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MODELLING THE RESPONSE OF TANKERS EXPOSED TO EXTERNAL FIRE IMPINGEMENT

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ABSTRACT

A computer model has been developed which can simulate the response of a tanker and its lading to external fire impingement. The model was developed as a tool to study the effectiveness of new concepts in thermal protection of tankers.

The computer model can simulate a long cylindrical tank filled partially with liquid and partially with vapour exposed to either an engulfing type fire, such as caused by a burning pool, or a torch type fire, such as that caused by a relief valve flare from a neighbouring tank. The model can account for the effects of a number of thermal protection devices such as pressure relief valves, thermal insulation, radiation shielding, temperature sensing relief valves, and novel internal protection devices, including heat dissipating matrices. The model can simulate the effects of roll and pitch of the tank.

The computer model is capable of predicting the tank internal pressure, mean lading temperatures, wall temperature distribution, relief valve flow rates, liquid level, tank wall stresses and tank failure all as functions of time from initiation of the fire impingement. The model has been validated by comparing its predictions with the results of numerous fire tests involving full and fifth-scale rail tank-cars exposed to engulfing fires. Several examples of these validation runs are presented and discussed.

INTRODUCTION

In the past two decades, considerable effort has been made in North America to understand the mechanisms involved when a tanker is exposed to external fire impingement.

In the early 1970's the US Federal Railroad Administration/ Department of Transport (FRA/DOT),the Railway Progress Institute (RPI) and the American Association of Railroads (AAR), in cooperation with major railroads, tank-car builders and operators carried out an extensive rail tank-car safety program called the Railroad Tank-car Safety Research and Test Project (TCSRTP) (1). This project looked at all aspects of tank-car safety including thermal and mechanical aspects. The TCSRTP included both significant experimental and analytical studies and resulted in technological improvements in tank-car design which have since been incorporated. This project also resulted in the development of a computer program that could simulate the effects of fire impingement on a rail tank-car (2).

In Canada in the late 1970's the Transportation Development Centre of Transport Canada carried out an independent tank-car safety project. This work focused primarily on the thermal aspects of tank-car design and involved the evaluation of novel concepts in thermal protection (3). Both experimental and analytical studies were involved, and this work also resulted in the development of a computer model to predict the effects of fire impingement on tankers (4). This computer model is known as the Tank-Car Thermal Computer Model (TCTCM) and is the subject of this paper.

The two computer models introduced above were developed with the intention that they would be valuable tools for evaluating novel concepts in thermal protection. The TCTCM has been used recently to evaluate a new internally mounted device intended to maintain wall temperatures at safe levels by enhancing convective heat transfer from the tank wall to the lading. The TCTCM is presently being used to evaluate an internally mounted device which cools hot areas of the tank wall by directing liquid lading along the wall when the tank relief valve is operating. It is believed that by using a tool such as the TCTCM to pre-screen novel concepts for thermal protection, the cost of testing can be significantly reduced.

EFFECTS OF FIRE IMPINGEMENT

When a tanker is exposed to external fire impingement heat is transferred from the fire to the tank outer surface by convection and thermal radiation. If the fire is large, radiation will dominate. If the fire impingement involves a high velocity jet (such as a burning relief valve flare from a neighbouring tank) then both convection and radiation are important.

Heat transferred to the tank outer surface is conducted through the insulation layer (if present) and through the tank shell to the tank wall inner surface. From the tank inner surface, heat is convected and radiated into the lading.

Where the tank inner surface is wetted by liquid, the heat transfer coefficients are relatively high, and therefore the heat is efficiently drawn out of the shell into the lading. In other words, in liquid wetted areas of the tank wall, the wall is effectively cooled by the liquid and as a result, the wall temperature in these regions is close to that of the liquid lading (this is especially true when boiling is taking place).

Where the tank inner surface is in contact with lading in the vapour phase, the heat transfer coefficient is relatively low. In this vapour space the heat is not effectively transferred from the tank shell, but remains in the tank wall with the result that the wall temperatures in these regions increase rapidly. As the wall temperatures increase in the vapour space, thermal radiation from the tank inner surface to the lading becomes increasingly important. However, wall temperatures in the vapour regions can, if heat fluxes are high enough, reach levels that cause significant degradation of the tank shell material properties.

The heat transferred into the lading causes the lading temperature to increase, which in turn causes the tank internal pressure to rise. Eventually the pressure will reach a level where the pressure relief valve will open.

The thermal rupture of a tank depends on the tank internal pressure, the tank wall temperature distribution, and the tank material strength at the elevated temperatures which exist during the fire. If very high wall temperatures are achieved, then the tank will rupture even if the relief valve maintains the tank pressure well below the nominal burst pressure for the tank. Thermal protection systems such as thermal insulation are used to maintain acceptable wall temperatures in the vapour space during an event such as accidental fire impingement.

The above processes have been recorded in a number of fire tests conducted using full and fifth-scale tank-cars. For further details the reader is directed to References (3,5,6).

THE MODEL

The TCTCM is a digital computer based model capable of simulating the response of a tank-car and its lading to conditions of external fire impingement (engulfing fire or torch type fire). The model is basically a two-dimensional representation of a circular cylindrical tank (i.e., axial gradients and end effects are not accounted for). The model has a pseudo-3D operating mode so that pitched and rolled tanks can be analyzed.

The TCTCM is capable of predicting tank internal pressure, tank wall temperature distributions, relief valve flow rates, tank fill level, and tank wall stresses and strength, all as functions of time from fire ignition. These various outputs define the response of the tank/lading system and provide valuable information for the design of a thermal protection system.

The model is made up of a series of submodels simulating the following processes:

(1) Flame to tank heat transfer,
(2) Heat transfer through the tank wall and associated coverings,
(3) Interior-surface to lading heat transfer,
(4) Thermodynamic process within the tank,
(5) Thermodynamic properties of the lading,
(6) Pressure relief device operating characteristics,
(7) Wall stresses and material property degradation,
(8) Tank failure.

The flame-to-tank heat transfer submodels can account for either an engulfing pool fire or a two-dimensional torch. The pool fire model accounts for thermal radiation and convection. The thermal radiation is calculated as a function of the circumferential position on the tank by accounting for the typical shape of large pool fires in the absence of cross wind effects. The convection calculations are based on empirical relations for convection to horizontal cylinders in a crossflow. The torch submodel is based on empirical relations for a jet impinging on a flat plate. The geometry of the jet/plate system in the submodel is similar to the US DOT Transportation Test Center Torch Simulator as described by Anderson (7).

The heat transfer through the tank wall and associated coverings is represented using finite difference techniques. The finite difference solution accounts for pure conduction through the tank wall and insulating layers, and pure conduction, convection, and radiation in the Explosafe regions and in the gap between the wall and any radiation shielding. The finite difference solution also accounts for the heat transfer from the fire to the tank outer surface and from the tank inner surface to the lading.

The interior surface heat transfer submodels account for convection and radiation in the vapour space, and convection and boiling in the liquid region. The radiation calculations are based on the assumption that the wall communicates only with the lading. The convection and boiling coefficients are based on empirical relations for inclined flat surfaces.

The thermodynamic process submodel treats the lading as three distinct regions -- the vapour space, the liquid boundary, and the liquid core. It is assumed that the vapour and liquid boundary (near wall, and free surface) are in thermodynamic equilibrium and saturated; the core is assumed to be subcooled initially, but after some period of venting it is assumed to be in equilibrium with the liquid boundary and vapour space. This submodel requires the setting of two empirical constants, the liquid boundary thickness, and the energy partition factor that determines how much of the fire heat is transferred into the vapour and liquid boundary, and how much is transferred to the liquid core. These constants have been determined from one set of fire test results and have remained unchanged for all subsequent validation runs and simulations. In the submodel it is assumed that the energy for venting comes from the vapour and liquid boundary. This energy drain is one reason that the liquid core eventually reaches equilibrium with the other regions.

The thermodynamic and transport properties of the lading are based on the Starling equation of state, and on available material property data, respectively.

The pressure relief valve submodel accounts for both the mechanical action of a relief valve and the fluid mechanics. The valve mechanics are accounted for using a steady state model. Valve cycling dynamics are not accounted for explicitly, but rather implicitly by having a model valve that sits partially open to represent the reduced flow capacity during cycling, and fully open when in reality the valve is fully open. The opening fraction is determined by the lading vaporization rate which relates to the valve cycling frequency. The valve flow submodels can account for dry vapour flow and for frozen liquid flow.

The wall stresses are calculated at the point on the wall circumference which experiences the highest temperature and includes pressure induced (hoop) stress and stresses due to radial temperature gradients in the tank wall. The tank failure analysis is based on the maximum normal stress theory of failure. Degradation in the wall material strength with increases in temperature is accounted for using available data for tank-car steel.

Further technical details about these various submodels are given in Reference (8).

VALIDATION

This section presents several examples of simulations performed as part of the TCTCM validation. Validation results are presented for two fifth-scale tests (3) conducted for the Transportation Development Centre (TDC) of Transport Canada, and for one full-scale test (5) and three fifth-scale fire tests (6) conducted as part of the AAR/RPI tank-car safety study.

These different validation runs will be discussed separately in the following sections. Further details of the actual tests can be found in the appropriate references.

TDC Fifth-Scale Fire Tests

As stated above, examples of validation runs will be presented for two fifth-scale tests conducted as part of the TDC tank-car safety studies. The two tests were labelled ENIGMA and NOVA. Details of these tests can be found in Reference (3).

For the ENIGMA case, the tank-car model was used to predict the response of a fifth-scale unprotected (except for a pressure relief valve) tank exposed to an engulfing fire. The pressure relief valve was sized for the fifth-scale tank using standard methods for tank-cars. The simulation was performed with boundary conditions which represented the actual fire conditions as closely as possible. The results of the simulation are presented in Figures 1 to 4 along with the actual measured data from the fire test.

Figure 1 presents the predicted tank pressure along with the measured pressure from the fire test. As can be seen from the Figure, the predictions are in good agreement with the test results. The initial pressurization rate prior to relief valve action is in good agreement with the test results. The length of the cycling period and the pressure rise during continuous venting is also well predicted. The predictions depart from the measured results after the peak pressure has been reached. The measured pressure drops more rapidly than the predicted values prior to tank failure at approximately 7 1/2 minutes.

Figure 2 resents the predicted wall temperatures along with the measured wall temperatures for the three different wall locations. As can be seen from the Figure, the predictions are in good agreement with the fire test results. The temperature rise

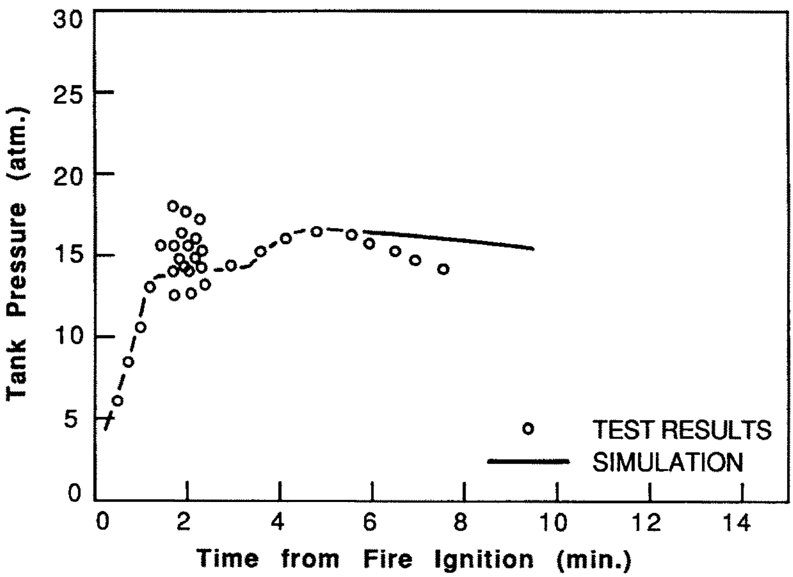

FIGURE 1: Predicted and Measured Tank Pressure vs Time from Fire Ignition for Upright Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (TDC Test ENIGMA, data from Reference (3)).

rates and the break times compare well with the test results. The wall temperatures in the liquid wetted regions are in excellent agreement with the measured data.

Figure 3 presents the predicted liquid level along with liquid level estimates from the actual fire test. As can be seen from the Figure, the predictions are in good agreement with the limited data available from the fire test. The model slightly

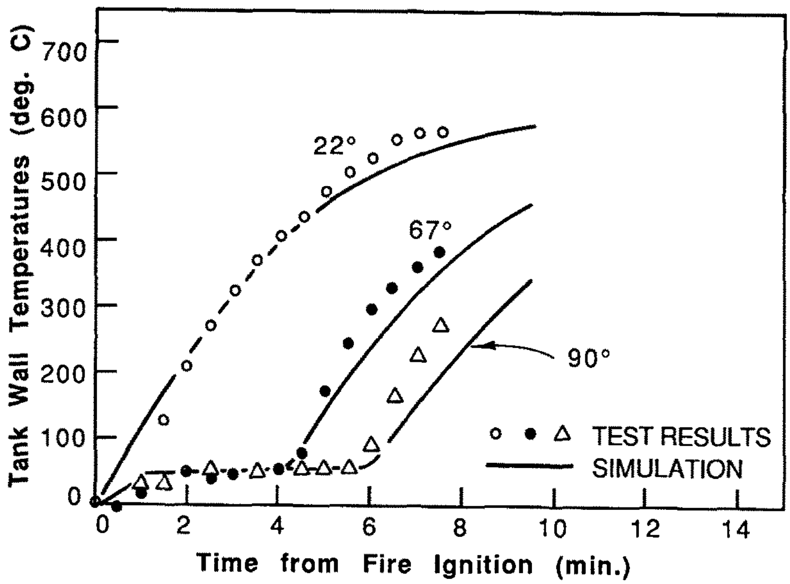

FIGURE 2: Predicted and Measured Tank Wall Temperatures vs Time from Fire Ignition for Upright Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (TDC Test ENIGMA, data from Reference (3)).

underpredicts the rate at which the tank empties. This inaccuracy in the prediction of the liquid level could explain the departure of the predicted tank pressure from the actual measured tank pressure.

Figure 4 presents the predicted wall stresses and material properties for the ENIGMA test. The only data point from the fire tests shown on this Figure is the actual time of failure of the tank at approximately 7 1/2 minutes into the fire. The Figure shows the predicted tensile strength of the tank wall as a function of time from fire ignition. This tensile strength is of course a function of the wall temperature. The tensile

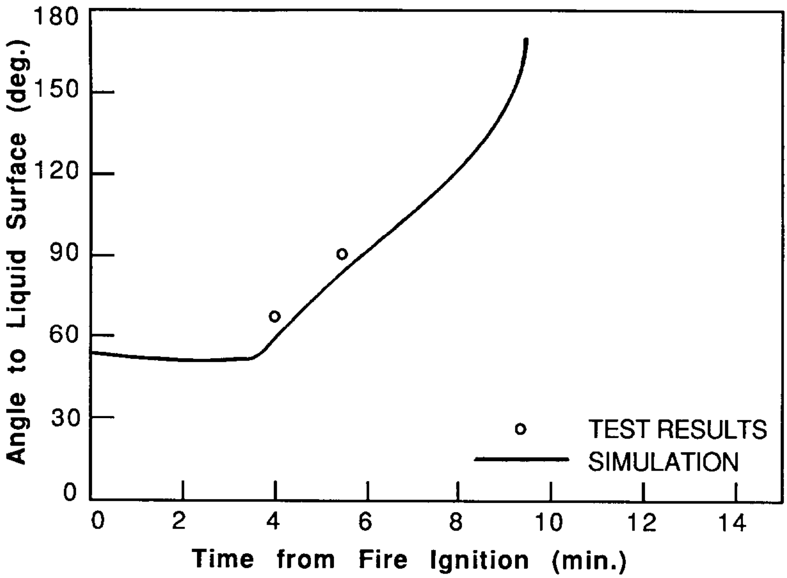

FIGURE 3: Predicted and Measured Tank Liquid Level vs Time from Fire Ignition for Upright Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (TDC Test ENIGMA, data from Reference (3)).

strength shown is for the location on the tank wall where the maximum temperature is reached (at top-dead-centre). The wall stresses at the inner and outer fibres of the tank wall are also shown. Failure is indicated when the tensile strength of the wall drops below the stress levels in the wall. This, of course, is the maximum normal stress theory of failure. As can be seen from the Figure, tank failure is not predicted. This disagrees with actual observations from the fire test where the tank failed as indicated in the Figure. The disagreement between the predictions and the test could be caused by a number of factors such as flaws in the tank wall, poor welds, or unpredicted hot spots in the tank wall.

For the NOVA case, the tank-car model was used to predict the response of a fifth-scale tank-car protected with internally applied material known as Explosafe (Registered Trade Mark of Vulcan Industrial Packaging). Explosafe is an expanded aluminum matrix that can be fitted within the tank.

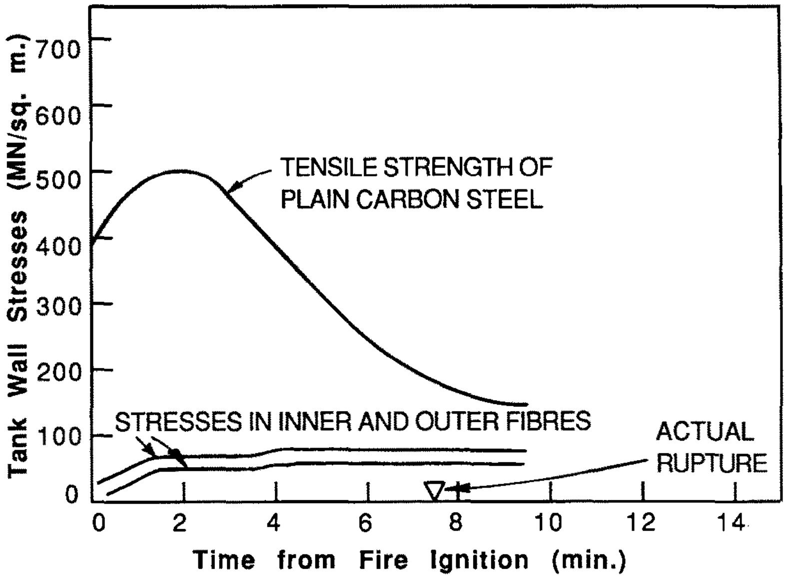

FIGURE 4: Predicted Tank Wall Stresses and Material Strength vs Time from Fire Ignition for Upright Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (TDC Test ENIGMA, data from Reference (3)).

The Explosafe material acts like fins in the vapour space to enhance the cooling of the tank wall areas in contact with vapour. This action is considered to be advantageous since the maximum wall temperatures are reached in the wall areas in contact with vapour. As in the unprotected tank case considered earlier, NOVA was exposed to an engulfing fire environment. NOVA was also equipped with a pressure relief valve of the same size as used in the ENIGMA test. The simulation was performed with boundary conditions which represented the actual fire conditions as closely as possible. The results of the simulation are presented in Figures 5 to 8 along with the actual measured data from the fire test.

Figure 5 presents the predicted tank pressure along with the measured pressure from the fire test. As can be seen from the Figure, the predictions are in good agreement with the test results. There is some disagreement in the initial pressurization rate prior to the relief valve opening. The length of the valve cycling period is well predicted. The tank pressurization during continuous venting is also well predicted up to the time where the

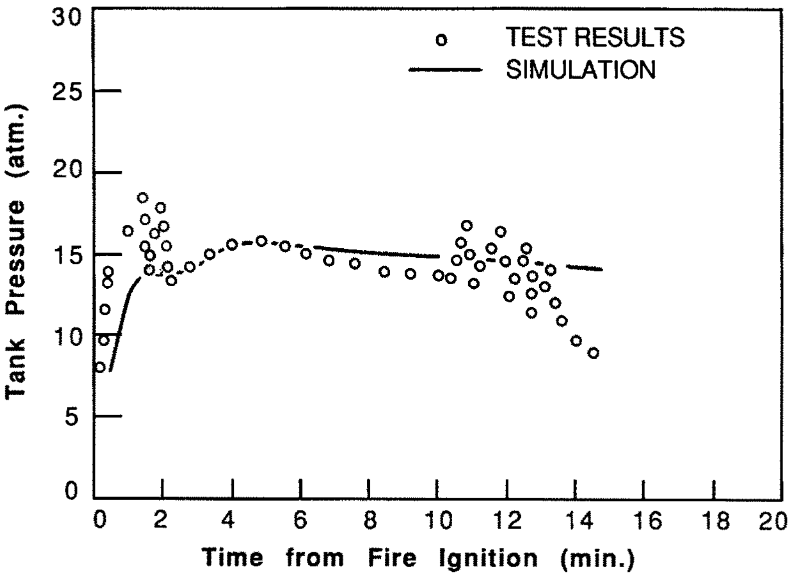

FIGURE 5: Predicted and Measured Tank Pressure vs Time from Fire Ignition for Upright Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (TDC Test NOVA, data from Reference (3)).

peak tank pressure for continuous venting is reached. As in the ENIGMA case, the tank pressure drops more rapidly than predicted by the model.

Figure 6 presents the predicted wall temperatures along with measured wall temperatures, from the NOVA test. As can be seen from the Figure, the wall temperature predictions are not in good agreement for the different locations indicated. However, the rates at which the temperatures increase at the different locations (slopes of the different curves) are well predicted by the model. A possible explanation for this disagreement may be that the heat transfer coefficients within a tank filled with Explosafe vary more dramatically than predicted by the model.

Figure 7 presents the predicted and experimentally obtained liquid levels. As with the ENIGMA case, the tank-car model underestimates the rate at which the tank empties. This may explain why the wall temperatures were not well predicted. The wall temperatures are of course significantly affected by the location of the liquid level. Possible reasons for the departure in the prediction of the liquid level are, an underprediction in

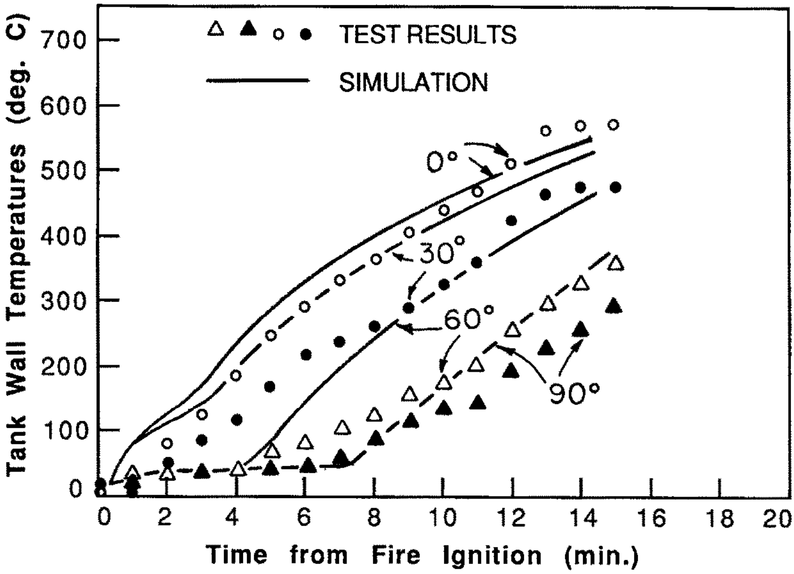

FIGURE 6: Predicted and Measured Tank Wall Temperatures vs Time from Fire Ignition for Upright Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (TDC Test NOVA, data from Reference (3)).

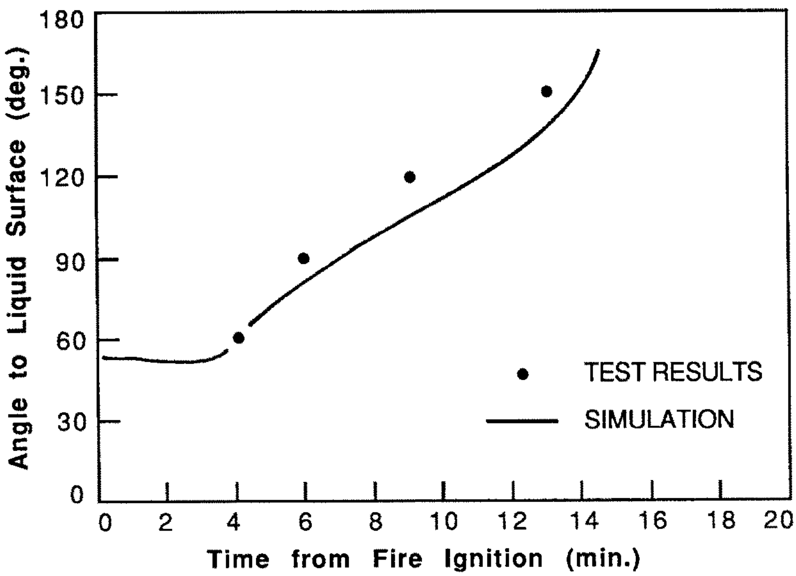

FIGURE 7: Predicted and Measured Tank Liquid Level vs Time from Fire Ignition for Upright Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (TDC Test NOVA, data from Reference (3)).

the rate of venting, an error in the internal surface heat transfer coefficients, or an error in the fire heat transfer.

Figure 8 presents the predicted wall stresses and the material properties for the NOVA test case. In the actual fire test the tank did not fail. As can be seen from the Figure the model predicts that the tank will not fail. However, it should be recalled that the tank-car model did not predict failure for the ENIGMA case either. It should be noted that the test data showed that the fire temperatures were higher in the ENIGMA test.

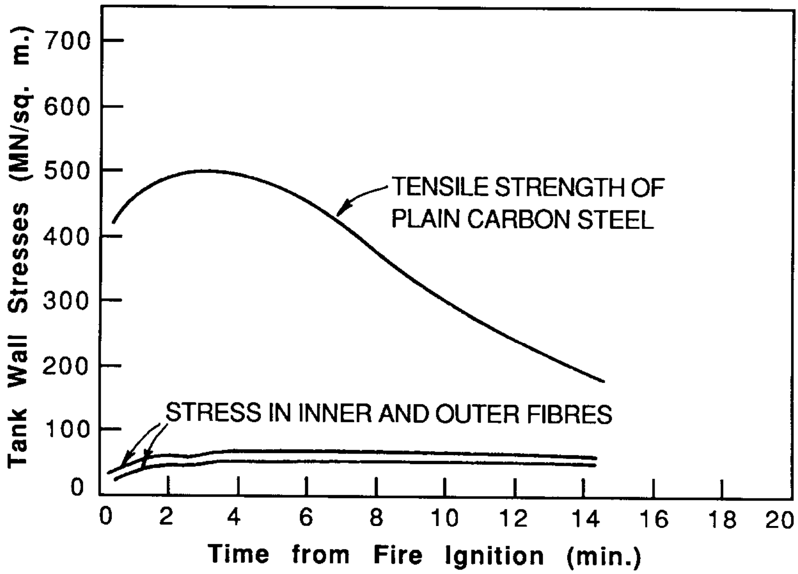

FIGURE 8: Predicted Tank Wall Stresses and Material Strength vs Time from Fire Ignition for Upright Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (TDC Test NOVA, data from Reference (3)).

AAR/RPI Full and Fifth-Scale Tests

Simulations have been performed to compare the model predictions with the results of a number of the AAR/RPI fire tests. Validation runs were performed to compare predictions with the AAR/RPI full-scale fire test of an unprotected tank, the fifth-scale fire test of an unprotected tank, the fire test of a fifth-scale unprotected tank rolled 90 degrees to one side so that the relief valve is initially submerged in the lading, and the fifth-scale fire test of a thermally protected tank.

The first case to be presented involves the full-scale tank. The tank-car model was used to predict the response of a full-scale unprotected tank exposed to an engulfing fire. The simulation used boundary conditions based on the AAR/RPI test entitled RAX 201 (5). The results of the simulation are presented in Figures 9 to 12 along with the actual measured data from the fire test.

Figure 9 presents the predicted tank pressure along with the measured pressure from the fire test. As can be seen from the Figure, the predictions are in fair agreement with the actual test results. The initial pressurization rate prior to the valve cycling is well predicted. The model predicts a valve cycling

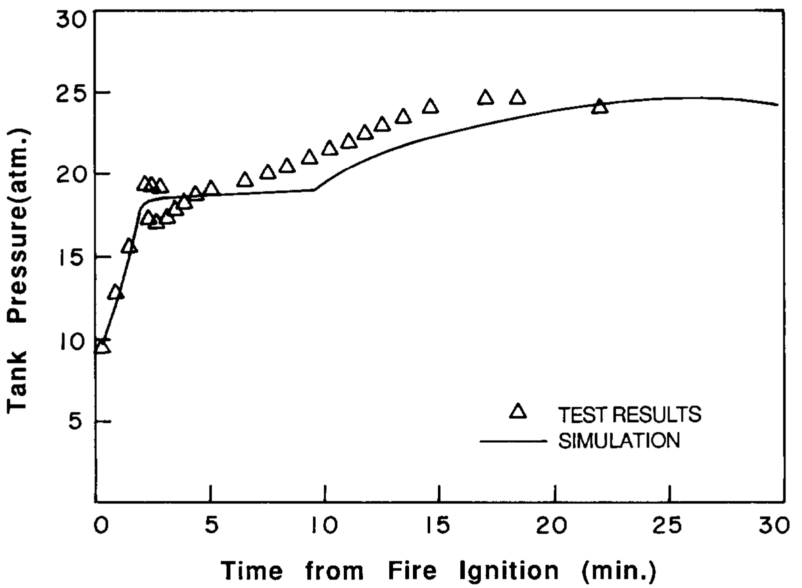

FIGURE 9: Predicted and Measured Tank Pressure vs Time from Fire Ignition for Upright Uninsulated Full-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test RAX 201, data from Reference (5)).

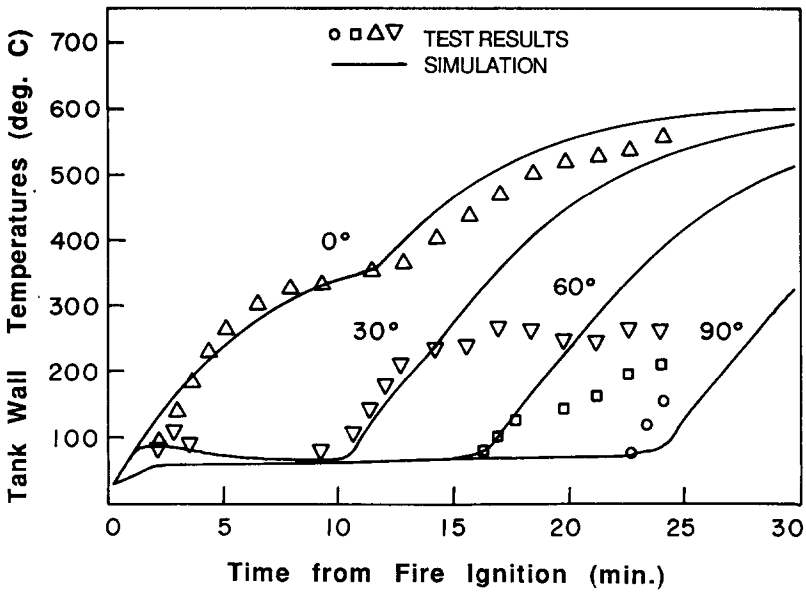

FIGURE 10: Predicted and Measured Tank Wall Temperatures vs Time from Fire Ignition for Upright Uninsulated Full-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test RAX 201, data from Reference (5)).

period which is longer than that observed in the fire test. A possible explanation of this disagreement may be that the relief valve on RAX 201, for some reason, remained in a partially open state during the time when normal valve cycling would have occurred. Beyond the valve cycling period, the tank pressure is seen to rise steadily to a peak pressure, and then the pressure begins to fall. As can be seen from the Figure, the predicted tank peak pressure is in good agreement with the measured peak tank pressure.

Figure 10 presents the predicted tank wall temperatures along with the temperatures measured from the fire test. As can be seen from the Figure, the predicted wall temperature for the tank top-dead-centre is in good agreement with the measured tank wall temperature. The predicted wall temperatures for the 30, 60 and 90 degree locations around the side of the tank do not agree as well with the measured temperatures. A possible reason for this is that the low wall temperatures around the side of the tank were

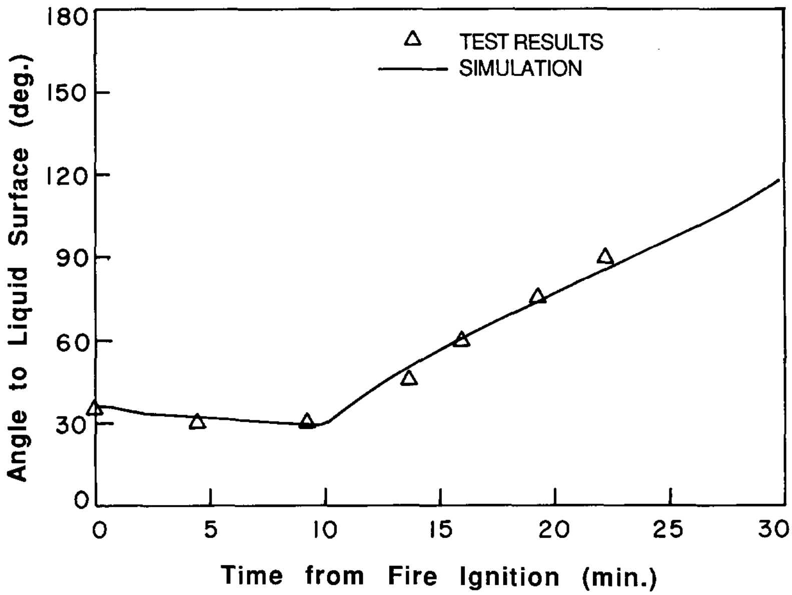

FIGURE 11: Predicted and Measured Tank Liquid Level vs Time from Fire Ignition for Upright Uninsulated Full-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test RAX 201, data from Reference (5)).

due to the uncontrollable nature of the test fire. Cross winds could have resulted in the fire shape being distorted such that the fully engulfing nature was lost.

Figure 11 presents the predicted liquid level for the RAX-201 test. As can be seen from the Figure, the predicted liquid level is in good agreement with the liquid level observed in the test. It is very important that the model be able to predict the position of the liquid level accurately, because this liquid level determines the way in which the tank wall responds to the fire.

Figure 12 presents the predicted tank wall stresses along with the tank wall strength. As can be seen from the Figure, the predicted tank wall strength dips below the predicted stress in the tank inner fibres at approximately 25 minutes. Also indicated in the Figure, is the actual observed tank rupture time of approximately 24 1/2 minutes. This good agreement between predictions and measurements is likely due to the accurate prediction of the peak wall temperature at the tank top-dead-centre, and the accurate prediction of the tank peak pressure.

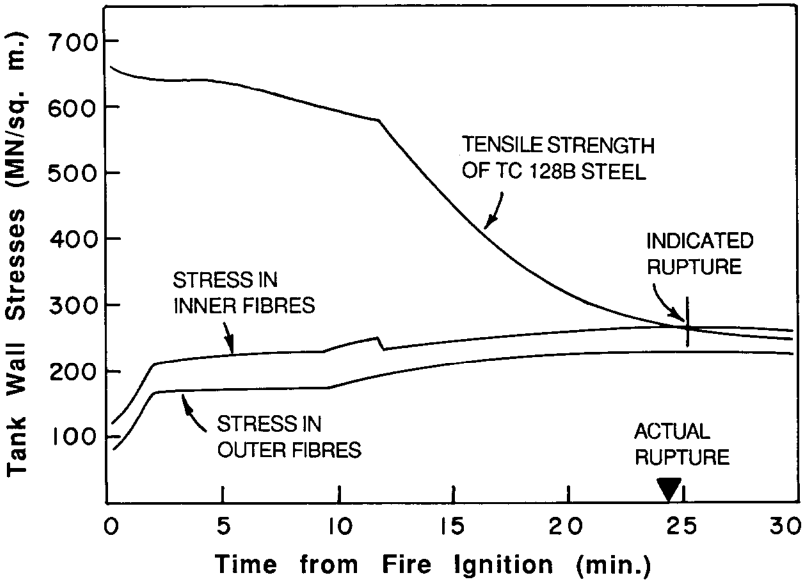

FIGURE 12: Predicted Tank Wall Stresses and Material Strength vs Time from Fire Ignition for Upright Uninsulated Full-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test RAX 201, data from Reference (5)).

The next case to be considered involves a fifth-scale tank and is based on the AAR/RPI test entitled Test #3 (6). This case involved the simulation of an unprotected fifth-scale tank filled with propane, exposed to an engulfing fire environment. The simulation was performed with boundary conditions matching those from the AAR/RPI test #3. As a special note, the tank was equipped with a full-sized (standard size for full-scale tank-car) pressure relief valve and the wall thickness was the same as for a full-sized tank-car. The results of the simulation are presented in Figures 13 to 16 along with the actual fire test results.

Figure 13 presents the predicted tank pressure along with the measured tank pressure from test #3. The test data shown represents the average pressure in the tank and does not show the actual pressure variations due to the valve cycling. the relief valve cycled throughout fire test #3 because of the fact that the relief valve was oversized for the fifth-scale tank. As can be seen from the Figure, the tank-car model predictions for

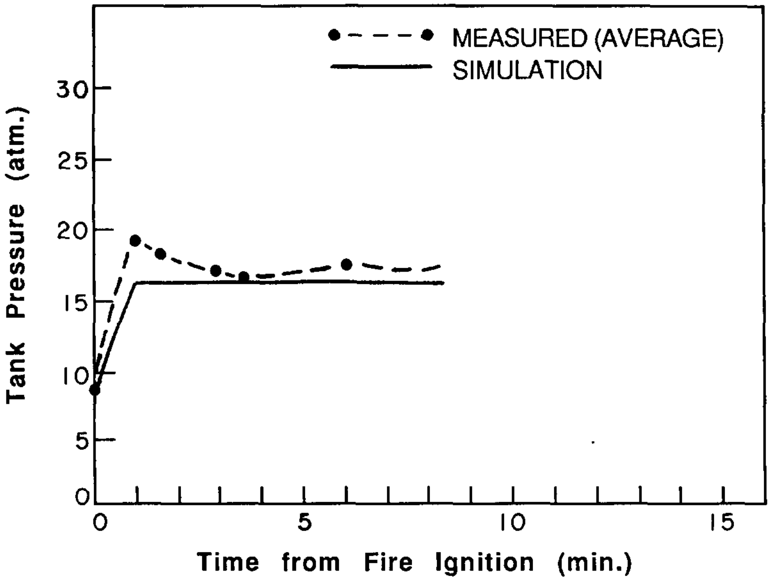

FIGURE 13: Predicted and Measured Tank Pressure vs Time from Fire Ignition for Upright Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test #3, data from Reference (6)).

the initial tank pressurization, prior to valve action, is very good. There is some disagreement in the valve opening pressure and this is clearly seen where there is a sudden leveling of the predicted pressure. This disagreement in the valve opening pressure is caused partially by the simplicity of the relief valve model, and also by the unknown variability in the operating characteristics of real pressure relief valves. This variability in relief valves was evident in every one of the simulations performed for the validation.

Figure 14 presents the predicted and measured wall temperatures for test #3. As can be seen from Figure, the model predictions are in good agreement with the measured temperatures. There is some disagreement in the wall temperatures for the lower wall locations (120, and 150 degrees from tdc). This disagreement can be explained by the small errors in the prediction of the liquid level. This will be discussed further with reference to Figure 15 which shows the predicted and experimentally obtained liquid level.

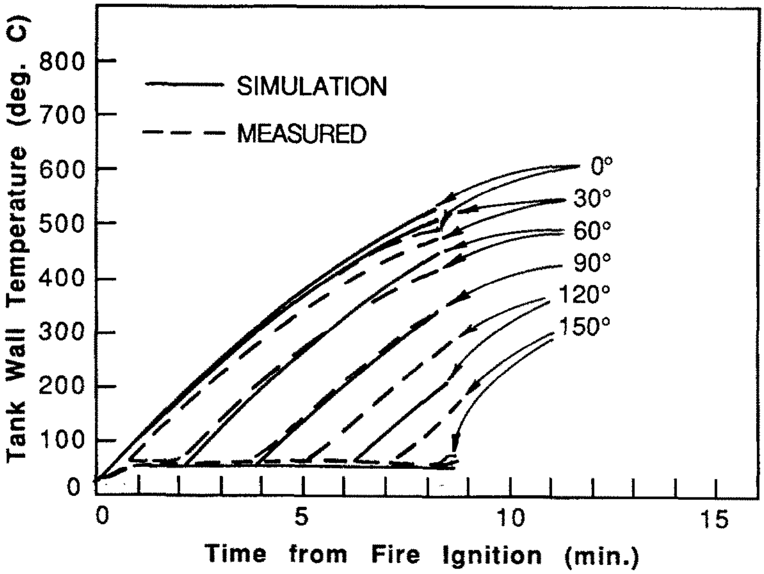

FIGURE 14: Predicted and Measured Tank Wall Temperatures vs Time from Fire Ignition for Upright Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test #3, data from Reference (6)).

As can be seen from Figure 15 the predicted liquid level is in fair agreement with the liquid levels derived from the actual fire test results. The fire test data shows that the tank approached the liquid full condition, whereas the model does not predict this condition. The liquid levels from the fire test are based on wall temperature break times. Therefore, it is possible that the estimated liquid level from the fire test data is really the top of the frothing two-phase region. If this is the case, then the model predictions may be more accurate than they appear.

At approximately the two minute mark, the predicted liquid level agrees with the test results. From that point on the predicted and measured liquid levels diverge. The maximum error is approximately 20 degrees in the angle to the liquid level. This error in predicting the liquid level results from inaccuracies in predicting the venting rate, and have a significant effect on the wall temperature predictions. The

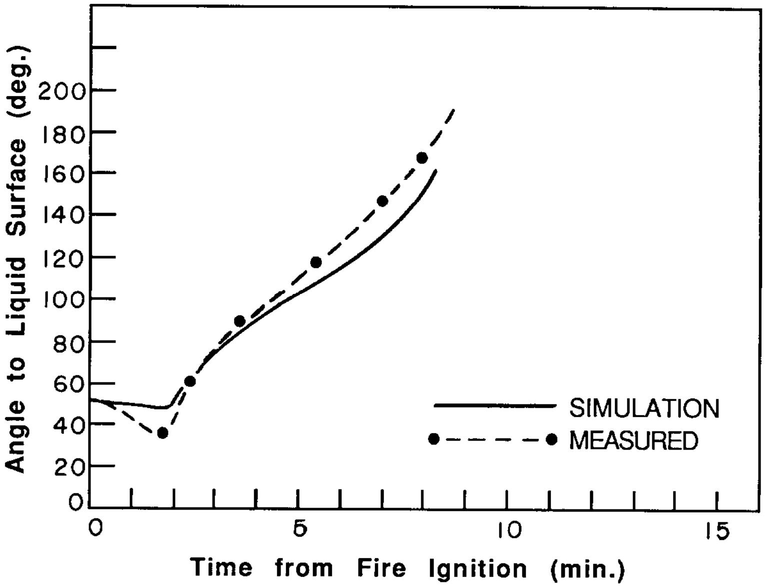

FIGURE 15: Predicted and Measured Tank Liquid Level vs Time from Fire Ignition for Upright Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test #3, data from Reference (6)).

disagreement between predicted and measured wall temperatures at locations around the side of the tank (especially near the bottom), are caused by this error in the prediction of the liquid level because the temperature break times are directly related to the liquid level position.

Figure 16 presents the predicted wall stresses and material strengths for test #3. As can be seen, the model does not predict tank failure, which is in agreement with the actual test results.

The next case to be considered involves a fifth-scale tank and is based on the AAR/RPI test entitled Test #6 (6). This case involved the the simulation of an unprotected fifth-scale tank, filled with propane, exposed to an engulfing fire environment. This case was different than that Test #3 because the tank was rolled 90 degrees to one side so that the pressure relief valve was initially submerged in liquid. The simulation was performed with boundary conditions matching those from the AAR/RPI Test #6. As with Test #3, the tank was equipped with a full-size (standard

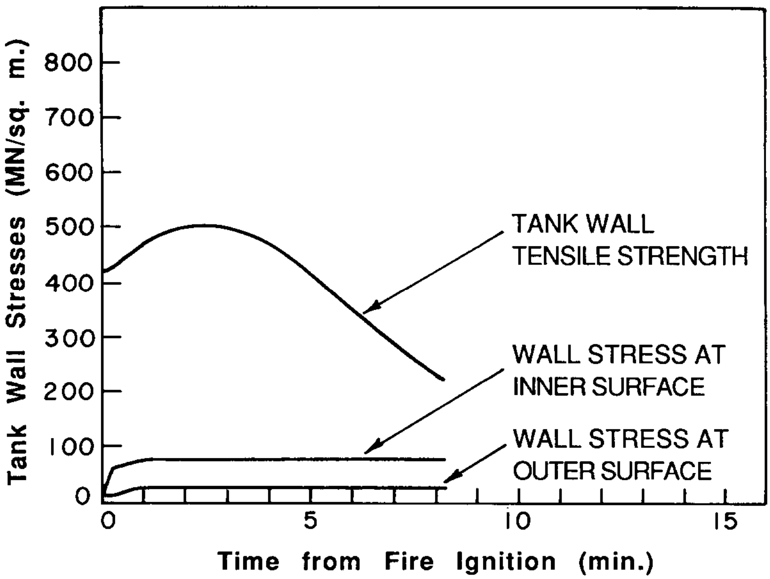

FIGURE 16: Predicted Tank Wall Stresses and Material Strength vs Time from Fire Ignition for Upright Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test #3, data from Reference (6)).

size for full-scale tank-car) pressure relief valve and the wall thickness was the same as for a full-size tank-car. The results of the simulation are presented in Figures 17 to 20 along with the actual fire test results.

Figure 17 presents the predicted tank pressure along with the measured tank pressure from test #6. The test data shown represents the average pressure in the tank and does not show the actual pressure variations due to the valve cycling. As a result of the valve oversizing, the valve cycled throughout the test. As can be seen from Figure 17, the tank-car model predictions for the initial tank pressurization rate are in good agreement with the actual measured pressurization rate. The predicted tank pressure for the remainder of the heating period is also in good agreement with the observed tank pressure from Test #6.

Figure 18 presents the predicted tank wall temperatures and those measured in Test #6. As can be seen from the Figure, the predicted temperature at the tank top-dead-center is in good agreement with the measured wall temperature in that area.

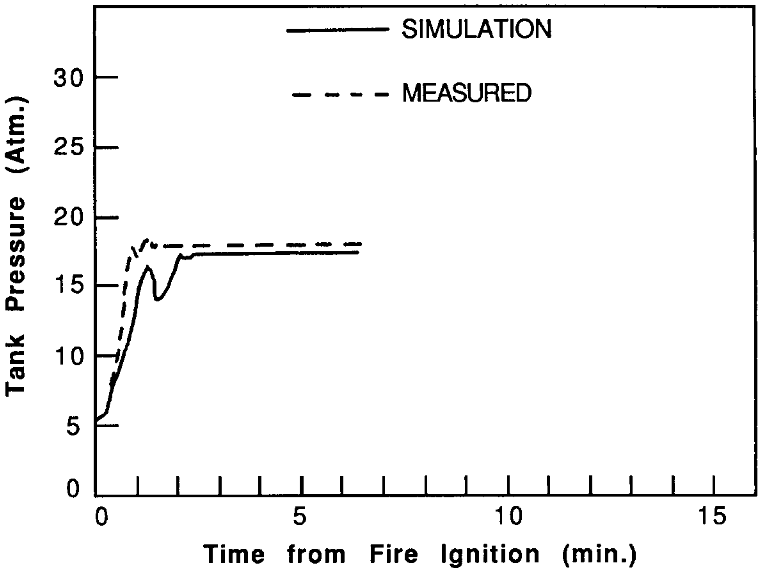

FIGURE 17: Predicted and Measured Tank Pressure vs Time from Fire Ignition for Rolled Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test #6, data from Reference (6)).

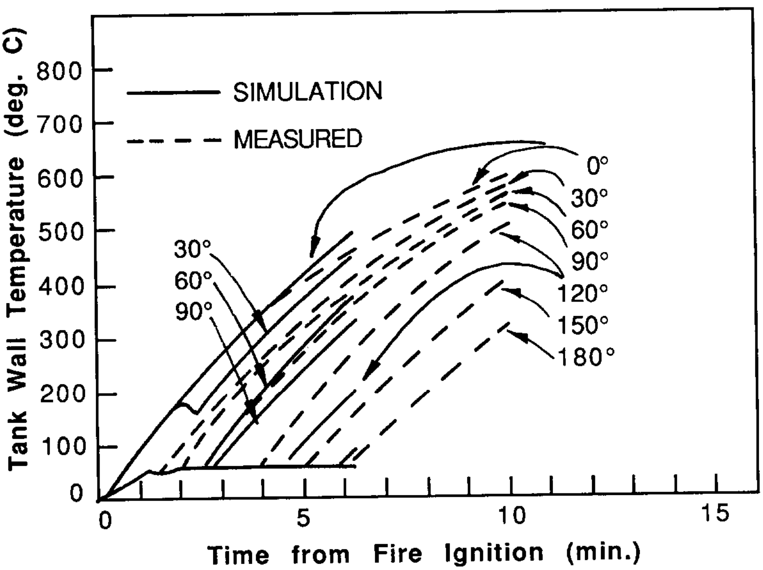

FIGURE 18: Predicted and Measured Tank Wall Temperatures vs Time from Fire Ignition for Rolled Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test #6, data from Reference (6)).

The predicted and measured wall temperatures for the remaining areas are not in good agreement in absolute terms, but the simulation results do correctly show the trends. As will be seen in a following Figure, the prediction of the liquid level is not very accurate and this results in an error in the prediction of the temperature for the wall locations around the side of the tank.

Figure 19 presents the predicted liquid level along with the liquid level estimated from the results of Test #6. As can be seen from the Figure, the model under predicts the rate at which the tank emptied. The liquid level in Test #6 began to drop rapidly after 2 minutes into the test. The model predictions show a similar rapid drop in the liquid level but at a slightly later time, and this results in a substantial error in the prediction of location of the liquid level.

As mentioned previously, Test #6 involved a tank rolled 90 degrees to one side so that the relief valve would be submerged in liquid, and therefore at least during the initial periods of the

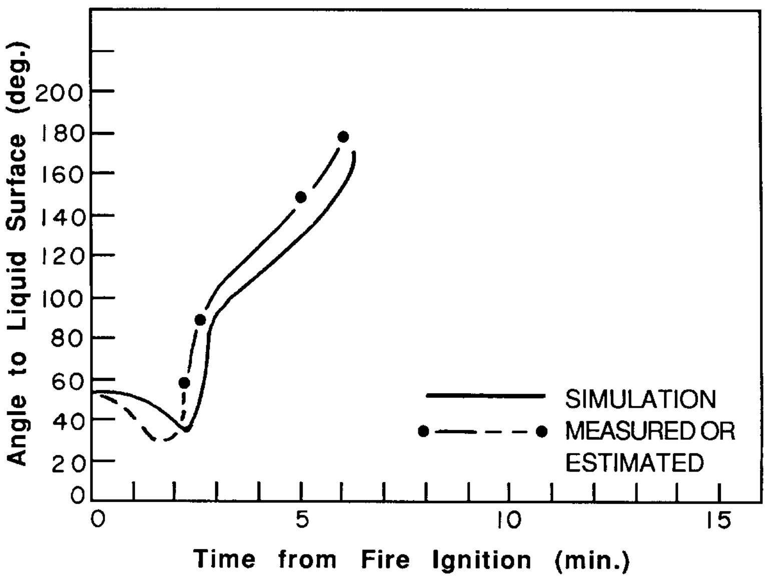

FIGURE 19: Predicted and Measured Tank Liquid Level vs Time from Fire Ignition for Rolled Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test #6, data from Reference (6)).

test the relief valve was passing liquid or two-phase fluid. At some point the valve would be passing vapour when the liquid level dropped below the pressure relief valve. The point in time when this change in the phase flowing through the relief valve occurs, is seen in the Figure as a slight bend in the plot showing the liquid level. For the predicted level, this bend occurs at approximately 3 minutes into the fire test. For the actual test results, this bend occurs about 1/3 of a minute before that predicted by the tank-car model. Although there is a significant error in the prediction of the liquid level, the actual rate at which the liquid level is dropping is quite well predicted. The error in the prediction is caused by the fact that the predicted response is slightly shifted along the time axis with respect to the measured liquid level. This slight shifting is of course due to an inaccuracy in the prediction of the relief valve action.

Figure 20 presents the predicted tank wall stresses and tank wall material strength for Test #6. As can be seen from the Figure, the tank-car model does not predict tank failure, in agreement with the actual test results.

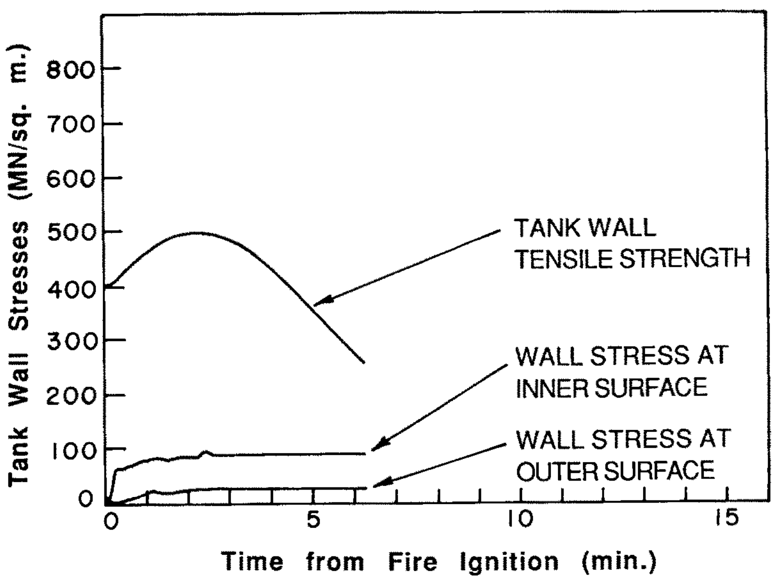

FIGURE 20: Predicted Tank Wall Stresses and Material Strength vs Time from Fire Ignition for Rolled Uninsulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test #6, data from Reference (6)).

The final case to be considered involves a fifth-scale tank and is based on the AAR/RPI test entitled Test #7 (6). This case involved the simulation of a thermally protected fifth-scale tank filled with propane exposed to an engulfing fire environment. As with the other AAR/RPI fifth-scale tests, the tank was equipped with a full-size pressure relief valve and the tank wall was equal to the wall thickness of a full-size tank-car. The simulation was performed with boundary conditions matching those from the AAR/RPI test.

The tank was insulated with a 102 mm thick cover of poly-urethane foam insulation covered by a steel jacket. Poly-urethane foam is known to degrade at high temperatures. However, this simulation did not include the accurate modelling of the insulation degradation. Instead, an effective average thermal conductivity was used for the poly-urethane foam to account for the degradation process. The results of the simulations are presented in Figures 21 to 24.

Figure 21 presents the predicted tank pressure along with the actual measured pressure from Test #7. As can be seen from the Figure, the tank initial pressurization rate is well predicted as is the average pressure during the valve cycling period. As a result of the relief valve oversizing, the relief valve cycled during the entire test.

Figure 22 presents the predicted tank wall temperatures along with the actual measured wall temperatures from Test #7. As can be seen from the Figure, the predicted wall temperatures are in fair agreement with the measured temperatures from the test. Some disagreement is evident and is likley due to the fact that the insulation degradation is not accurately modelled.

Figure 23 presents the predicted liquid level along with the estimated liquid level from the results of Test #7. As can be seen from the Figure, the test results seem to indicate that the tank reached the near liquid full condition. However, it may not be that the tank approached the liquid full condition. It could be that the frothing 2-phase region resulted in a perceived high liquid level. The model, does not predict that the tank reached the near liquid full condition. Beyond approximately 3 minutes, the model predictions are in good agreement with the estimated liquid level from Test #7. The predicted and measured liquid levels diverge slightly in the later minutes of the fire.

Figure 24 presents the predicted tank wall stresses and the

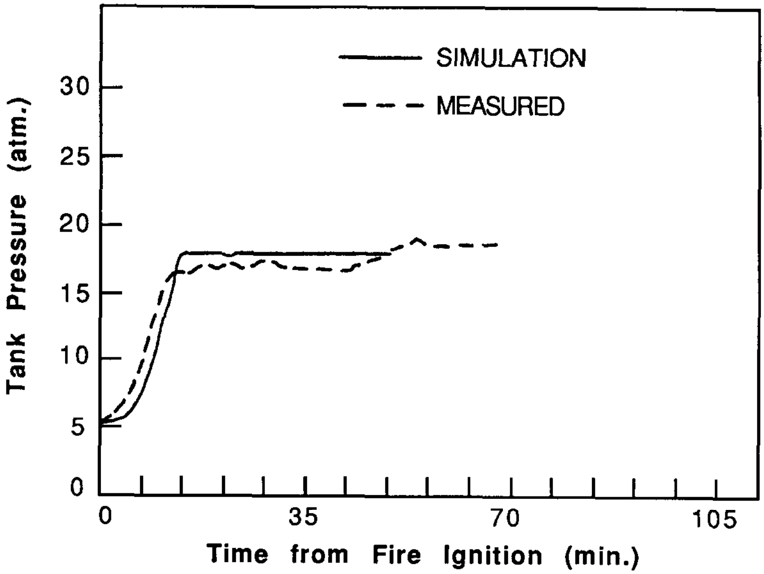

FIGURE 21: Predicted and Measured Tank Pressure vs Time from Fire Ignition for Upright Insulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test #7, data from Reference (6)).

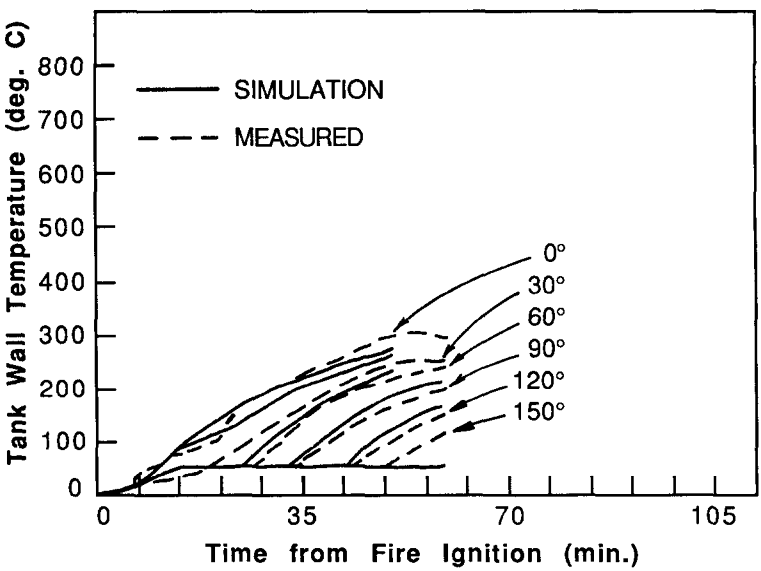

FIGURE 22: Predicted and Measured Tank Wall Temperatures vs Time from Fire Ignition for Upright Insulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test #7, data from Reference (6)).

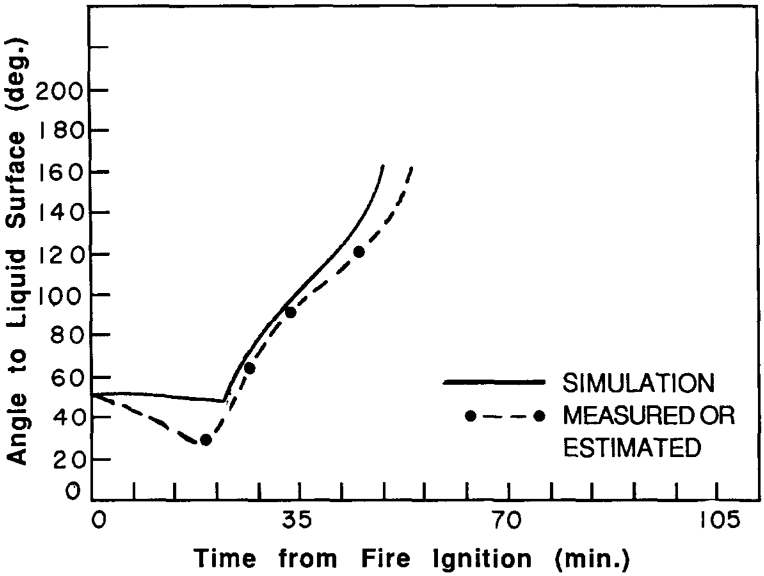

FIGURE 23: Predicted and Measured Tank Liquid Level vs Time from Fire Ignition for Upright Insulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test #7, data from Reference (6)).

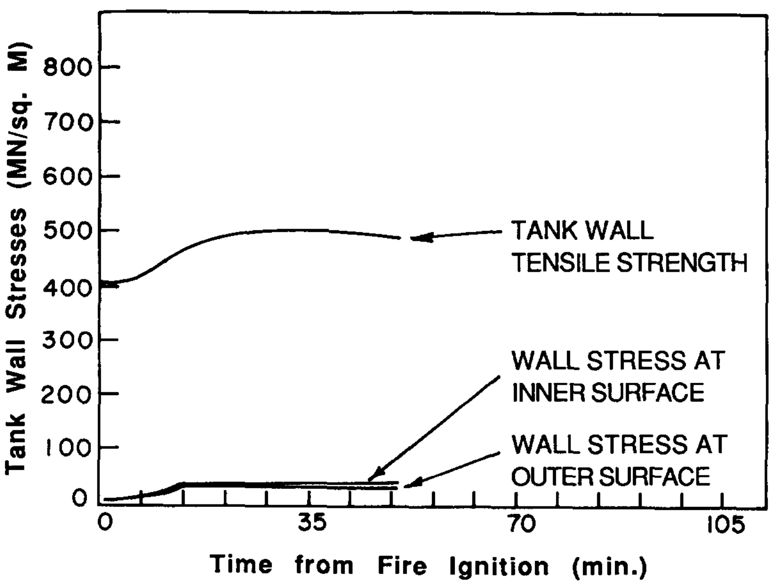

FIGURE 24: Predicted Tank Wall Stresses and Material Strength vs Time from Fire Ignition for Upright Insulated Fifth-Scale Tank-Car Exposed to an Engulfing Fire (AAR/RPI Test #7, data from Reference (6)).

predicted tank wall material strength for Test #7. As can be seen from the Figure the model did not predict tank failure. This, of course, is due to the fact that the tank wall temperatures were maintained well below levels that would result in significant degradation in the tank wall material strength. In addition, the presence of the insulation resulted in small radial temperature gradients in the tank wall which resulted in small thermal stresses.

CONCLUSIONS

A computer model has been developed which can simulate the response of a cylindrical tank, and its lading, to external fire impingement. The model has been validated using data obtained from a number of full and fifth-scale fire tests of both unprotected and thermally protected tanks.

The computer model is intended as an aid in the design of thermal protection systems. It allows a designer to compare quickly a number of different system configurations. The model also makes it possible to compare complex thermal protection systems that incorporate several different thermal protection devices. The model can lower the costs and time involved in evaluating and developing new technologies proposed for reducing the risk of tank explosions.

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