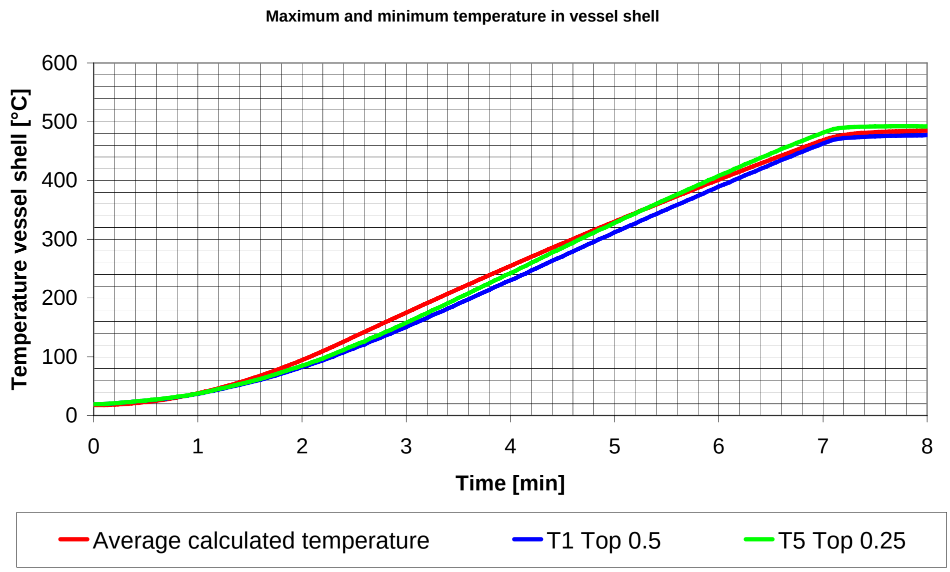

Figure 14 **The figure shows the steel temperature for the case. The temperature T1 is measured on top of the cylinder 500 mm from the exit opening. The temperature T5 is measured 250 mm from the exit opening.**

6.2 Cylinder partly filled with water

This calculation correspond to the experiment no. 7 in ref. 1. The cylinder was initially filled with 1 kg water. The radial emissivity for the cylinder surface was 0.8 and the heat element emissivity was 0.9. The emissivity for the heat element was estimated based on measurements.

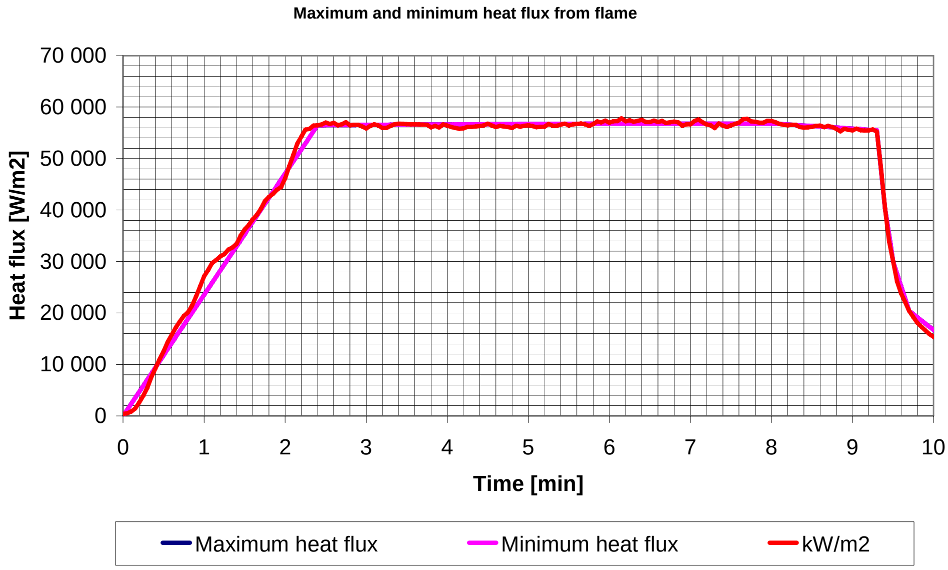

Figure 15 **The figure shows the heat load from the experiment compared to the heat load used in the calculations as function of time. Here the maximum and minimum heat load is the same.**

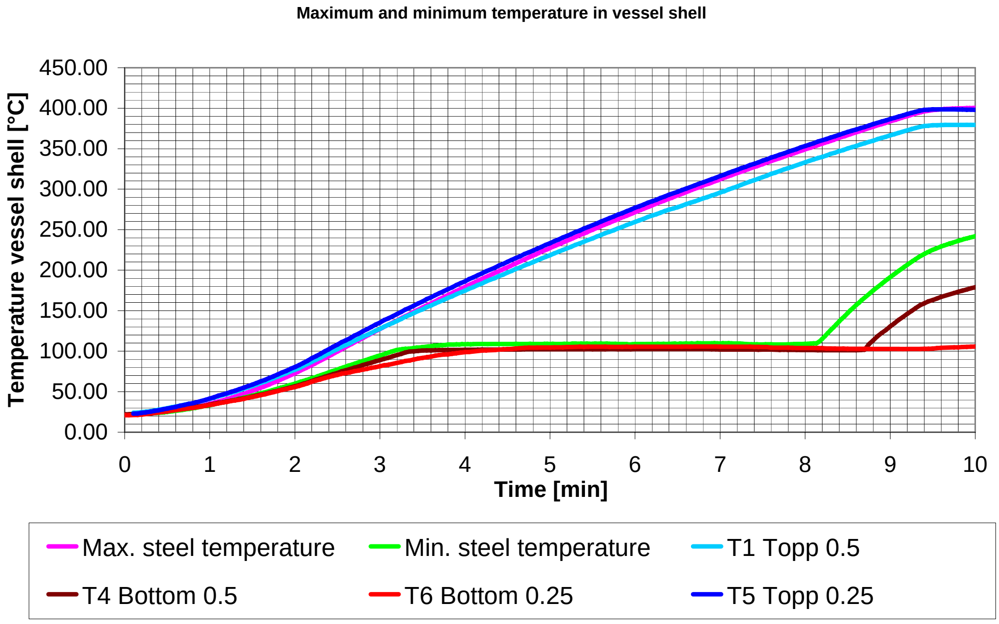

Figure 16 **The figure shows the steel temperature for case 7. The temperature T1 is measured on top of the cylinder 500 mm from the exit opening. The temperature T5 is measured 250 mm from the exit opening. The temperatures at the bottom, T4 and T6, are located at the bottom of the cylinder in respective 500 and 250 mm from the cylinder exit.**

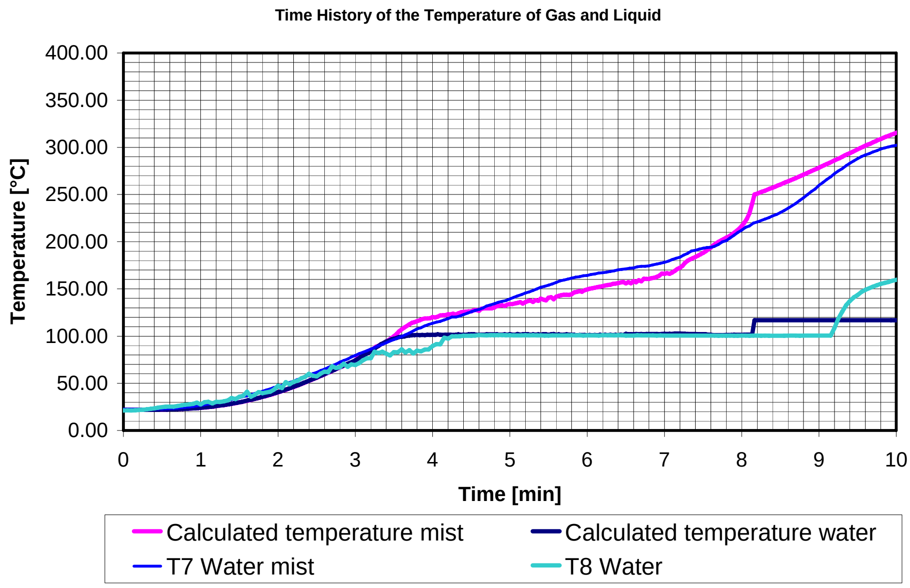

Figure 17 **The figure shows the temperature in the water and the water mist compared to the calculations.**

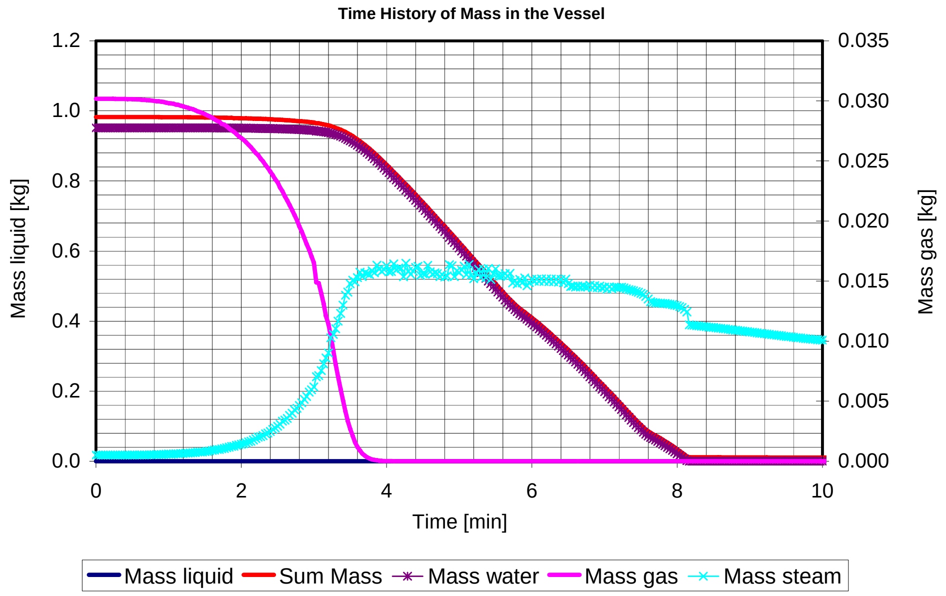

Figure 18 **The calculated mass balance of the cylinder is shown in the figure . The "mas gas" line indicate the air content.**

7 Blowdown of a vessel filled with air

This case is based on an experiment performed at Cowley, England in 1968, ref. 9. A horizontal cylindrical gas storage vessel, about 48 m long and 4 m in diameter (volume 525 m^3 and dry weight 127 000 kg) was pressurized with air. The tank had an initial pressure of 21.5 bar a. It was than depressurized during a period of 2 hours with a constant release rate. The documentation available does not indicate how this was done, but having reached a sub-critical pressure inside the vessel (1.8 bar a) it is assumed in the calculations that a sub-critical flow is established. It is also assumed that the vessel and the air temperature initial were of the same magnitude. The result of the calculation is shown in the figure below.

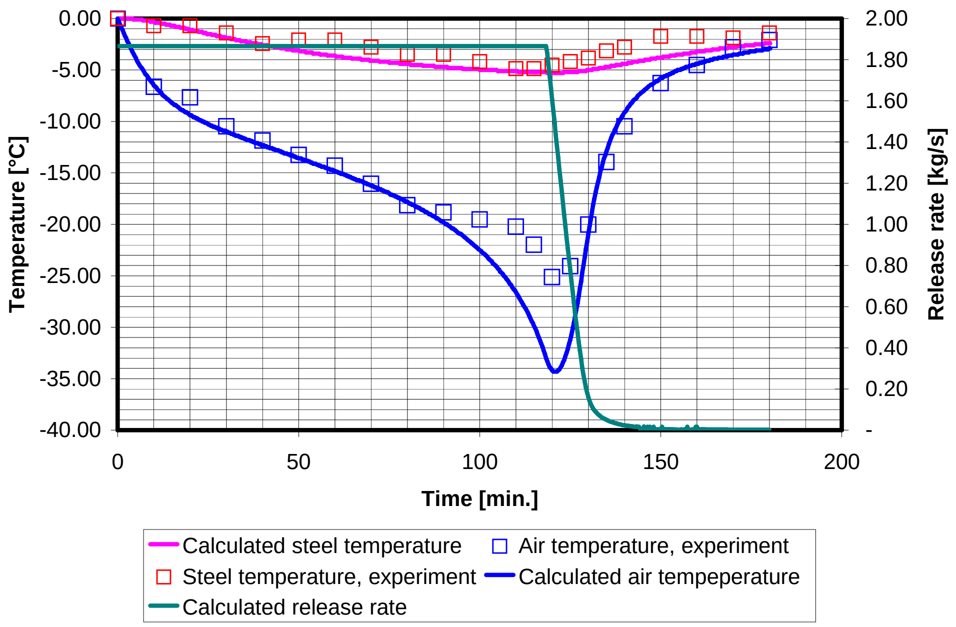

Figure 19 **The figure shows calculated and measured air and steel temperature. The release rate is also indicated. After 2 hours, it is assumed that the orifice flow is sub-critical.**

8 Vessel partly filled with propane and exposed to fire

This case is based on experiments documented in ref. 10. A LPG vessel is exposed to an engulfing fire from a pool of kerosene. Results are reported for different filling levels. The one used here is the 22 volume % filling. The vessel was filled with commercial propane. In the calculations, 95 mol% propane and 5 mol% normal butane were used. The outer diameter of the vessel was 1.7 m and the length 4.88 m (TT), giving a total volume of 10.25 m^3. The wall thickness of the shell was 11.85 mm. The initial pressure was set to 5.5 bar a, and the initial temperature of the inventory was 5.7 °C. Two PSV each with an effective area of 8.87 10^{-4} m^2 and an opening pressure of 14.3 bar a (fully opened at 15.5 bar a), where installed. The average heat flux measured with heat flux thermocouples is showed in Figure 20.

The vessel was originally built as a road tanker. For that reason it is assumed, in the calculations that the vessel is made of stainless steel. The flame emissivity is set to unity and the surface emissivity to 0.7.

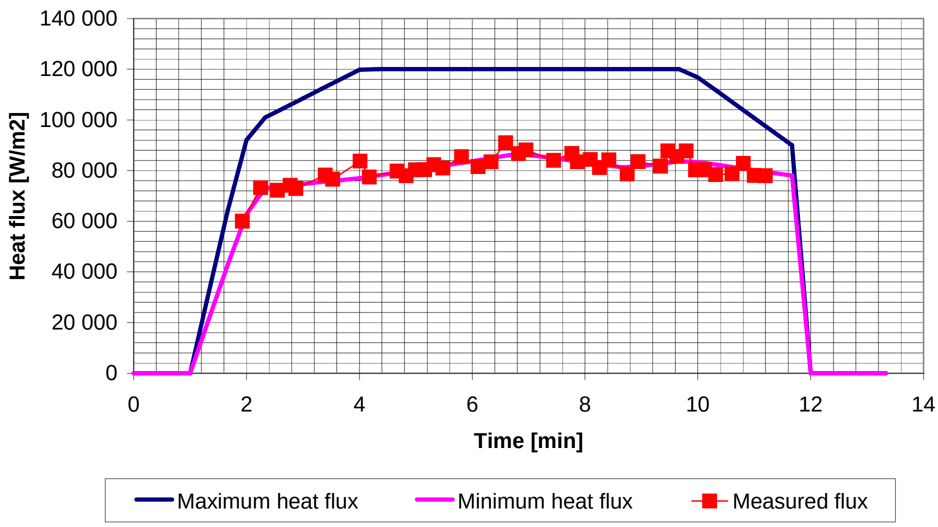

Figure 20 **Measured and applied heat flux for the case. It was reported that the fluxes varied around the tank, but only the average flux where available. The highest flux was exposing only on a minor part of the vessel and did not influence the inventory. It was applied just to indicate the magnitude of the heat load necessary to achieve the highest steel temperature reported.**

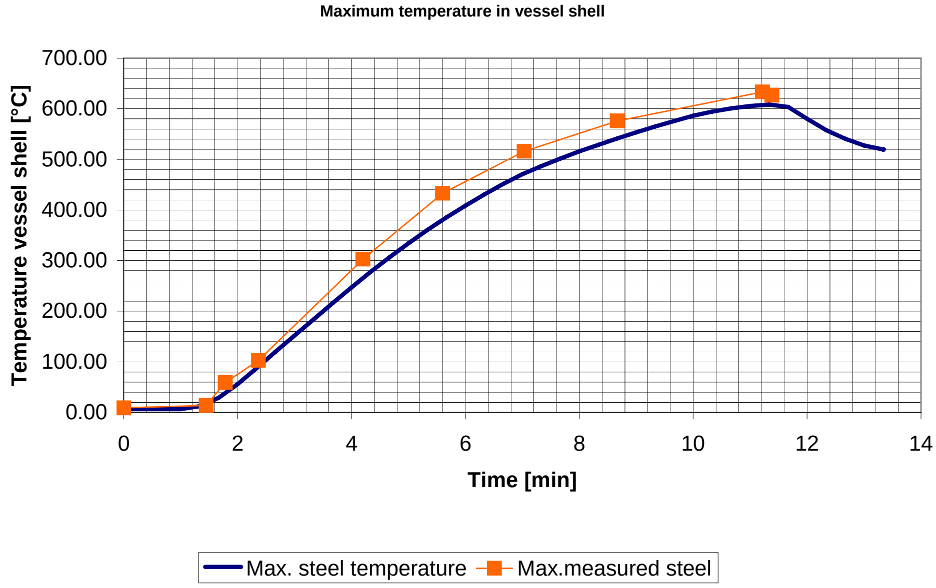

Figure 21 **The figure shows the maximum measured shell temperature and the maximum calculated temperature. This was the only temperature included in the reference. Temperature differences were nevertheless measured on the shell in the range of 170 °C. The high temperature was reported to indicate a difference in heat load over the shell.**

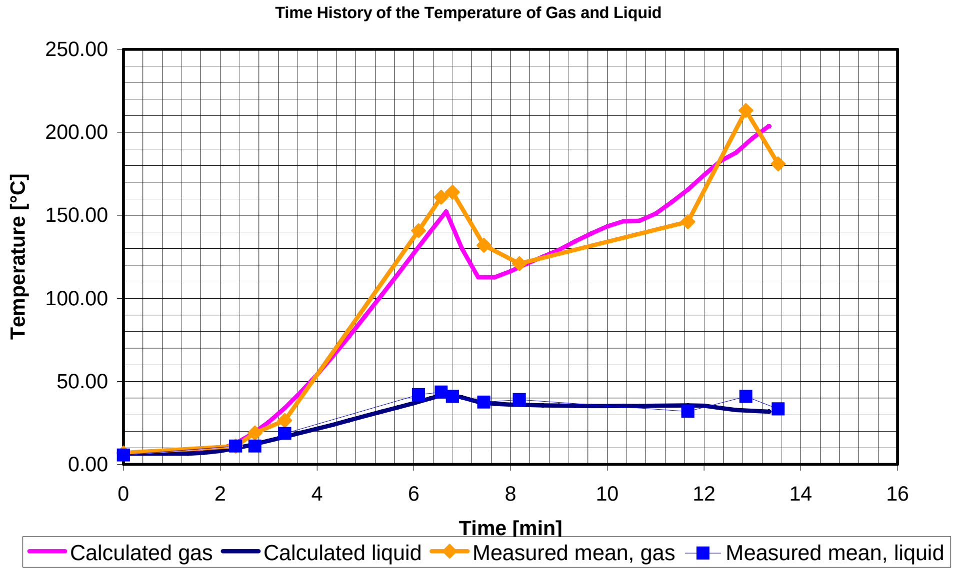

Figure 22 **Calculated temperatures of liquid and gas compared to measured values. A variation in temperature inside was also reported. This was the reported inside average gas temperature.**

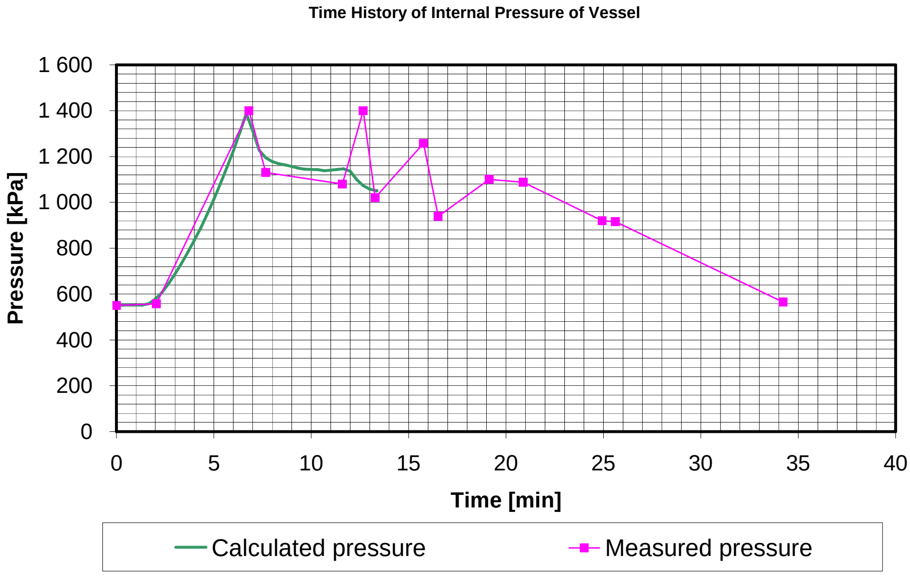

Figure 23 **The figure shows the measured and calculated pressure history. The opening and closing of the PSV are dependent on the type PSV applied. It is not known what kind of PSV that was applied in the experiments. In the calculation, the triangular type (see User Manual) is used.**

9 Long term exposure

There are no experiments available for this case. The case is included here to show the effect of a long-term exposure. The case is a vessel insulated by a 5mm thick insulation. The vessel is constantly exposed to 300 kW/m^2 during the whole period until the vessel is emptied for liquid. The requirement from the customer was that the vessel should not break at any time until it was emptied.

The results of the simulation are shown on the figures below.

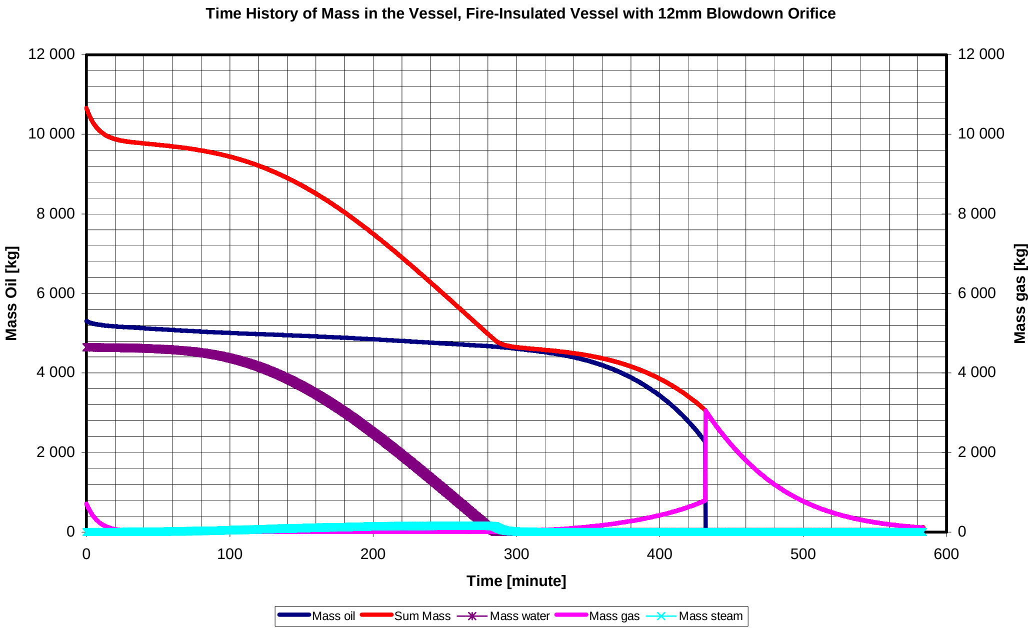

Figure 24 **The figure shows the mass content of liquid and gas inside the vessel with time. Note that at a certain stage the liquid turn into gas. The inventory pressure and temperature are than above the critical point.**

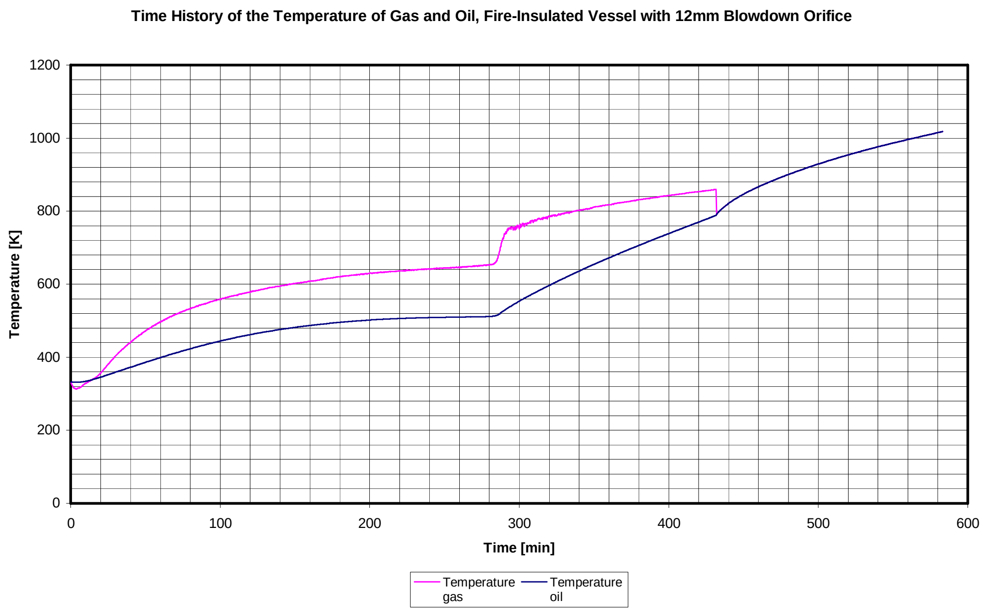

Figure 25 **The figure shows the temperature history for liquid and gas. Note that at a certain point the temperature for gas and liquid is equal. The liquid has than turned into gas.**

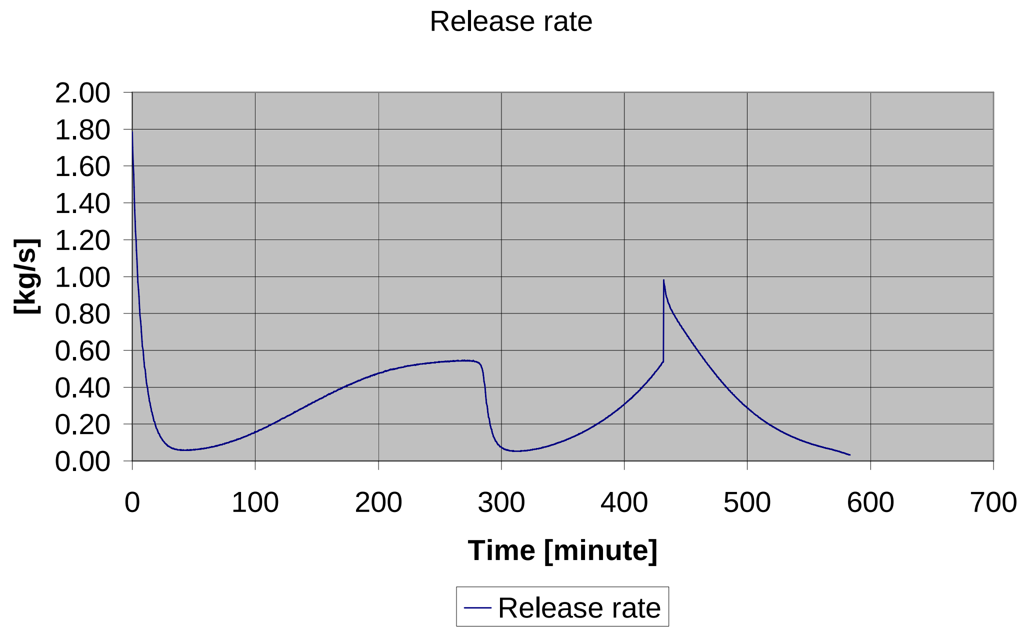

Figure 26 **The figure shows the release rate with time. When the liquid turn into gas, there is a peak in the rate.**

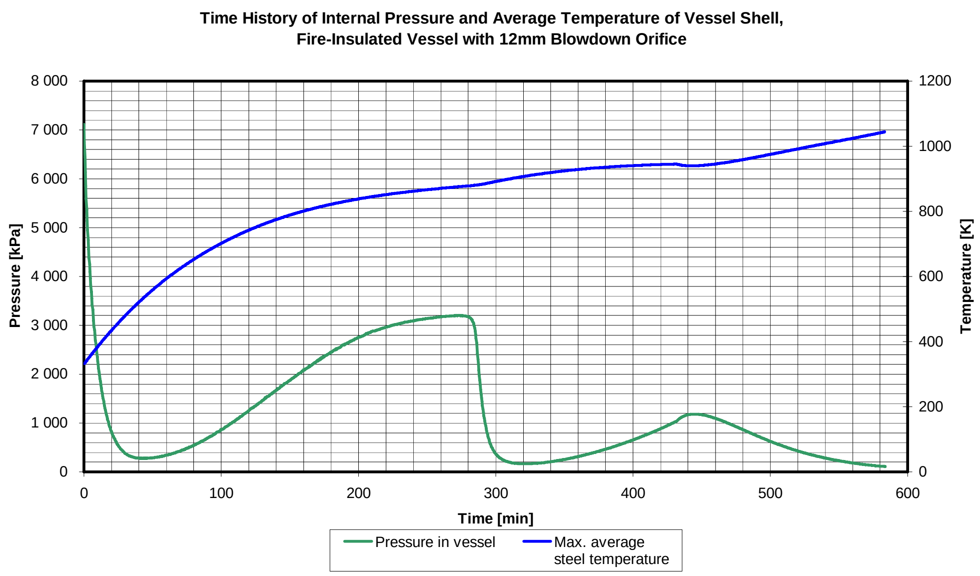

Figure 27 **The figure shows the pressure of the inventory together with the maximum steal pressure. Note the second pressure peak where the liquid is evaporated.**

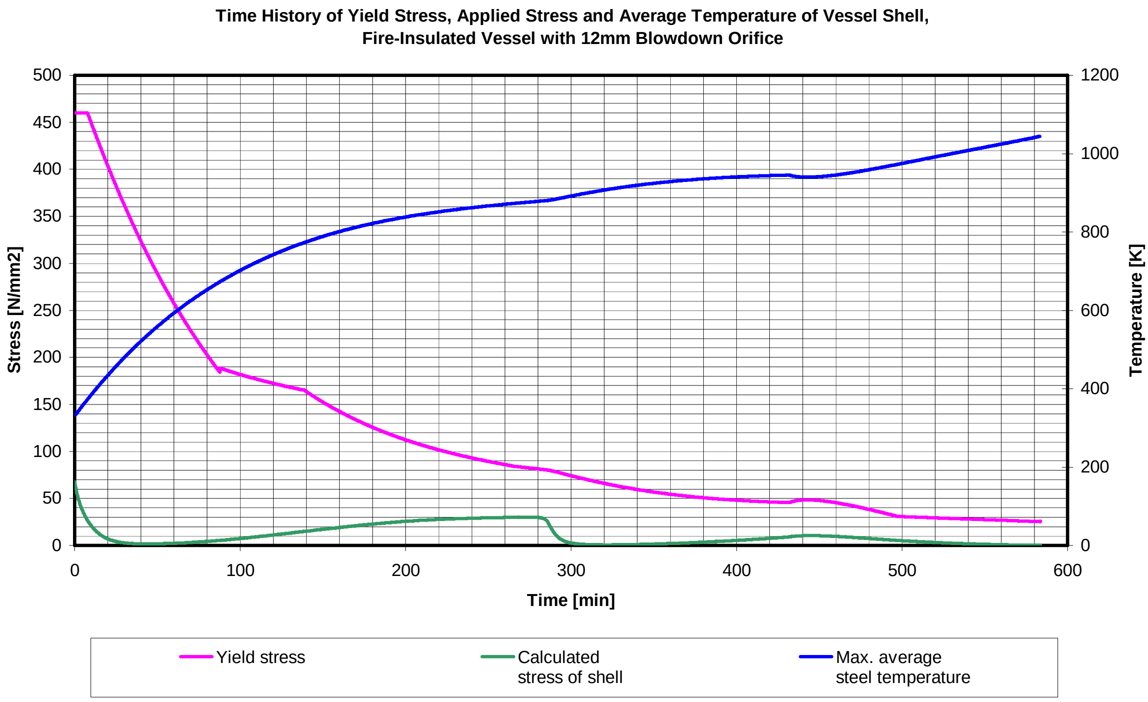

Figure 28 **The figure shows the time history for the shell material yield stress ($\sigma_{0.2}$), the calculated shell stress and the maximum shell temperature.**

10 References

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