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Review of AFFTAC Thermal Model

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by

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16. Abstract

The Analysis of Fire Effects on Tank Cars (AFFTAC) is a computer model that simulates the effects of fire on rail tank-cars. It is used by Transport Canada, the U.S. DOT, and tank-car manufacturers for evaluating and qualifying thermal protection systems for rail tank-cars.

This report is a review and critique of AFFTAC. The review is limited to analysis of how AFFTAC simulates thermal protection systems incorporating 13 mm of high temperature thermal insulation and a steel jacket. The analysis is based on propane as the commodity, because test data is available for this commodity.

This study looked at various aspects of the AFFTAC thermal model, to assess whether the AFFTAC code is conservative in its assumptions, how and why the AFFTAC code differs from the plate test standard for thermal insulating materials, and how the AFFTAC code can be improved.

The report provides significant conclusions from the review of the AFFTAC model, and recommendations for changes are included.

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16. Résumé

Le modèle informatique AFFTAC (Analysis of Fire Effects on Tank Cars) simule les effets d'un incendie sur les wagons-citernes. Il est utilisé par Transports Canada, le DOT des États-Unis et les fabricants de wagons-citernes pour évaluer et homologuer les systèmes de protection thermique de ce type de matériel roulant.

Ce rapport présente un examen critique de ce modèle, qui se limite à l'analyse de la simulation par l'AFFTAC de systèmes de protection thermique formés d'un revêtement isolant haute température de 13 mm d'épaisseur et d'une jaquette en acier. L'analyse porte sur un wagon-citerne à propane car on dispose de données d'essai sur ce produit.

Elle s'intéresse à divers aspects du modèle AFFTAC et vise à déterminer si les hypothèses de départ appliquées pour la construction des algorithmes sont trop prudentes, comment et pourquoi ces algorithmes s'écartent des paramètres des essais standard sur plaque des matériaux isolants et, enfin, comment on peut perfectionner le modèle.

Le rapport présente les conclusions importantes de l'analyse effectuée, ainsi que des recommandations pour la modification du modèle.

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Executive Summary

The Analysis of Fire Effects on Tank Cars (AFFTAC) is a computer model that simulates the effects of fire on rail tank-cars. It is used by Transport Canada, the U.S. DOT, and tank-car manufacturers for evaluating and qualifying thermal protection systems for rail tank-cars.

This report is a review and critique of AFFTAC. The review is limited to analysis of how AFFTAC simulates thermal protection systems incorporating 13 mm of high temperature thermal insulation and a steel jacket. The analysis is based on propane as the commodity, because test data is available for this commodity.

This study looked at various aspects of the AFFTAC thermal model, to answer the following questions:

- Is the AFFTAC code conservative in its assumptions?
- How and why is the AFFTAC code different from the plate test standard for thermal insulating materials?
- How can the AFFTAC code be improved?

This study involved the following main tasks:

- a discussion of the current standards for thermal protection systems including both the qualification of thermal insulation materials by test (engulfing fire and torch fire plate test) and the evaluation of thermal protection systems on tank-cars by thermal modeling (AFFTAC).
- a comparison between the AFFTAC predictions and actual fire test results
- a review of AFFTAC methods, assumptions used, and weaknesses

Based on the outcomes from conducting these tasks, the following conclusions have been reached:

- the current plate test standard for the pool fire test is not consistent
- the current plate test standard for the torch fire is not consistent
- the AFFTAC model for the engulfing fire is not consistent with the plate test standard
- the AFFTAC model for torch fire simulation is consistent with the plate test standard but is not representative of a real-world credible torch fire event

To correct the exposed deficiencies, the plate test standard should be changed as follows:

- for the pool fire case, the time to heat the plate to 427°C should be 6 minutes not 13 minutes. This is consistent with a strongly radiating pool fire at 816°C temperature. This condition should cause an uninsulated tank-car to fail in about 24 minutes, in agreement with RAX 201 test data, as reported in the Anderson, Norris report entitled

Fragmentation and Metallurgical Analysis of Tank Car RAX 201, FRA-OR &D of April 1974.

- for the torch test, the time to heat the plate to 427°C should be 2 minutes rather than 4 minutes. This is consistent with a 1204°C torch that provides a heat flux about three times as intense as the pool fire. (This torch test should fail a tank-car in about 5 minutes in agreement with reports of tanks failing as quickly as that when not thermally protected.)

The following AFFTAC modeling deficiencies should be addressed.

- the isothermal liquid temperature assumption is inaccurate and causes simulation errors including:
  - late prediction of first opening of PRV
  - shell full prediction not in agreement with RAX 201 data
  - large errors in the prediction of vapour space temperatures (because of the prediction of shell full)
- the failure model is simplistic and is validated only by a single test point (RAX 201)
- the PRV model is not representative of real PRV and is not conservative in its assumptions where there is uncertainty

Because of these modeling deficiencies the following are recommended:

- if AFFTAC is used in its present form then the failure prediction should include a factor of safety as defined in this report.
- AFFTAC should be modified so that even when the tank goes shell full of liquid it continues to calculate a wall temperature in the vapour space. This vapour space temperature should be used to calculate the tank burst strength. This method should be used until we have confidence that AFFTAC correctly predicts shell full conditions.

Sommaire

Le modèle informatique AFFTAC (Analysis of Fire Effects on Tank Cars) simule les effets d'un incendie sur les wagons-citernes. Il est utilisé par Transports Canada, le DOT des États-Unis et les fabricants de wagons-citernes pour évaluer et homologuer les systèmes de protection thermique de ce type de matériel roulant.

Ce rapport présente un examen critique de ce modèle, qui se limite à l'analyse de la simulation par l'AFFTAC de systèmes de protection thermique formés d'un revêtement isolant haute température de 13 mm d'épaisseur et d'une jaquette en acier. L'analyse porte sur un wagon-citerne à propane car on dispose de données d'essai sur ce produit.

Elle s'intéresse à divers aspects du modèle AFFTAC et vise à déterminer :

- si les hypothèses de départ appliquées pour la construction des algorithmes sont trop prudentes
- comment et pourquoi ces algorithmes s'écartent des paramètres des essais standard sur plaque des matériaux isolants
- comment on peut perfectionner le modèle

Cette étude a comporté les principaux éléments suivants :

- examen critique des normes actuelles concernant les systèmes de protection thermique, y compris les essais de qualification des matériaux d'isolation thermique (essais sur plaque plongée dans un bain de flammes enveloppantes ou soumise à un jet de gaz enflammé) et l'évaluation des systèmes de protection thermique des wagons-citernes par modélisation thermique (AFFTAC)
- comparaison des résultats de la modélisation AFFTAC à ceux d'essais réels de réaction au feu
- examen du protocole, des hypothèses et des faiblesses du modèle AFFTAC

Les chercheurs ont tiré les conclusions suivantes au terme de leurs travaux :

- la norme actuelle d'essai sur plaque plongée dans un bain de flammes enveloppantes comporte des incohérences
- la même remarque vaut pour l'essai au jet de gaz enflammé
- la modélisation AFFTAC en bain de flammes enveloppantes n'applique pas les paramètres de l'essai standard sur plaque dans ces conditions
- la modélisation AFFTAC reproduit bien les paramètres de l'essai standard sur plaque soumise à un jet de gaz enflammé, mais elle ne représente pas fidèlement les conditions d'un accident réel donnant lieu à un jet de gaz enflammé

Pour remédier aux incohérences notées, il est proposé de modifier l'essai standard sur plaque de la façon suivante :

- pour l’essai en bain de flammes enveloppantes, ramener de treize minutes à six minutes le temps de chauffage de la plaque à 427 °C. Cela permet de reproduire les conditions d’un bain de flammes à rayonnement intense à 816 °C qui devrait entraîner la rupture d’un wagon-citerne non protégé en 24 minutes environ, en accord avec les résultats de l’essai RAX 201 que l’on trouve dans le rapport Anderson et Norris intitulé *Fragmentation and Metallurgical Analysis of Tank Car RAX 201, FRA-OR &D*, datant d’avril 1974.
- pour l’essai au jet de gaz enflammé, ramener de quatre minutes à deux minutes le temps de chauffage de la plaque à 427 °C. Cela permet de reproduire les conditions associées à un jet de gaz enflammé de 1 204 °C dont le flux thermique est environ trois fois plus intense que celui d’un bain de flammes. (Cet essai devrait mener à la rupture du wagon-citerne en cinq minutes environ, en accord avec les cas documentés de défaillance aussi rapide de wagons-citernes non protégés.)

Les chercheurs proposent de remédier aux anomalies suivantes de la modélisation AFFTAC :

- l’hypothèse d’une température uniforme du produit est erronée et entraîne des erreurs de modélisation, notamment :
  - première ouverture tardive de la soupape de sûreté
  - prévision de remplissage intégral de la citerne contraire aux données de l’essai RAX 201
  - températures au-dessus de la marge de remplissage largement erronées (découlant de la prévision de remplissage intégral)
- algorithme de rupture trop simpliste, validé par un seul point de mesure (RAX 201)
- modélisation inexacte des soupapes de sûreté fondée sur des hypothèses trop optimistes dans les cas entachés d’incertitude

Pour remédier à ces anomalies, les chercheurs proposent :

- d’intégrer au modèle AFFTAC, s’il doit être utilisé dans sa forme actuelle, le facteur de sécurité défini dans leur rapport pour les fins des prévisions de rupture
- de modifier le modèle AFFTAC de façon que, même dans un scénario de remplissage intégral de la citerne par le produit liquide, il continue à calculer une température pariétale au-dessus de la marge de remplissage, paramètre à être utilisé pour le calcul de la résistance à la rupture de la citerne. Cette approche modifiée devrait être utilisée jusqu’à ce que le modèle AFFTAC soit en mesure de bien prévoir les conditions de remplissage intégral de la citerne.

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1 Introduction

1.1 Background

AFFTAC is a computer model that simulates the effects of fire on rail tank-cars. It has been referenced in CFR 49 and CGSB for evaluating thermal protection systems for rail tank-cars.

The AFFTAC computer code is used to analyse a tank-car thermal protection system under “credible” accident conditions. We know from analysis that if a tank-car is thermally protected by insulation that meets the plate test standard (i.e. insulation keeps plate temperature below 427^{o}C for 100 minutes when exposed to a 816^{o}C engulfing fire), this tank will far exceed the requirements of the AFFTAC pool fire simulation (no tank failure before 100 minutes when exposed to 816^{o}C engulfing fire). This means that the AFFTAC simulation is a far less demanding standard for thermal protection systems than the plate test.

1.2 Scope

This review will limit its analysis to how AFFTAC simulates thermal protection systems incorporating 13 mm of high temperature thermal insulation and a steel jacket. The analysis will be based on propane as the commodity, because test data is available for this commodity.

This study will discuss various aspects of the AFFTAC thermal model, to answer the following questions:

i) Is the AFFTAC code conservative in its assumptions?
ii) Why is the AFFTAC code so different from the plate test?
iii) How can the AFFTAC code be improved?

2 Thermal Protection Standards

The standards that govern the thermal protection of tank-cars are contained in CAN/CGSB – 43.147-97. This standard has two parts: one covers the qualification of thermal insulation materials for use in tank-car thermal protection systems; the other covers the actual performance requirements for the complete thermal protection system as it is installed on the tank-car. This chapter looks in detail at these standards.

2.1 Insulation Qualification (Plate Test)

The insulation fire test standard (CAN/CGSB – 43.147-97, Appendix D) applies to the testing done to qualify a thermal insulation material for use on a tank-car. The standard involves using a steel plate as a test sample for evaluating thermal insulation materials. Two different tests exist: one for an engulfing fire and one for a torch fire.

2.1.1 Engulfing Pool Fire Plate Test

The following describes the test procedure for the pool fire test (this material has been extracted from the referenced standards).

(1) A pool-fire environment shall be simulated in the following manner:

(i) The source of the simulated pool fire shall be hydrocarbon fuel with a flame temperature of 871 ± 56^{o} C ($1600 \pm 100°$F), throughout the duration of the test.

(ii) A square bare plate with thermal properties equivalent to the material of construction of the tank car shall be used. The plate dimensions shall be not less than 30.48×30.48 cm (1×1 ft) by nominal 1.6 cm (0.625 in) thick. The bare plate shall be instrumented with not less than nine thermocouples to record the thermal response of the bare plate. The thermocouples shall be attached to the surface not exposed to the simulated pool fire and shall be divided into nine equal squares with a thermocouple placed in the centre of each square.

(iii) The pool-fire simulator shall be constructed in a manner that results in total flame engulfment of the front surface of the bare plate. The apex of the flame shall be directed at the centre of the plate.

(iv) The bare plate holder shall be constructed so that the only heat transfer to the back side of the bare plate is by heat conduction through the plate and not by other heat paths.

(v) Before the bare plate is exposed to the simulated pool fire, none of the temperature recording devices may indicate a plate temperature in excess of 37.8°C (100°F) nor less than 0°C (32°F).

(vi) A minimum of two thermocouple devices shall indicate 427°C (800°F) after 13 ± 1 min of simulated pool-fire exposure.

(2) A thermal protection system shall be tested in the simulated pool-fire environment described in par. (a)(1) of this appendix in the following manner:

(i) The thermal protection system shall cover one side of a bare plate as described in par. (a)(1)(ii) of this appendix.

(ii) The non-protected side of the bare plate shall be instrumented with not less than nine thermocouples placed as described in par. (a)(1)(ii) of this appendix to record the thermal response of the plate.

(iii) Before exposure to the pool-fire simulation, none of the thermocouples on the thermal protection system configuration may indicate a plate temperature in excess of 37.8°C (100°F) nor less than 0°C (32°F).

(iv) The entire surface of the thermal protection system shall be exposed to the simulated pool fire.

(v) A pool-fire simulation test shall run for a minimum of 100 min. The thermal protection system shall retard the heat flow to the plate so that none of the thermocouples on the non-protected side of the plate indicate a plate temperature in excess of 427°C (800°F).

(vi) A minimum of three consecutive successful simulation fire tests shall be performed for each thermal protection system.

2.1.2 Torch Fire Plate Test

The following describes the torch fire test (this material has been extracted from the referenced standards).

(1) A torch-fire environment shall be simulated in the following manner:

(i) The source of the simulated torch shall be a hydrocarbon fuel with a flame temperature of 1204 ± 56°C (2200 ± 100°F), throughout the duration of the test. Furthermore, torch velocities shall be 64.4 ± 16 km/h (40 ± 10 mph) throughout the duration of the test.

(ii) A square bare plate with thermal properties equivalent to the material of construction of the tank car shall be used. The plate dimensions shall be at least 121.92 × 121.92 cm (4 × 4 ft) by nominal 1.6 cm (0.625 in) thick. The bare plate shall be instrumented with not less than nine thermocouples to record the thermal response of the plate. The thermocouples shall be attached to the surface not exposed to the simulated torch and shall be divided into nine equal squares with a thermocouple placed in the centre of each square.

(iii) The bare plate holder shall be constructed so that the only heat transfer to the back side of the plate is by heat conduction through the plate and not by other heat paths. The apex of the flame shall be directed at the centre of the plate.

(iv) Before exposure to the simulated torch, none of the temperature recording devices may indicate a plate temperature in excess of 37.8°C (100°F) or less than 0°C (32°F).

(v) A minimum of two thermocouples shall indicate 427°C (800°F) in 4 min ± 30 s of torch-simulation exposure.

(2) A thermal protection system shall be tested in the simulated torch-fire environment described in par. (b)(1) of this appendix in the following manner:

(i) The thermal protection system shall cover one side of the bare plate identical to that used to simulate a torch fire under par. (b)(1)(ii) of this appendix.

(ii) The back of the bare plate shall be instrumented with not less than nine thermocouples placed as described in par. (b)(1)(ii) of this appendix to record the thermal response of the material.

(iii) Before exposure to the simulated torch, none of the thermocouples on the back side of the thermal protection system configuration may indicate a plate temperature in excess of 37.8°C (100°F) nor less than 0°C (32°F).

(iv) The entire outside surface of the thermal protection system shall be exposed to the simulated torch-fire environment.

(v) A torch-simulation test shall be run for a minimum of 30 min. The thermal protection system shall retard the heat flow to the plate so that none of the thermocouples on the backside of the bare plate indicate a plate temperature in excess of 427°C (800°F).

(vi) A minimum of two consecutive successful torch-simulation tests shall be performed for each thermal protection system.

2.1.3 Plate Temperature Limit

Why is 427^{o}C important for the plate temperature?

As reported by Anderson (1982), 427^{o}C was selected because this is the temperature at which the tank-car steel begins to lose strength in a significant way. It is also a temperature at which the micro structure of the steel has not yet changed. If there is no microstructure change then theoretically a tank-car can be put back into service with minimal refurbishment after a fire exposure.

It should also be noted that at 427^{o}C the tank steel is still very strong (i.e. it has over 80 percent of its ambient temperature strength, assuming TC 128 pressure vessel steel). As reported by Anderson (1982), at 427^{o}C the 112 type pressure tank-car has a burst strength of about 5.6 MPa (for a 3 m diameter tank with 16.5 mm wall) compared to a PRV pop pressure of about 2 MPa (i.e. there is a factor of safety of about 5.6/2 = 2.8).

2.1.4 Plate Heat-Up Times

Why heat up the plate in 4 minutes for the torch and 13 minutes for the pool fire?

As reported by Anderson (1982), the 4 minute heat up time for the torch was implemented because actual tank-cars had ruptured from torch fire in as little as 5 minutes. So they decided to build a torch test facility that would heat a plate sample to 427^{o}C in 4 minutes. In other words they somehow concluded that heating a plate to 427^{o}C in 4 minutes simulated a real tank-car failing in 5 minutes under the exposure of a credible accident torch fire. It is difficult to explain this reasoning. A tank should not fail when the wall reaches 427^{o}C (as discussed in 2.1.3). It is the authors opinion that they developed a torch test facility and as it turned out, this facility could heat the plate in 4 minutes to 427^{o}C. This torch test facility may or may not represent a real-world torch fire accident environment.

The 13 minute heat up time for the pool fire test comes from the full scale fire test of an uninsulated tank-car RAX 201 (Townsend et al, 1974). In that test the wall temperature in the vapour space of the tank-car reached 427^{o}C in about 13 minutes. After about 24 minutes the tank-wall temperature reached just under 640^{o}C and the tank failed. Anderson (1982) reports that they simulated a pool fire by moving the torch fire apparatus back away from the plate sample. This increased standoff distance would result in a reduction in the torch fire heat transfer and increase the time for the plate to reach 427^{o}C (i.e. the time increased from 4 to 13 minutes). This approach is not consistent with an engulfing fire radiating at 871^{o}C as will be demonstrated in a following section.

In any case, it should be stressed that it was originally intended that the torch test be a more severe test than the pool fire test in terms of plate heatup: the plate was to heat up more than three times faster than in the engulfing fire test. This suggests that the torch local heat flux was to be more than three times that of the pool fire.

2.1.5 Test Duration

Why choose a duration of 30 minutes for a torch event and 100 minutes for a pool fire?

As reported by Anderson (1982), the 30 minutes for the torch fire was selected because this is the estimated time for the fuel source of the torch to be depleted. The scenario they assumed was a torch coming from a tank punctured by a coupler impact at 135 degrees from the tank top. They estimated that this tank would blow down to atmospheric pressure in 29 minutes. Anderson also notes that a tank-car with a torch coming from a PRV could last for 40 to 45 minutes. Anderson stated that 30 minutes was reasonable because of the "slight factor of safety" associated with the allowable temperature of 427°C. He stated that at 427°C the tank is still quite strong (in fact this represents a factor of safety = burst pressure/ actual pressure of about 2.5 to 3).

The 100 minute limit for the pool fire case comes from the full-scale fire test of an insulated car (RAX 202, Anderson, 1982). In this case the tank failed at 94.5 minutes in the fire and when it failed it was estimated to be 2 percent full of liquid. It was then estimated that the tank would have been empty at 100 minutes. The time limit of 100 minutes was based on the assumption the tank would be empty at 100 minutes. In other words, they consider the event to be over when the tank is empty of liquid.

2.1.6 Thermal Analysis of Plate Test

The plate test can be modeled as a simple one-dimensional heat transfer problem including thermal radiation, convection and heat conduction. The following equations describe the heat balance on the bare plate.

$$q_{back} = -\sigma\varepsilon(T_p^4 - T_\infty^4) - h(T_p - T_\infty)$$

$$q_{front} = \sigma\varepsilon\varepsilon_f(T_{fire}^4 - T_p^4) - \sigma\varepsilon(1-\varepsilon_f)(T_p^4 - T_\infty^4)$$

$$\rho C w \frac{dT_p}{dt} = q_{front} - q_{back}$$

where

C = specific heat of steel
T_p = plate temperature
σ = Stefan-Boltzman constant
ε = steel emissivity
ε_f = fire emissivity
w = plate thickness
T_∞ = ambient temperature
h= convective heat transfer coefficient
q = heat flux (heat transfer per unit area W/m^2)

t= time
ρ = surface reflectivity
T_{fire} = effective black-body radiating temperature of fire

These equations ignore the temperature gradient through the plate and heat convection from the fire. If these three equations are solved simultaneously it is possible to estimate the plate temperature over time. For the insulated plate the heating of the steel jacket and the conduction through the thermal insulation must be included. For the details of this analysis the reader is directed to Appendix A, where a computer code listing can be found.

2.1.7 Analysis of Engulfing Fire Plate Test

The test procedure for the engulfing fire test provides enough data to show that the test requirements are in conflict with themselves. The basic requirements are:

i) 16 mm steel plate
ii) 816- 927^{o}C engulfing fire
iii) plate T must reach 427^{o}C in 13 minutes plus or minus 1 minute

A simple analysis of a plate shows that a 816^{o}C fire will heat the plate to 427^{o}C in less than 6 minutes. This is based on the following assumptions:

i) surface emissivity is 0.9
ii) plate surface exposed 100 percent to the fire
iii) no fire convection
iv) convection on plate back with h = 6 W/m^{2}K
v) thermal radiation from plate back to ambient surroundings
vi) fire radiates as a black body (emissivity = 1)

It should be noted that if fire convection were also included the plate would heat up even faster.

The following is suggested to explain this discrepancy. The plate test was designed to mimic a tank engulfed in a fire based on the fire test results of Townsend et al, (1974). In that fire test an unprotected propane tank-car was exposed to an engulfing JP-4 fueled fire. It was estimated that the pool fire had effective black body radiating temperatures in the range of 800 – 900^{o}C.

The 13 minutes to reach 427^{o}C was observed in the tank-car fire test (RAX 201) because the tank in the actual fire test was probably not 100 percent engulfed during the early part of the fire test. It is also likely the slower heat-up time was due to the more complex heat transfer conditions on the inside of the tank when compared to a simple plate test (tank has a liquid cooling effect, plate does not). In any event, the 13 minute heat-up time for the plate is not consistent with the 816^{o}C temperature for an engulfing fire that radiates like a black body.

The only ways to increase this heat-up time for a simple steel plate with an 816°C engulfing fire is to reduce the emissivity of the fire or increase the cooling effect on the back-side of the plate. Increasing the cooling effect on the plate back-side would be the most realistic compared to the tank-car but would add to the complexity of the test. If the emissivity of the fire is reduced to 0.55, then a 13 minute heat-up time to 427°C can be achieved with a 816°C fire. However, this low emissivity is not consistent with a large hydrocarbon (HC) pool fire. Large HC pool fires radiate as black bodies (emissivity = 1).

2.1.8 Analysis of Torch Fire Plate Test

The test procedure for the torch fire test also has some problems. The reader is reminded that the torch fire test was intended to be a much more severe fire test condition (i.e. a fire that could make a tank-car fail in 5 minutes). The basic requirements are:

i) 16 mm steel plate
ii) 1150 - 1260°C torch fire
iii) torch velocity 48 – 80 km/hr
iv) plate T must reach 427°C in 4 minutes plus or minus 30 seconds

A simple analysis of a plate shows that a strongly radiating torch fire at 1204°C will heat the plate to 427°C in about 1.5 minutes. This is based on the following assumptions:

i) surface emissivity is 0.9
ii) plate surface exposed 100% to the torch fire
iii) no torch fire convection
iv) convection on plate back with $h = 6\ W/m^2K$
v) thermal radiation from plate back to ambient surroundings
vi) torch radiates as a black body

This is a much faster heat-up than the standard asks for. Torch convection has been ignored here to simplify the analysis. If torch convection were accounted for, the plate would heat up even faster. As with the engulfing fire test, the only ways to increase the heat-up time is to reduce the torch heat transfer or increase the plate back-side cooling effect.

One way to reduce the heat flux from the torch is to reduce the effective emissivity of the torch flame. If this is done, the emissivity must be reduced to about 0.42 to achieve the desired temperature-time relationship. An emissivity of 0.42 is reasonable for a small torching fire and this may be representative of the torch fire apparatus that was used for conducting the torch tests. However this value may not be appropriate for larger-scale torches that could take place in credible accident scenarios.

It should be noted that if the torch emissivity is reduced to 0.42 this torch is not much more severe than the pool fire test. It is certainly not three times as severe as was originally intended.

2.1.9 What Should the Fire Conditions be?

The plate test conditions should be consistent with the following known tank-car conditions:

i) full-scale unprotected tank fails in 24 minutes by engulfing fire
ii) full-scale unprotected tank fails in 5 minutes by torch fire

We will assume that a tank-car (i.e. 112A340W, no thermal protection, properly sized PRV, etc.) will fail with a vapour space wall temperature around 630^{o}C (RAX 201 failed at that temperature). This assumes the tank pressure is near the PRV start-to-discharge pressure.

Figure 2-1 shows predicted heat-up times for the various fire possibilities considered so far. As can be seen from the figure, the heat-up times vary dramatically depending on the assumed fire conditions. The various fire possibilities are summarized in

Plate Fire Test with Insulation and Steel Jacket

In this case it is assumed the plate sample is covered with a layer of thermal insulation and this is covered with a 3 mm steel jacket. The requirement is to keep the plate temperature below 427oC for 100 minutes for the pool fire simulation and 30 minutes for the torch fire simulation.

An analysis was performed to calculate the conductance of the insulation material that would just meet the plate test requirements. This conductance was calculated to be around 35 W/m2K for the engulfing fire and 34 W/m2K for the torch fire. In other words, both tests can be passed with nearly the same insulation conductance. This is based on the following assumed fire and plate conditions:

fire temperature 816oC for engulfing fire, and 1204oC for the torch
i) fire emissivity = 1 for engulfing and 0.42 for torch
ii) fire convection h = 0.0
iii) plate outer surface emissivity = 0.9
iv) plate inner surface emissivity = 0.9
v) backside convection h = 0.0 (worst case)

Table 2-1. The table shows how variations in assumed fire properties change the plate test outcome dramatically. As can be seen, both the 13 minute heat-up time for the pool fire and the 4 minute heat-up time for the torch are inconsistent with the desired outcomes for the unprotected tank-cars.

For the pool fire case, a pool fire that meets the 13 minute plate heat-up time (i.e. 816^{o}C fire with fire emissivity 0.55) does not represent a credible engulfing pool fire at 816^{o}C. With this fire environment the real tank-car would probably not fail at all because the wall temperature would never achieve 630^{o}C. However the 816^{o}C black body fire does cause the plate sample to reach 630°C in 21 minutes which agrees well with the observed RAX 201 tank failure time of 24 minutes. Note that the plate heats up to 427°C in 6 minutes in this case.

The torch case is similar. If we use the 4 minute heat-up time the plate will reach 630°C in about 7.5 minutes. This is a little slow compared to the 5 minute tank failure time that we want. We must increase the torch emissivity to 0.6 (from 0.42) to get the desired 630°C in under 5 minutes (4.5 minutes to be exact). This torch heats the plate to 427°C in 2.7 minutes rather than the specification time of 4 minutes.

The above suggest that we need to change the current plate test standards if we want them to accurately represent credible fire conditions.

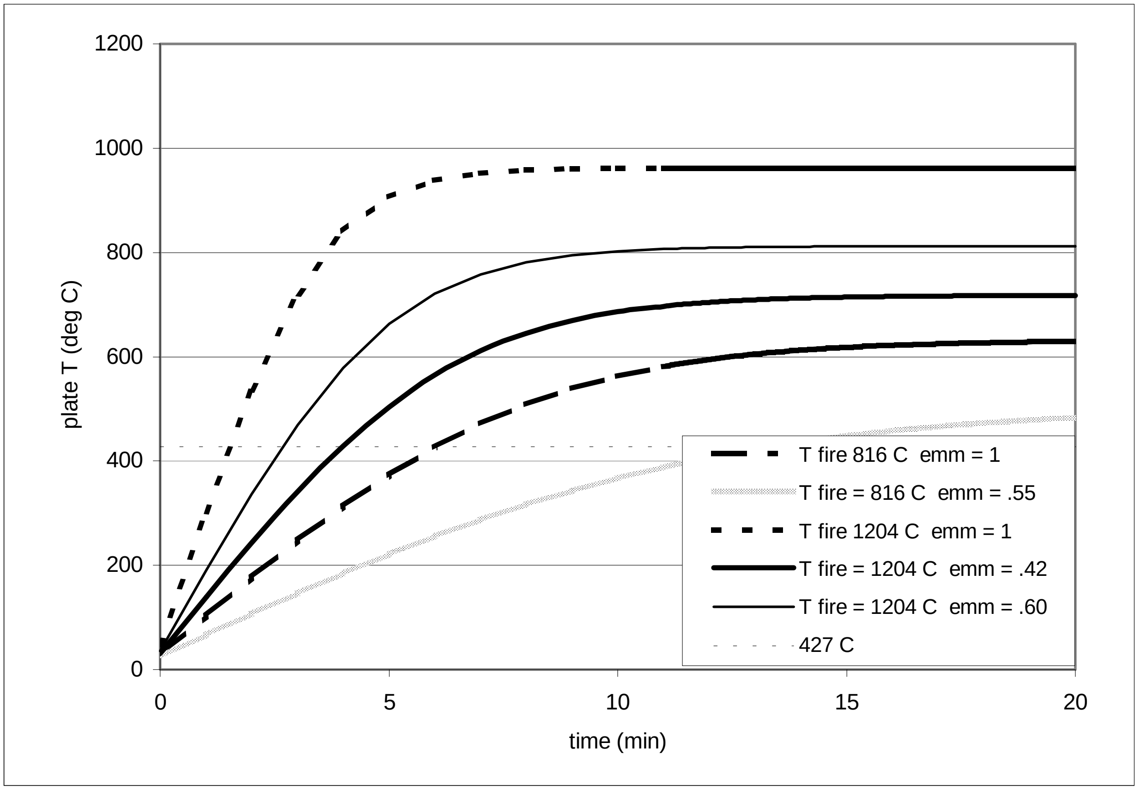

Figure 2-1: Plot of Heat-up Times for Plate with Various Fire Conditions

2.1.10 Plate Fire Test with Insulation and Steel Jacket

In this case it is assumed the plate sample is covered with a layer of thermal insulation and this is covered with a 3 mm steel jacket. The requirement is to keep the plate temperature below 427°C for 100 minutes for the pool fire simulation and 30 minutes for the torch fire simulation.

An analysis was performed to calculate the conductance of the insulation material that would just meet the plate test requirements. This conductance was calculated to be around 35 W/m^{2}K for the engulfing fire and 34 W/m^{2}K for the torch fire. In other words, both tests can be passed with nearly the same insulation conductance. This is based on the following assumed fire and plate conditions:

vi) fire temperature 816°C for engulfing fire, and 1204°C for the torch
vii) fire emissivity = 1 for engulfing and 0.42 for torch
viii) fire convection h = 0.0
ix) plate outer surface emissivity = 0.9
x) plate inner surface emissivity = 0.9
xi) backside convection h = 0.0 (worst case)

Table 2-1: Summary of Fire Conditions

Fire condition	**Heat Flux to Surface at 25°C**	**Heat Flux to Surface at 600°C**	**Time from 25 to 427°C**	**Time from 25 to 630°C (i.e. tank failure)**
Pool Fire at 816°C with emm = 1 (i.e. black body)	72 kW/m^2	42 kW/m^2	6 min	21 min
Pool Fire at 816°C with emm = 0.55	30	Temperature not achieved	13	Temperature not achieved
Torch at 1204°C with emm = 1 (i.e. black body)	242	216	1.5	2.5
Torch at 1204°C with emm = 0.6	146	117	2.7	4.5
Torch at 1204°C with emm = 0.42	102	73	4	7.5

Assumptions: surface emissivity = 0.9, back-side h = 6 W/m^{2}K

With the above assumptions the torch test is not that much more demanding than the engulfing fire test as far as insulation conductance is concerned. Of course the torch test will result in higher insulation temperatures.

It is recommended that the torch test standard be changed such that the time to heating of the plate be reduced to something more representative of a large scale torching fire. It is suggested that the time to 427°C for the bare plate be changed to 2 minutes plus or minus 30 seconds from 4 minutes plus or minus 30 seconds. This would allow the torch emissivity to be set in the range 0.6 – 1.0 which is more in agreement with large scale hydrocarbon torching fires. If this is done then the torch fire test determines the maximum allowable conductance of the insulation sample at around 23 W/m^{2}K. Modern high temperature ceramic blanket materials can achieve even lower conductances than this with a 13 mm layer of material (as is used in current practice on some tanks).

2.2 Thermal Protection Systems

If an insulation material passes the plate test, then it can be used on tank-cars for thermal protection. The tank-car system with thermal protection must meet a different requirement from that for the insulation material by itself. The following is the requirement for thermal protection systems (also from Appendix D, CAN/CGSB – 43.147-97).

(a) Performance Standard.

When this standard requires thermal protection on a tank-car, it shall have sufficient thermal resistance so that there will be no release of any lading from within the tank-car, except release through the pressure relief device, when subjected to:

(1) A pool fire for 100 min, and

(2) A torch fire for 30 min.

(b) Thermal Analysis

(1) Compliance with the requirements of par. (a) of this section shall be verified by analysing the fire effects on the entire surface of the tank. The analysis must consider the fire effects on and the heat flux through tank discontinuities, protective housings, underframes, metal jackets, insulation, and thermal protection. A complete record of each analysis shall be made, retained and, upon request, made available for inspection and copying by an authorized representative of Transport Canada. The procedures outlined in *Temperatures, Pressures and Liquid Levels of Tank Cars Engulfed in Fires*, DOT/FRA/OR&D-84/08.11, (1984) shall be deemed acceptable for analyzing the fire effects on the entire surface of the tank-car.

(2) When the analysis shows that the thermal resistance of the tank-car does not conform to par. (a) of this section, the thermal resistance of the tank car shall be increased by using a system listed by Transport Canada under par. (c) of this section or by testing a new and untried system and verifying it in accordance with Appendix D of this standard.

(c) Systems that No Longer Require Test Verification. Transport Canada maintains a list of thermal protection systems that comply with the requirements of Appendix D of this standard and that no longer require test verification. Information necessary to equip tank cars with one of these systems is available from the Director.

(d) Jacketed thermal protection systems shall be flashed around all openings so as to be weathertight. The exterior surface of a carbon steel tank and the inside surface of a carbon steel jacket shall be given a protective coating.

2.3 Plate Test Standard vs Thermal Protection Standard

In the plate test standard the plate temperature cannot exceed 427^{o}C for 100 minutes in an engulfing fire and 30 minutes for a torch fire. However in the thermal protection standard, the tank is not allowed to fail in 100 minutes of engulfing fire or 30 minutes of torching fire. It was shown in a full scale fire test (RAX 201) that a tank-car can fail when the vapour space wall temperature reaches about 630^{o}C. This means the thermal protection standard allows 630^{o} C wall temperature while the plate test allows 427^{o} C. In other words, the plate test is much more conservative than the thermal protection standard. The question then is – was this difference intended?

As we will see, the current practice of simulating (computer modelling) tank-cars exposed to pool and torch fires is based on the plate test standards. It was shown earlier that the plate test standard is not consistent with itself or its original objective. Therefore the current practice of computer modelling of thermal protection systems is also inconsistent. This will be shown in detail in the following chapters.

2.3.1 Do we need both torch and pool fire tests?

A question should be asked – do we need both the torch test and the pool fire test? If an insulation material passes a severe torch test, will it always pass the pool fire test? As shown earlier the thermal protection system conductance is dictated by the torch fire test. Normally this conductance is more then adequate to pass the pool fire test. Why do we need both tests?

The pool fire test lasts for 100 minutes and the thermal barrier must survive high temperature for this long a period. It is very unlikely that an insulation material could last 30 minutes under a torch and not last 100 minutes under a pool fire. However, it is not unreasonable to confirm this by testing. In both cases the material will probably have to be a high temperature thermal insulation material like a ceramic blanket. This material must be able to withstand temperatures approaching 900^{o}C temperatures for 30 minutes and 800^{o}C for 100 minutes.

For tank thermal modelling both tests are definitely needed. The pool fire is assumed to engulf the tank and therefore this condition is the most demanding on the pressure relief valve system and therefore is needed to prove the PRV flow capacity. The pool fire case will also result in the fastest emptying of the tank through the PRV and this too has an impact on the test outcome. The torch test is the most demanding test for vapour space wall temperature. Therefore both tests are needed to prove the thermal protection system on the tank-car.

3 AFFTAC vs Experiments

The following section provides an overview and critique of this computer code. Further details about AFFTAC can be found in Johnson (1998).

Important factors in fire exposure simulation include the following:

i) fire heat flux
ii) tank exposure (fraction of tank involved in fire and fire location relative to vapour space)
iii) tank lading thermodynamic response
iv) PRV operating characteristics
v) vapour space heat transfer and wall temperature prediction
vi) tank material properties and failure criteria

The AFFTAC computer code is used to simulate the effects of fire impingement on tank-cars equipped with thermal protection systems that use qualified thermal insulation materials (as determined by the plate test standard). If an insulation material meets the plate test standard then we would expect it to also meet the thermal protection standard. We would also expect that an insulation material that fails the plate test standard should fail the thermal protection standard. As will be shown, this is not the case. In general insulation that meets the plate test standard usually exceeds the thermal protection standard by a fair margin.

Let us begin by looking at the current capabilities of the AFFTAC code.

3.1 AFFTAC and Full Scale Engulfing Pool Fire Test Results

Before the AFFTAC model is described in detail, AFFTAC predictions will be compared to actual fire test data for an uninsulated tank-car (RAX 201) exposed to an engulfing fire (data from Townsend et al 1974). We will also look at an AFFTAC simulation of a torch fire event with an uninsulated tank-car.

AFFTAC was run with the following case which closely models the RAX 201 test:

lading is pure propane
127000 litre tank (3.04 m diameter)
TC 128 pressure vessel steel
wall thickness 16 mm
PRV set pressure 1.93 MPa (280.5 psig)
PRV flow rating 16.5 m^3/s (35000 scfm air) at 2.1 MPa
Initial fill 95%
Initial temperature 21^oC

No thermal protection
Fire temperature 816^{o}C (emissivity = 1.0)
Tank surface emissivity 0.9
100% tank exposure

The following sections compare the AFFTAC model to available data from the RAX 201 test. The output of this simulation is shown below.

Table 3-1: Summary of AFFTAC Simulation Result

Time	**Temperatures**		**Pressures**		**volume fill**	**PRV Flow**
	Liquid Product	Vapour Product	Tank	Burst		
min	^{o}C	^{o}C	MPag	MPag		kg/s
0	21.1	21.1	0.76	5.87	0.95	0.0
1	24.9	87.0	0.84	5.86	0.961	0.0
2	28.7	151.8	0.94	5.84	0.973	0.0
3	32.6	214.7	1.04	5.77	0.987	0.0
4	36.7	36.2	1.59	5.87	1	1.3
5	41.1	40.6	1.59	5.87	1	17.4
6	45.3	44.9	1.59	5.87	1	16.9
7	49.6	49.2	1.63	5.87	1	17.1
8	53.8	53.3	1.79	5.87	1	17.2
9	57.9	57.5	1.96	5.87	1	17.2
10	60.1	110.3	2.03	5.86	0.98	23.9
11	61.2	172.2	2.08	5.82	0.951	28.2
12	62.2	230.4	2.12	5.74	0.919	29.0
13	63.1	286.3	2.16	5.58	0.884	29.8
14	63.8	341.1	2.20	5.31	0.848	30.4
15	64.4	391.5	2.23	4.93	0.81	30.9
16	64.9	437.1	2.25	4.59	0.771	31.4
17	65.4	477.5	2.28	4.09	0.731	31.8
18	65.8	512.8	2.30	3.65	0.69	32.2
19	66.2	543.3	2.32	3.28	0.647	32.6
20	66.6	569.3	2.33	2.96	0.604	32.9
21	66.9	591.2	2.35	2.68	0.559	33.2
22	67.1	609.7	2.36	2.45	0.514	33.4
22.5	67.2	617.9	2.35	2.35	0.492	26.8

The above table shows two temperatures, one for the liquid product and one for the vapour product. However, no printout is given for the vapour space wall temperature or the liquid wall temperature. It is believed that the vapour product temperature is actually the vapour space wall temperature since this appears to be the temperature used to calculate the tank burst pressure. The liquid product temperature shown is very close to the liquid wall temperature.

The above table shows that the tank burst pressure drops down to the tank internal pressure at 22.5 minutes indicating tank failure. This is a little short of the 24.5 minutes for failure observed in the RAX 201 test. This difference is probably due to fact that we have used 0.9 for the tank surface emissivity whereas AFFTAC recommends 0.8 be used. This difference in emissivity is discussed elsewhere in this report.

3.1.1 Wall Temperatures

Figure 3-1 shows a comparison between AFFTAC and experiment for a full scale uninsulated propane tank-car exposed to engulfing fire. As can be seen from the figure there is significant disagreement between AFFTAC and the data. Initially the AFFTAC predicted temperature for the vapour space climbs rapidly but then suddenly drops back down. This is because AFFTAC predicts that the tank goes shell full of liquid (from about 4 minutes to 9 minutes in the test). There is no evidence that this actually happened in the fire test of RAX 201.

The AFFTAC predicted wall temperature begins to increase again after the 9 minute mark in the test. At 24 minutes when the tank fails the AFFTAC wall temperature has caught up with the measured data.

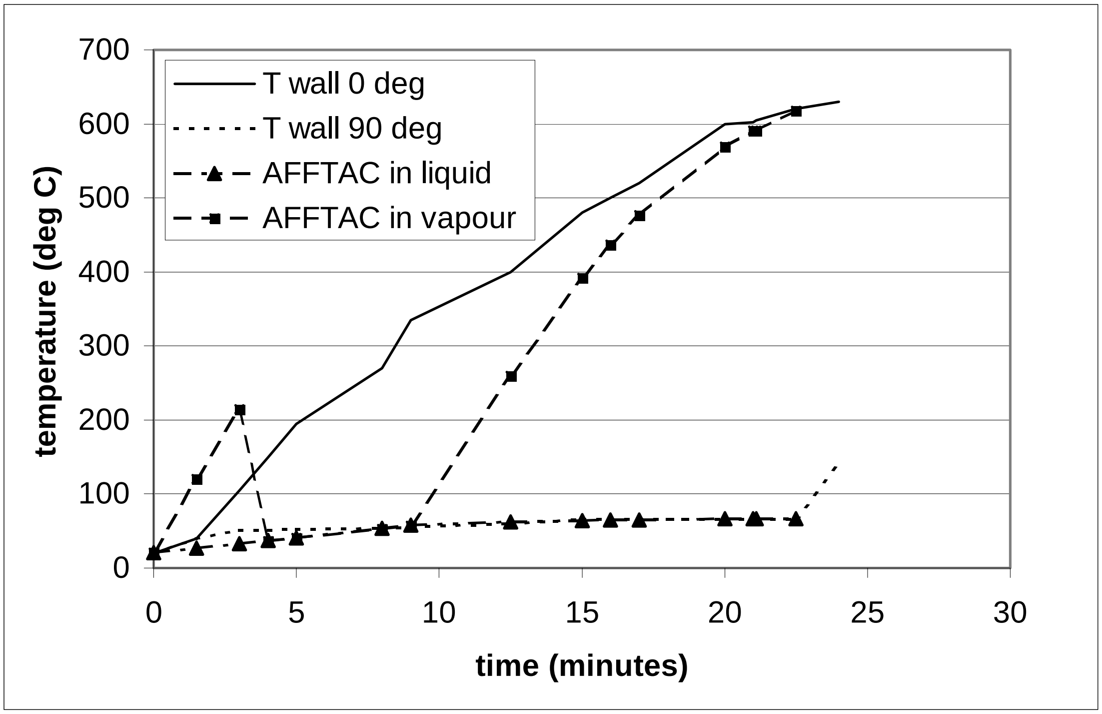

Figure 3-1: AFFTAC Predicted Wall Temperatures vs Measured for Uninsulated Tank-Car Exposed to Engulfing Fire (data from RAX 201 Townsend et al, 1974)

It should also be pointed out that the tank wall did not achieve 427°C in 13 minutes as it did in the actual fire test of RAX 201. This is the heat-up time that is used in the plate test standard.

The error in the AFFTAC prediction is due to an error in prediction of the liquid level. This will be discussed further in later sections.

3.1.2 Tank Pressure

Figure 3-2 shows a comparison between AFFTAC predictions and full-scale experiment. As can be seen from the figure, AFFTAC under-predicts the rate of tank pressurization early on in the event. However later on in the event the AFFTAC prediction catches up with the actual tank pressure. This error in the prediction of the tank pressure suggests that the thermodynamic model in AFFTAC has some deficiencies.

The reason for the error in the prediction of tank pressure is due to the fact that AFFTAC assumes a uniform liquid temperature. Assuming the liquid temperature is uniform causes the liquid temperature to increase very slowly. The tank pressure is calculated as the saturation pressure based on the liquid temperature. The error in estimating the pressure rise causes an error in the prediction of the first pressure relief valve action. This leads to errors in the prediction of the liquid level and this causes the errors in the prediction of the tank wall temperatures.

Experiments have shown that the liquid temperature is not uniform (see for example, Townsend et al, 1974). In a fire, the liquid temperature is higher near the heated wall and at the top of the tank and this warm layer of liquid drives the tank pressure. For this reason the tank pressure rises more rapidly than predicted by AFFTAC. This will be discussed further in the next section.

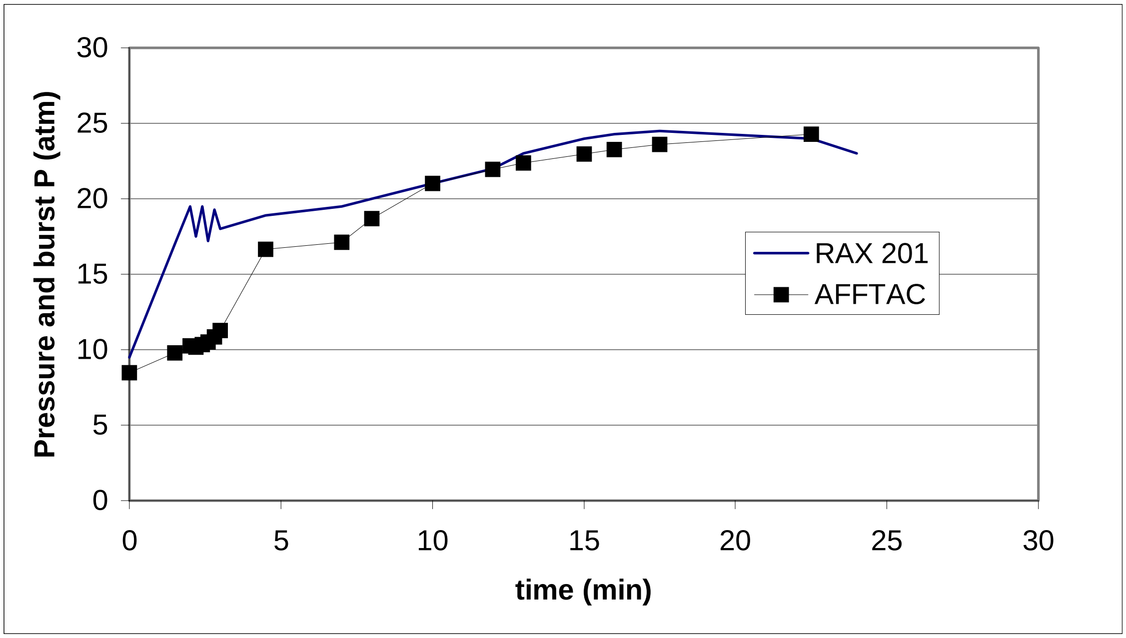

Figure 3-2: AFFTAC Predicted Tank Pressure vs Measured for Uninsulated Tank-Car Exposed to Engulfing Fire (data from RAX 201 Townsend et al, 1974)

3.1.3 Lading Temperature

Figure 3-3 shows a comparison between AFFTAC predictions for the liquid temperature and full-scale experiment. As can be seen from the figure, AFFTAC does a good job predicting the average liquid temperature. However the data shows that the liquid temperature varies significantly from the tank bottom to the top. The data at the top of the tank may be showing vapour temperatures part of the time and liquid temperature part of the time. The data suggests the tank came very close to liquid full for a few minutes (at 10 to 12 minutes in the test). The AFFTAC code predicts the tank is shell full from about 4 minutes into the test until the 9 minute point. This error in predicting shell full explains several problems with AFFTAC.

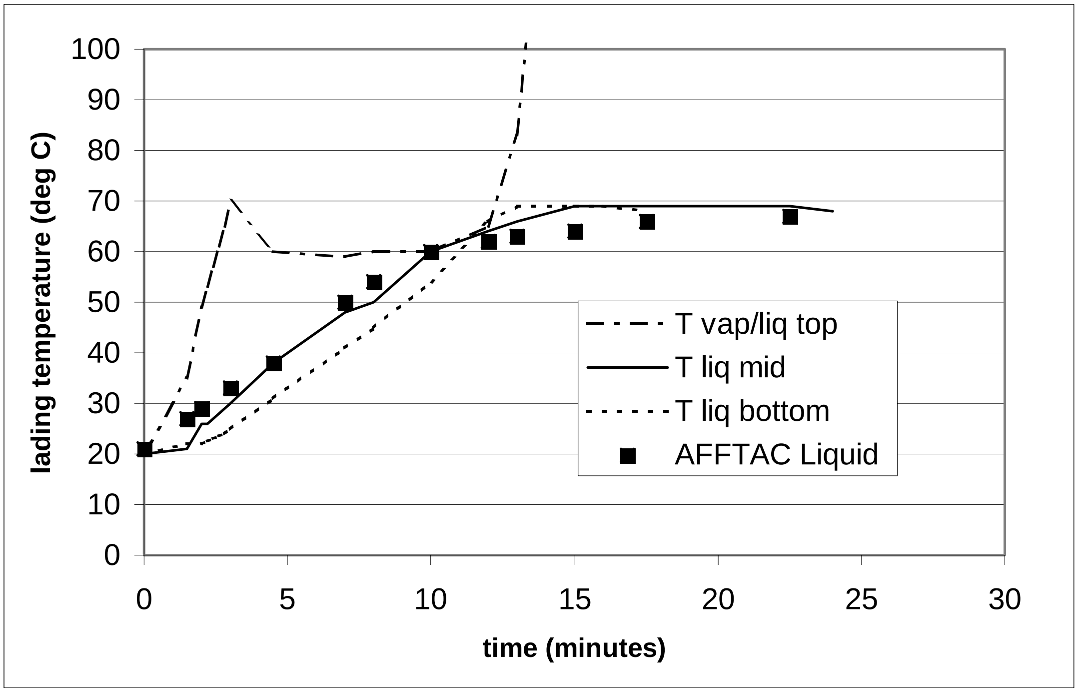

Figure 3-3: AFFTAC Predicted Liquid Temperature vs Measured for Uninsulated Tank-Car Exposed to Engulfing Fire (data from RAX 201 Townsend et al, 1974)

AFFTAC predicts the shell full condition because AFFTAC fails to predict early opening of the PRV. In the fire test the PRV opened at about 2 minutes into the test and this early opening stopped the tank from going shell full at five minutes into the test. In fact, the wall temperature measurements suggest the tank never went completely full of liquid.

3.1.4 Liquid Fill

If a tank starts off 95 percent full of liquid propane and if heat is added to the liquid uniformly then the tank will go liquid full before the PRV opens and vents material. In AFFTAC it is assumed that the heat is added uniformly and therefore it predicts a tank will go shell full if it starts with a high fill level. In the full-scale test of an uninsulated tank-car (RAX 201) the tank did not appear to go shell full based on observations of wall temperatures at the top of the tank.

Figure 3-4 shows the liquid position predicted by AFFTAC along with liquid position estimates from the RAX 201 test based on wall temperature break away times. As can be seen the AFFTAC predictions are in good agreement with the limited data points from the RAX 201 experiment. However this agreement is somewhat misleading because we have no data between 3 and 10 minutes. It is in this period of time where AFFTAC predicts the shell full condition. However wall temperatures at the top of the tank suggest that tank did not go shell full at any time in the test. The figure also shows some estimates of fill in this time range where no data exists. These estimates are based on limited lading temperature data from the RAX 201 test.

In any case, it is believed that AFFTAC does not adequately model the behavior of high fill level tanks because it will predict the shell full condition before the PRV opens.

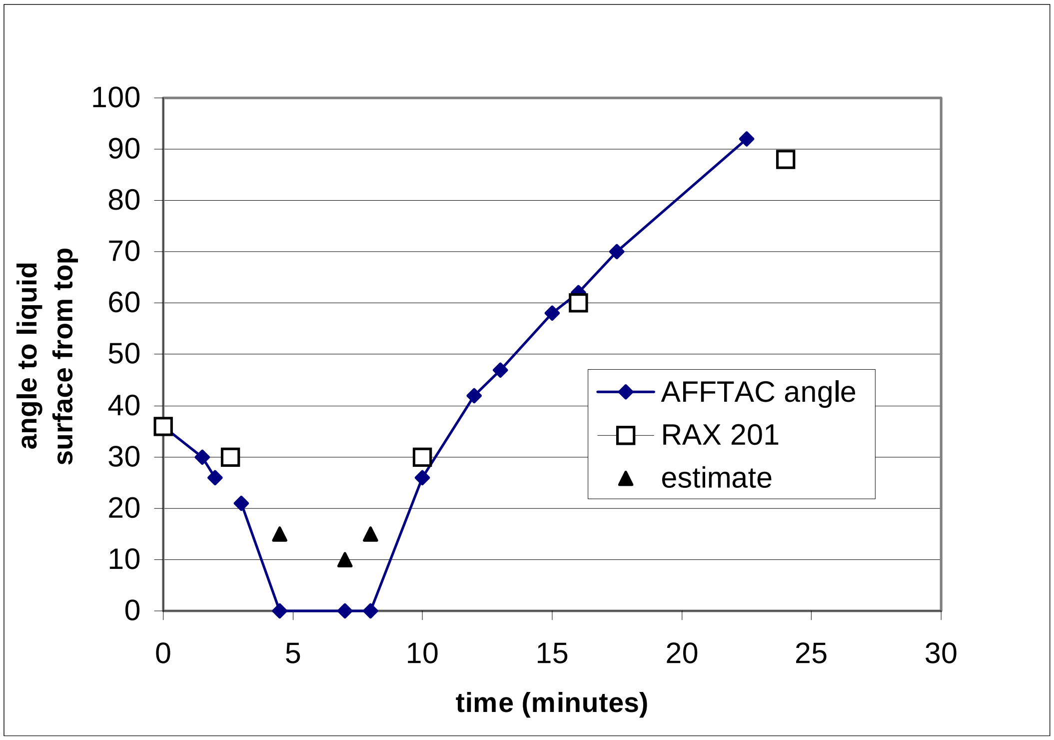

Figure 3-4: AFFTAC Predicted Liquid Level vs Estimated from data for Uninsulated Tank-Car Exposed to Engulfing Fire (data from RAX 201 Townsend et al, 1974)

3.1.5 Tank Failure Prediction

Figure 3-5 shows the predicted tank pressure and burst pressure from AFFTAC. As can be seen from the figure AFFTAC predicts tank failure (when hoop stress = material ultimate strength) at just under 23 minutes. The RAX 201 tank failed at about 24 minutes. The agreement is excellent even though AFFTAC was not able to predict tank pressure or wall temperatures early in the fire exposure event. This excellent agreement between predicted time to failure and actual time to failure is why AFFTAC was recommended as the computer code for analyzing thermal protection systems.

When a computer model is selected as a standard method of analysis then it should accurately represent the physics of the problem. AFFTAC clearly has some deficiencies when it comes to the fundamentals of this problem.

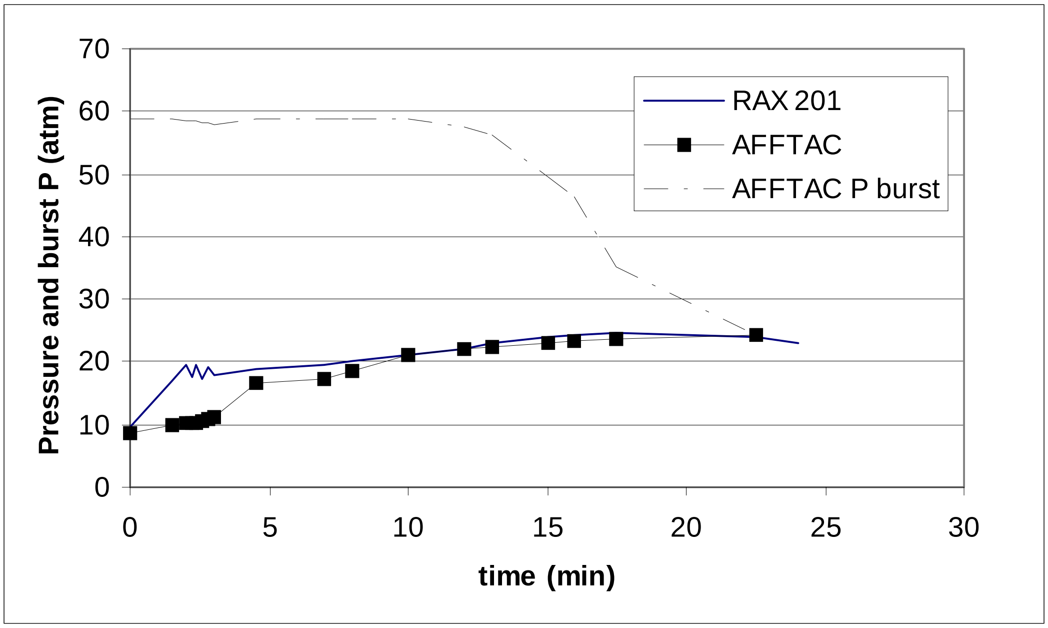

Figure 3-5: AFFTAC Predicted Tank Pressure and Burst Pressure for Uninsulated Tank-Car Exposed to Engulfing Fire (data from RAX 201 Townsend et al, 1974)

3.2 AFFTAC and the Torch Fire Case

AFFTAC was run with the following case:

propane
127000 litre propane tank (112A340W, 3.04 m diameter)
TC 128 steel
wall thickness 16 mm
PRV set pressure 1.9 MPa
PRV flow rating 16.5 m^3/s (35000 cfm) at 2.1 MPa
Initial fill 95%
Initial temperature 21^{o}C
No thermal protection
Fire temperature 1204^{o}C with torch emissivity at 0.536
Tank surface emissivity 0.9
Tank exposure 1.2 m x 1.2 m

The results of this simulation are as follows:

i) tank failure predicted at 9.1 minutes
ii) no tank pressure rise (P constant at 0.64 MPa)
iii) no liquid temperature rise (liquid T = 21°C)
iv) fill at failure = 95%
v) no PRV action
vi) vapour wall temperature at failure 760 °C

In this simulation the vapour wall temperature reached 427°C in 4 minutes as per the plate test standard. Recall that the original standard was designed to correlate to accident reports where tanks failed after 5 minutes of torch fire exposure. This simulated torch event is very severe – but it is not as severe as originally intended.

4 AFFTAC Review

This chapter analyzes the main assumptions used in AFFTAC. The objective is to identify areas in AFFTAC that need improvement.

Prediction of tank failure needs accurate prediction of tank pressure and tank wall strength. The prediction of pressure requires a good fire model and thermodynamic process model. Prediction of material strength requires good prediction of wall temperature. Prediction of wall temperature requires a good prediction of liquid level and external (fire) and internal (vapour space) heat transfer.

The following assumptions play an important role in how AFFTAC simulates fire exposure:

- fire conditions
- external and internal heat transfer
- PRV action
- thermodynamic model
- failure criteria

Chapter 3 shows that the thermodynamic model used in AFFTAC produces erroneous estimates of tank pressure and liquid level and this leads to errors in wall temperatures. However other aspects of the model need further consideration.

4.1 AFFTAC Source Code

Before the assumptions are discussed it is appropriate to comment on the AFFTAC source code. AFFTAC is programmed in the FORTRAN programming language. This language is still extensively used in engineering computer codes and therefore is widely understood and accepted. However the programming style used in AFFTAC is outdated which makes reading the code extremely difficult. For example:

i) Very few comments are included in the code for documentation
ii) Few subroutines are used. The main program is one long series of if-then-else statements with goto statements throughout
iii) many variable names are less than 4 characters in length and therefore are difficult to interpret
iv) equations have been modified to reduce floating point math and this makes them almost impossible to recognize

If this code is to remain the standard it should be recoded to meet current software practices. It should also include an improved user interface and more detailed output.

4.2 Fire Conditions

The AFFTAC code can model both the engulfing pool fire and the torch fire. The AFFTAC fire models were developed to satisfy the plate test standard.

4.2.1 Pool Fire Heat Flux

In AFFTAC the fire model is based on the plate test standard as described earlier in this report. The pool fire is modelled as a black body radiating at 816^o C. Fire convection is not accounted for separately.

In the CGSB standard the pool fire test specification requires a pool fire temperature of 871^{o}C plus or minus 56^{o}C. Therefore AFFTAC is using the lowest possible fire temperature to satisfy this specification. It is believed this was done to make the AFFTAC predicted tank failure time agree with the RAX 201 test.

As shown in the following table, pool fire temperatures can be much hotter than 816^{o}C. Nakos and Keltner (1989) reported very detailed heat transfer measurements in a JP4 pool fire (9 m x 18 m rectangle). They recorded average total heat fluxes of between 120 and 128 kW/m^2 which is in good agreement with the table. Therefore it is clear that the AFFTAC assumption of 816^{o}C is not conservative for a large JP4 pool fire.

Table 4-1: Maximum Pool Fire Radiating Temperatures (data from Rew et al, 1997)

Fuel	**Maximum Pool Fire Heat Flux**	**Maximum Effective Radiating Temperature (assuming flame emissivity of 1.0 and flux is 100% radiation)**
AFFTAC	79 kW/m^2	816^{o}C
Plate test	97	871
Butane	225	1140
Diesel oil	130	960
Gasoline	130	960
JP 4	130	960
Kerosene	130	**960**
Propane	250	1180
Octane	200	1100
LNG	265	1200
Pentane	200	1100
Toluene	130	960

4.2.2 Torch Fire Heat Flux

A torch fire will heat a surface by both convection and thermal radiation. In AFFTAC the torch is modelled considering radiation only.

The DOT standard torch must have a temperature of 1204°C plus or minus 56°C and must heat a 16 mm steel plate from ambient temperature to 427°C in 4 minutes (plus or minus 30 seconds). In the AFFTAC code this heat-up time is achieved if the torch black body radiation is multiplied by a factor of 0.536 (assuming a tank surface emissivity of 0.8; which gives a total factor of 0.536 x 0.8 = 0.43). This factor accounts for the effective emissivity and view factor for the torch used in the 1.2 m x 1.2 m plate tests.

It has already been shown that this approach to modelling a torch will result in a torch fire that is not that much more severe than the engulfing fire model. Recall that the original plate test was intended to have the torch local heat flux about three times that of the pool fire.

4.2.3 Tank Exposure

The fraction of the tank exposed to the fire is an important factor because it affects how the tank pressurizes and how it empties through the PRV.

In AFFTAC it is assumed the tank is 100 percent engulfed in fire for the pool fire simulation. This is a straightforward assumption and it correlates well with the plate test standard and a credible engulfing fire accident. However, this assumption does not agree very well with the AAR pressure relief valve sizing formula which uses the following expression for tank area exposed to fire.

$$A_f = A_{\tan k}^{0.82}$$

where,

A_f = tank area affected by fire for PRV sizing
A_{tank} = tank surface area

For a 112 type tank-car the tank surface area is about 180 m^2. The PRV sizing formula reduces this to about 70 m^2 which is a reduction of about 60 percent. This 60 percent reduction in area would result in a 60 percent reduction in total fire heat transfer. However, AFFTAC and the AAR also use different fire temperatures. These discrepancies are beyond the scope of this study but it is suggested here that AFFTAC and the AAR PRV sizing formula should be more consistent with each other.

The torch fire simulation is another matter. AFFTAC allows the user to specify the area of tank surface exposed to a torch. In the original DOT steel plate tests, the plate measured 1.2 m x 1.2 m (4 ft x 4 ft). This exposure area has now been applied in the AFFTAC computer model for modelling a tank-car exposed to a torch fire.

If the AFFTAC model is being used to model the real-world tank-car system then it should be modelling a credible torch environment. A 1.2 m by 1.2 m torch area (i.e. 1.5 m^2) covers less than 1 percent of the tank surface of a 112 type tank-car, and this in no way represents a credible torch fire accident. In a credible torch fire impingement case where one tank's PRV flare is impinging on another tank, the area of coverage could be more like 20-30 percent of the tank surface.

If it is assumed that the torch covers only 1 percent of the tank then the tank will pressurize very, very slowly. In the CGSB standard a thermally protected tank must survive a torch for 30 minutes. If the tank does not pressurize in that 30 minutes, it has a much better chance of surviving the test. Therefore, assuming such a small torch area is not a conservative or credible assumption.

4.3 External and Internal Heat Transfer

The accurate prediction of wall temperatures requires accurate models for the internal and external heat transfer conditions.

4.3.1 External Heat Transfer

The external heat transfer is driven by the fire model and the tank external surface radiating properties. In AFFTAC it is assumed that the tank outer and inner surface has an emissivity of 0.8. It is the opinion of the authors that this value is low and should be closer to 0.9. A low surface emissivity reduces the heat transfer from the fire to the tank. Therefore it should be noted that using 0.8 is not a conservative assumption.

Table 4-2 shows emissivity data (Hottel and Sarofim, 1967) for a variety of surfaces.

Table 4-2: Summary of Surface Emissivities (Hottel and Sarofim, 1967)

Surface	Emissivity Range	Comment
sheet steel, rough oxide layer	0.8	Used in AFFTAC
steel plate, rough	0.94 – 0.97	
white enamel fused on iron	0.90	
black or white lacquer	0.8 – 0.95	
flat black lacquer	0.96 – 0.98	
candle soot	0.95	

Based on the above list it appears a reasonable assumption for emissivity would be 0.9 for the outer surface of the tank. It may be justifiable to use 0.8 or even lower on the tank inside assuming the tank inner surface is clean and unpainted. The lower the inside surface emissivity the hotter the wall gets.

4.3.2 Internal Heat Transfer

The internal heat transfer involves convection and boiling in the liquid wetted regions and convection and thermal radiation in the vapour region. The wall temperatures in the liquid filled part of the vessel exposed to fire will be effectively cooled by the liquid. As a result the liquid wetted wall temperatures will be close to the liquid temperature. The vapour space wall temperatures will get very hot because of the poor cooling effect of the vapour. To predict tank failure, a thermal model must be able to accurately predict vapour space wall temperatures.

4.3.2.1 Liquid Space

In the liquid space AFFTAC uses a high value for the convective heat transfer coefficient. This results in the liquid wetted wall temperature always being within 100^oC of the liquid temperature. This means that the liquid wetted wall will always maintain its strength. This is in good agreement with experiments.

4.3.2.2 Vapour Space

The vapour space wall temperature is affected by the vapour and the liquid. The hot vapour space wall convects heat to the vapour and radiates heat to the vapour, the liquid surface and to itself (because the wall is concave). The liquid surface will be relatively cool (its temperature is limited by the PRV set pressure). Therefore the vapour space wall will be cooler for high fill levels than for low fill levels. Also, heat will be conducted from the hot vapour space wall to the wall cooled by liquid. This also results in lower vapour space wall temperatures when the fill level is high.

In AFFTAC it is assumed that the vapour space wall has a uniform temperature and this temperature is calculated from an energy balance that accounts for the fire heat transfer on the outside of the tank and for convection and radiation on the inside of the tank.

Vapour Space Radiation

The following assumptions are used to model the vapour space radiation in AFFTAC:

i) Vapour space consists of two radiating zones, the wall and the liquid surface
ii) Liquid surface has an emissivity of 0.9
iii) Absorption of radiation by the vapour is ignored

With this simple model the vapour space wall has a single uniform temperature. In fact we would expect a higher temperature at the top of the tank and a lower temperature near the liquid surface. This difference could be significant when trying to predict tank failure at high wall temperatures.

With the above assumptions, the view factor from the vapour space wall to the liquid surface is equal to the ratio of liquid surface area/ vapour space wall area.

$$F_{wl} = \frac{180 \sin\theta}{\pi\theta}$$

where θ is the angle in degrees from the tank top to the liquid surface.

The assumption that the vapour does not absorb radiation is probably not accurate. It is likely that the vapour absorbs significantly and this could result in higher wall temperatures in the vapour space. However, to account for this accurately would require a rather complicated model.

Vapour Space Convection

For convection heat transfer from the vapour space wall AFFTAC uses a range of convective heat transfer coefficients. The values used depend on the tank fill level and the PRV flow rate. Table 4-3 gives a summary of the values used. The AFFTAC manual suggests that these values were “ deduced, in part from the full scale fire tests”.

The most important convective effect in the vapour space is when the liquid level is high. In this case it is possible that swelling and frothing of the liquid during PRV action could cause intermittent wetting of the vapour space wall. This was suggested by Birk (1983). In that case the wall would be cooled but not as well as if it were totally wetted by liquid as in the case of the shell liquid full condition. In AFFTAC the tank goes shell full as shown earlier.

Table 4-3: Summary of Convective Heat Transfer Coefficients used in AFFTAC

Fill Condition	**Liquid Full or PRV Venting Liquid**	**Vapour and Liquid in Tank with PRV Open**	**Vapour and Liquid in Tank with PRV Open**
		1.5 < mdot < 11.4 kg/s	mdot > 11.4 kg/s
Default	h = 0 W/m^2K	h = 0 W/m^2K	h = 0 W/m^2K
fill > 0.99	h = 11.4		
0.95 < fill < 0.99	h = 2.9		
Fill > 0.9		h = 11.4	h = 34
0.6 < fill < 0.9		h = 2.9	
0.4< fill < 0.6		h = 1.5	h = 8.5
Fill = 0		h = 5.7	h = 5.7

1 W/m^2K = 0.17612 Btu/hr ft^2 ^oF

The above table suggests that the vapour space convection h = 8.5 W/m^2 K when the tank is about half full of liquid and the PRV is flowing more than 11.4 kg/s (as was the case with RAX 201 at failure). At failure for RAX 201 the vapour space wall temperature was about 630^{o}C, and therefore radiation dominated the heat transfer in the vapour space. When the fill is less than 0.4, the h value will become the default value of 0.0. When the tank becomes empty of liquid the h value once again jumps up to 5.7 W/m^{2}K. This variation in h seems odd.

4.4 Pressure Relief Valve Operation

The PRV is a critical part of the thermal analysis of a tank exposed to fire. In AFFTAC the PRV opening and closing are modelled using four reference pressures:

i) PRV starts the open stroke when the tank pressure reaches the start-to-discharge pressure (P std)
ii) PRV assumed to be fully open when the pressure is 103 percent of the std pressure (P fo) or higher.
iii) The closing stroke is assumed to start when the pressure drops below the std pressure.
iv) The PRV closes at an increased rate when the pressure has dropped below 88 percent of the std pressure (P c).
v) The valve is assumed to reclose fully at 82 percent of the std pressure (P fc).

This is illustrated in Figure 4-1.

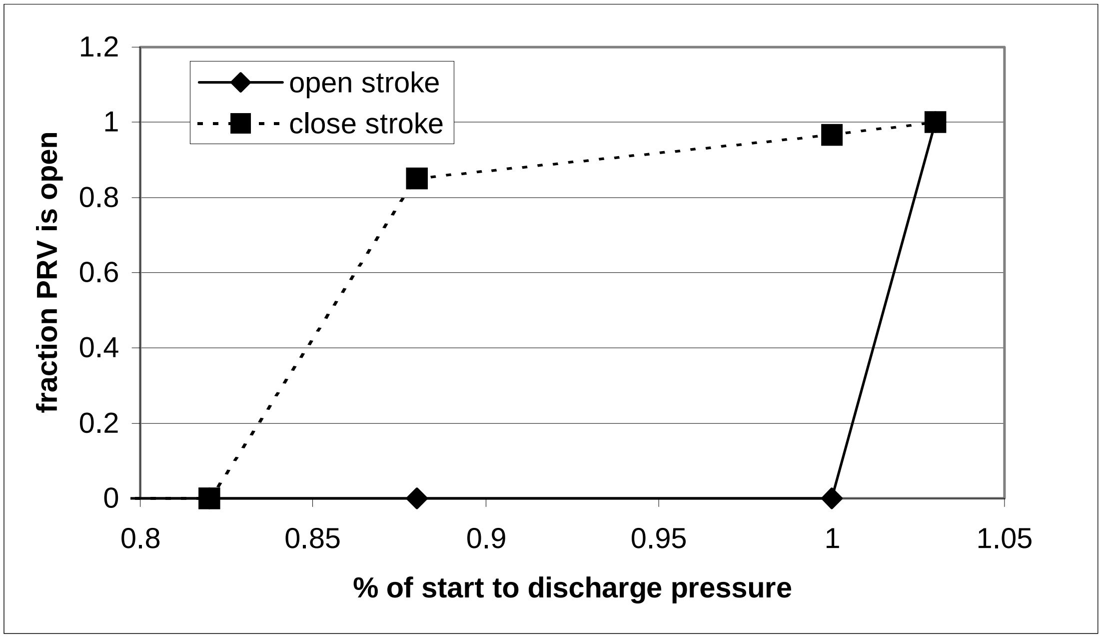

Figure 4-1: PRV open and close pressures used in AFFTAC

The blowdown of the valve is typically = pop pressure – reclose pressure. Here we assume the pop takes place at 103 percent of the std pressure. In this case AFFTAC is assuming a 21 percent blowdown. It should be noted that the maximum allowable blowdown is 20 percent (see Appendix J for PRV for CGSB requirements) but PRVs may not have a blowdown this large. It is probably not conservative to assume a 21 percent blowdown.

The open area of the PRV is assumed to be linearly interpolated between these reference pressures as shown in Figure 4-1. It is not clear where these piece-wise linear PRV operating characteristics have been obtained. It is very likely this method was used because it was numerically stable to do it this way in a computer model. In our opinion this is not a conservative way to model PRV action.

Real pop action relief valves do not generally fit the model described above. Typical relief valves have the following reference pressures

i) Start-to-discharge pressure (simmer pressure, very little flow)
ii) pop pressure (pop to full open)
iii) reclose pressure (PRV closes to full close)
iv) reseal pressure (PRV closes bubble tight)

With real valves the open area is not linearly related to these pressures. With a pop action PRV the valve is supposed to pop full open at some pressure and reclose fully when the pressure drops by some amount. A pop action PRV normally does not sit partially open (although they do sometimes, but not with great consistency) unless the valves flow capacity is being approached (see Pierorazio and Birk, 1998). In pop action PRVs the valves cycle open-and-closed if the tank is generating vapour at a rate less than the PRV flow capacity. If the tank is generating vapour at a rate greater than or equal to the valve’s flow capacity then the PRV will be held full open. If the PRV is undersized for a given fire condition and tank size then the pressure will continue to rise even if the PRV is full open.

A cycling PRV exposes the tank to a pressure range between a high of the pop pressure and a low of the reclose pressure. This range may vary during a fire exposure event. The first few pops may be at higher pressures due to valve seat sticking (see Pierorazio and Birk, 1998). Later in the fire the pop and reclose pressures may decrease due to PRV spring softening due to high spring temperatures. However, this spring softening may not be significant until the tank is nearly empty. In any event the tank pressure is most likely going to cycle between about 103 percent of the std pressure and about 83 percent of the std pressure (assuming a 20 percent blowdown) if the PRVs flow capacity is not exceeded.

A conservative analysis would assume that the PRV would cycle between its pop and reclose pressure when the full flow capacity of the PRV is not being used. Since we do not know what the blowdown is we should not assume a large value such as 20% because a large blowdown reduces the risk of failure. To be conservative we should assume no blowdown – i.e. the tank pressure is at 103 percent of the std pressure while the PRV is flowing below its capacity.

4.5 Tank Thermodynamic Response

In AFFTAC it is assumed that the tank pressure is dictated by the liquid thermal properties (i.e. the liquid saturation pressure). It is also assumed the liquid is isothermal. This single assumption is the reason for the major modelling deficiencies of AFFTAC.

The isothermal model results in a late prediction of the first opening of the PRV. The late first opening of the PRV may allow the tank to go shell full of liquid (as it did in the simulation of the RAX 201 test). When the tank goes full of liquid the vapour space is lost and the wall temperatures drop down. With low vapour space wall temperatures the tank will probably not fail. As it turns out AFFTAC correctly predicts tank failure near 24 minutes for RAX 201 because eventually the vapour space will reappear and high wall temperatures will be established. However there is not enough experimental data on other tank designs or fire conditions to show that AFFTAC will do this correctly in other cases.

The assumption of isothermal liquid is incorrect based on numerous test results of tanks in fires (see for example Townsend et al, 1974, Moodie et al, 1988, Birk et al, 1997). In reality the liquid temperature is stratified in the tank during fire exposure (hot near the top and cooler near the bottom). This is due to free convection within the tank. This stratification causes the pressure to rise faster than if the liquid were well mixed and isothermal.

The full-scale uninsulated tank tests of Townsend et al, (1974) showed that the PRV opened after about 2 minutes and because of this early opening of the PRV the tank never went shell full of liquid. A uniform liquid thermal model will not predict this behaviour. With a uniform liquid thermal model the tank pressurizes about five times slower which means the tank goes shell full of liquid and this causes the PRV to open.

This detail is very important to remember because when the tank goes shell full it means there is no vapour space and therefore there is no hot wall that can lead to tank failure. If a uniform liquid thermal model predicts a shell full condition in a tank exposed to fire then it is very likely the model will give poor predictions of wall temperature.

The uniform liquid temperature assumption in AFFTAC results in the following simulation errors:

i) Tank pressurization is too slow
ii) First opening of PRV is late
iii) late opening of PRV may result in tank going liquid full
iv) liquid full causes elimination of vapour space and erroneous wall temperature estimates

These errors mean that AFFTAC results may not be conservative. The following case illustrates how these assumptions can lead to large errors in the prediction of time to failure.

Let us consider the same tank as in previous simulations (RAX 201, a 127,000 litre propane tank, 16 mm wall thickness, no thermal protection). Using all the same assumptions as described earlier, AFFTAC was run for the tank with a range of initial fill levels. Figure 4-2 shows the outcome of these simulations. The results clearly show a sudden increase in time for predicted failure at a fill of approximately 85 percent. This jump is because AFFTAC predicts that tanks filled above 85 percent will go shell full – and tanks filled to less than 85 percent will not. Recall that the tank did not go shell full in the RAX 201 fire test with 95 percent initial fill. This means a tank filled to 84 percent will fail at 16 minutes and a tank filled to 86 percent will fail at 23 minutes. In other words a 2 percent change in fill causes a 44 percent change in failure time as predicted by AFFTAC. This fill effect may be real or it may be wrong. The RAX 201 test suggests it is wrong. This sudden increase in time to failure is caused by the assumption of isothermal liquid. This illustrates the hidden uncertainties in AFFTAC.

The AFFTAC assumption of isothermal liquid may not be very important if the tank is well insulated and therefore the fire heat is added very slowly to the tank. However, the use of AFFTAC in other situations may result in poor predictions.

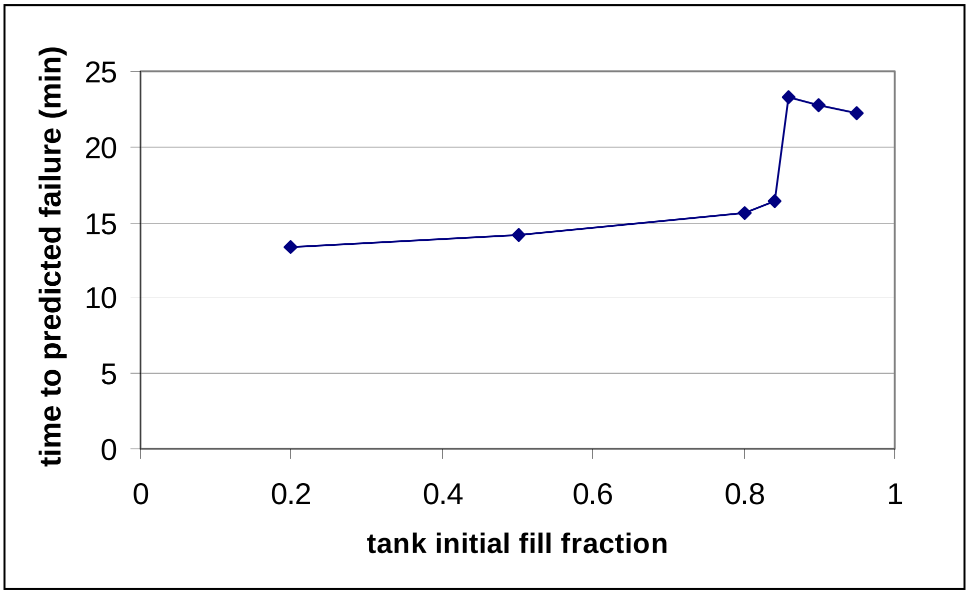

Figure 4-2: Effect of Initial Fill on Predicted Time to Failure by AFFTAC (for 127000 litre propane tank, 16 mm wall, TC 128 steel, 1.9 MPa PRV setting, no thermal protection)

With torch exposure the AFFTAC model predicts very little pressure build-up in the tank due to the small torch exposure area and the isothermal liquid assumption. However, it is expected (based on the fire test results of Birk et al, 1997) that an actual tank system would experience rapid pressure build-up due to liquid temperature stratification. This is another uncertainty in AFFTAC.

The conclusion here is that AFFTAC may not be conservative in the prediction of pressure build-up and vapour space wall temperatures. This is especially true for tanks with damaged or inadequate thermal protection systems, and cases involving torch impingement.

4.6 Failure Criteria

In AFFTAC the tank is assumed to fail immediately when the tank pressure equals 100 percent of the tank burst pressure. The burst pressure is calculated from the following expression:

$$P_b = \frac{2\sigma t}{D}$$

where t = wall thickness in m
D = tank diameter in m
σ = wall material ultimate strength at temperature

TC 128 has a minimum ambient temperature ultimate strength of 560 MPa (81000 psi). For a 3 m diameter tank with 16 mm wall thickness the nominal burst pressure is 6.0 MPa (866 psi).

In the AFFTAC model, the following equation is used to account for the high temperature degradation of TC-128. AFFTAC assumes that all low to moderate alloy carbon steels have similar high temperature properties.

for T wall < 1260 R

$$FCTR = 1.0 - 0.54(TTNV - 0.46)^4$$

for T wall > 1260 R

$$FCTR = 1.74 - 1.17(TTNV - 0.46)$$

For T wall > 1947 R

$$FCTR = 0.0$$

where,

TTNV = vapour space wall temperature (^{o} R/1000)
FCTR = ratio of ultimate stress at T to ultimate stress at ambient temperature

The ultimate strength of the material can then be determined by multiplying FCTR times the material ultimate strength at ambient temperature. The tank burst pressure is determined by multiplying the FCTR times the ambient temperature burst pressure. At 630^{o} C, the tank burst pressure for the previous example would drop from 866 psi to 326 psi.

However, if the tank pressure were say 99 percent or even 90 percent of the burst pressure then AFFTAC would not predict failure. However, in reality, the tank would probably still fail after some time has accumulated. This is because of the stress-temperature-time rupture characteristics of steel. This is not accounted for in AFFTAC.

Anderson and Norris (1974) show stress-temperature-time to rupture data for TC 128 steel samples. This data is shown in Table 4-4. The data clearly shows how stress and temperature affect the time to failure of a test sample. The data shows that it does not take tensile stress at 100 percent of ultimate strength to cause failure. For example, at 649^{o}C steel temperature it took only 6 minutes to fail a sample even though it was only stressed to 65 percent of its ultimate strength. However, at 482^{o}C it took 244 minutes to fail a sample that was stressed to 81 percent of the sample ultimate strength.
With TC 128 at 649^{o}C the samples failed even at low stress levels (65 percent of ultimate). We should never let the tank steel achieve such temperatures. At 566^{o}C a stress at 82 percent of the ultimate resulted in failure after 52 minutes. This time fits well within the pool fire 100 minute requirement.

AFFTAC uses 100% of the ultimate strength for failure prediction because this method agrees with one experiment (RAX201). This agreement could be a coincidence and should not be considered a strong validation. If 100 percent of the ultimate strength is used as a failure criteria then a factor-of-safety should be applied.

4.7 Assumptions that Dominate the Simulation Outcome

Certain assumptions in AFFTAC dominate the simulation outcome. They are as follows:

i) Fire model (temperature, exposure and emissivity)
ii) Isothermal liquid
iii) Vapour space heat transfer
iv) PRV operating characteristics
v) Failure criteria

Table 4-4: Stress-Temperature-Time to Rupture Data for TC 128 Pressure Vessel Steel (from Anderson and Norris, 1974).

Sample Temperature (^oC)	**Stress in Sample (000's of psi)**	**% of Ultimate Strength at Temperature**	**Time to Failure (min)**
482	77	100	0 tensile test
482	65	84	16
482	62	81	244
566	60	100	0 tensile test
566	49	82	52
566	42	70	138
649	49	100	0 tensile test
649	32	65	6
649	30	61	36
649	20	41	115

Relatively small changes in any of these assumptions can lead to large changes in the prediction of time to failure. It is suggested that the current settings used in AFFTAC were selected so that AFFTAC predictions fit with the results from the RAX 201 test. However, as shown earlier in this report AFFTAC methods may not be conservative and therefore may result in significant uncertainty. The following table summarizes these concerns.

4.8 Factor of Safety

As long as AFFTAC is used with uncertainty, it is suggested that a factor-of-safety (FOS) be implemented in the model. This factor-of-safety could be applied in two ways, one based on burst pressure and one based on time to fail as follows:

FOS(time) = (time to failure)/(test duration)

OR FOS(BURST PRESSURE) = (BURST PRESSURE AT END OF TEST)/(TANK PRESSURE AT END OF TEST)

For example, if a pool fire simulation resulted in a time to failure prediction of 170 minutes the FOS(time) = 170/100 = 1.7. For the same simulation the tank pressure at 100 minutes may be predicted to be 2.4 MPa and the burst strength at 100 minutes is predicted to be 3.5 MPa then FOS(burst pressure) = 3.5/2.4 = 1.5.

Table 4-5: Summary of Model Assumptions

Assumption	Effect	Comment
Fire model	- torch exposure too small - small change in assumed fire temperature has large effect on simulation outcome	need real world torch model need range of pool fire models for different fuels
Isothermal liquid	- late first opening of PRV - shell full predicted - slow rise of vapour space wall temperature	need model that accounts for liquid temperature stratification
Vapour space heat transfer	- small change in assumed coefficients changes wall temperature and failure prediction significantly	need improved vapour space model (convection and radiation)
PRV operation	- valve sits partially open at reduced pressures - tank pressure prediction (and hoop stress) may be low	need conservative and realistic PRV model
Failure criteria	- tank will not fail unless stress is at ultimate stress	need to include stress-time-rupture properties of steels

It should be noted that these two factors-of-safety do not give the same answer and the one based on burst pressure is extremely non-linear. Figure 4-3 shows how the FOS based on burst pressure varies with time in the AFFTAC simulation of RAX 201. As can be seen the FOS starts at 8 and falls to below 2 at about 15 minutes. Any time after this the tank is dangerously close to failure. We know from the RAX 201 test that the tank burst at 24 minutes. However, if this test were repeated a number of times, it is very probable that the tanks would have failed anywhere from 15 to 30 minutes. This uncertainty should be accounted for somehow in AFFTAC.

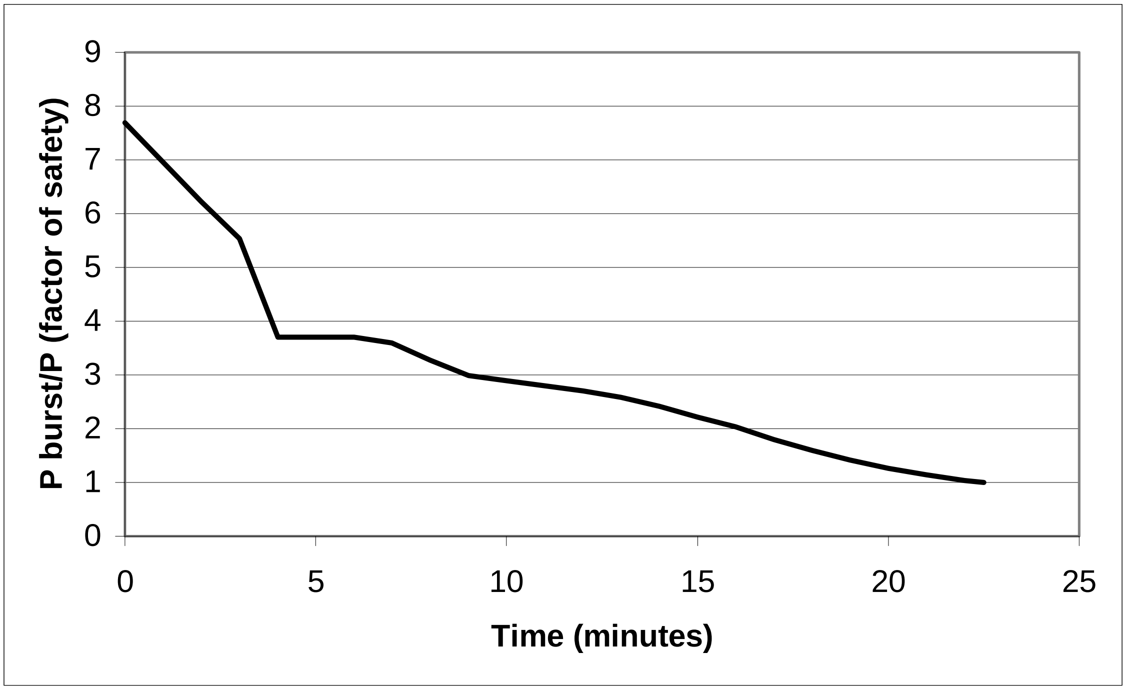

Figure 4-3: FOS based on Burst Pressure for RAX 201 Simulation.

5 Conclusions and Recommendations

The following conclusions have been made:

- i) the current plate test standard for the pool fire test is not consistent
- ii) the current plate test standard for the torch fire is not consistent
- iii) the AFFTAC model for the engulfing fire is not consistent with the plate test standard
- iv) the AFFTAC model for torch fire simulation is consistent with the plate test standard but by doing this it is not representative of a real world credible torch fire event

It should also be noted that the methods used in AFFTAC to simulate an engulfing fire are not the same as those used by the AAR in the sizing of pressure relief valves. Since the pressure relief valve is a critical component it is suggested that AFFTAC and the ARR PRV sizing standard should agree.

The plate test standard should be changed as follows:

- i) for the pool fire case the time to heat the plate to 427^{o}C should be 6 minutes not 13 minutes. This is consistent with a strongly radiating pool fire at 816^{o}C temperature. This fire condition should cause an uninsulated tank-car to fail in about 24 minutes in agreement with RAX 201 test data.
- ii) for the torch test the time to heat the plate to 427^{o}C should be 2 minutes rather than 4 minutes. This is consistent with a 1204^{o}C torch that provides a heat flux that is about three times as intense as the pool fire (this torch should fail a tank-car in about 5 minutes in agreement with reports of tanks failing as quickly as 5 minutes when not thermally protected)

The AFFTAC model as it currently exists has some modelling deficiencies that should be addressed. These include the following:

- i) the isothermal liquid temperature assumption is inaccurate and causes simulation errors including
    - a. late prediction of first opening of PRV
    - b. shell full prediction not in agreement with RAX 201 data
    - c. large errors in the prediction of vapour space temperatures (due to the prediction of shell full)
- ii) the failure model is simplistic and is validated only by a single test point (RAX 201).
- iii) the PRV model is not representative of a real PRV and is not conservative in its assumptions where there is uncertainty.

Because of these modelling deficiencies the following is recommended:

i) if AFFTAC is used in its present form then the failure prediction should include a factor of safety as defined in this report.

ii) AFFTAC should be modified so that even when the tank goes shell full of liquid it continues to calculate a wall temperature in the vapour space. This vapour space temperature should be used to calculate the tank burst strength. This method should be used until we have confidence that AFFTAC correctly predicts shell full conditions.

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Appendix A: Computer Program Listing

This program is used to simulate the plate test used for qualifying thermal insulation materials for use in Tank-car thermal protection systems.

```
      program platetest
c
      implicit real(a-z)
c
      common/failtime/ temp(100),sigult(100),sigyld(100),slope(100),
      &timerange(100),ndata
c
      OPEN(2,FILE='plate test.OUT',STATUS='old')
c     open(3,file='AARtc128.dat',status='old')
c
c     read(3,*) ndata
c     read(3,*) (temp(i),sigult(i),sigyld(i),slope(i),
c     &timerange(i),i=1,ndata)
c     write(*,*) (temp(i),sigult(i),sigyld(i), slope(i),
c     &timerange(i),i=1,ndata)
c
      write(*,*) 'enter outside surface emmissivity'
      read(*,*) emmout
c
      write(*,*) 'enter backside surface emmissivity'
      read(*,*) emmback
c
      write(*,*) 'enter fire temp (C)'
      read(*,*) tfire
c
      write(*,*) 'enter fire h (W/m2K)'
      read(*,*) hfire
c
      tankd = 0.3048
      write(*,*) 'enter fire emissivity '
      read(*,*) ffire
c
      wallthick = 16
      write(*,*) 'enter backside h (W/m2K)'
      read(*,*) h
      write(*,*) 'enter critical wall T (deg C)'
      read(*,*) tcrit
c
      dtime = 0.1
      tamb = 20
c     tfire = 871
      sig = 5.67e-8
c     h = 6
c     hfire = 0
c
      flading = 1

      rhosteel = 7800
      csteel = 447
```

```
      wjacket = 3
      winsul = 13
c
c     emm = 0.9
c
      write(2,*) 'fire temp (C)    = ',tfire
      write(2,*) 'fire h (W/m2K)   = ',hfire
      write(2,*) 'fire emissivity   = ',ffire
      write(2,*) 'backside h (W/m2K) = ',h
      write(2,*) 'critical wall T (C) = ',tcrit
c
      write(2,*) ' '
      write(2,*) 'plate L (m)    = ',tankd
      write(2,*) 'wall thick (mm)  = ',wallthick
      write(2,*) 'ambient T (C)   = ',tamb
      write(2,*) 'outside surface emmiss  = ',emmout
      write(2,*) 'backside surface emmiss  = ',emmback
      write(2,*) ' '
      write(2,*) '  cond  time   T jack  T wall'
      write(2,*) '  W/m2K  min   deg C   deg C      '
      write(2,*) '  ___________________________________'
      write(2,*) ' '
c
c     write(2,*) ' tfire  time  walltemp stressratio yieldratio
c     &cummdamage delay'
c
      write(2,*) ' '
c
      do 500 cond = 20, 50, 2
      kinsul = cond*(winsul/1000)
      walltemp = tamb
      tjacket = tamb
      tlading = tamb
c
      do 100 time = 0,100,dtime
c
      qfire = ffire*emmout*sig*((tfire+273)**4-(tjacket+273)**4)
      & + (1-ffire)*emmout*sig*((tamb+273)**4 - (tjacket+273)**4)
      qconvfire = hfire*(tfire-tjacket)
c
      qinsulcond = kinsul/(winsul/1000) *(tjacket-walltemp)
      dtempjacket = (qfire + qconvfire - qinsulcond)*dtime*60
      & /rhosteel/csteel/(wjacket/1000)
c
      tjacket = tjacket + dtempjacket
c
      qbackside = sig*emmback*((walltemp+273)**4-(tamb+273)**4)
c
      qconv = h*(walltemp-tamb)
c
      dtemp = (qinsulcond - qconv - qbackside)*dtime*60
      & /rhosteel/csteel/(wallthick/1000)
      walltemp = walltemp + dtemp
c
      if(walltemp.gt.tcrit) go to 200
c
```

```
c       call failuretime(walltemp,stress,dtime,stressratio,yieldratio,
c       &damage,delay)
c
c       cummdamage = cummdamage + damage
c       if(cummdamage.ge.1.0) go to 200
c
  100 continue
c
  200 continue
        write(2,20)cond,time,tjacket,walltemp
   20 format(4f9.1)
c
c
c       write(2,20)tfire,time,walltemp,stressratio,yieldratio,
c       &cummdamage,delay
c
  300 continue
  500 continue
c
        stop
        end
c
c++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++
c
c
c
c
c++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++
c
        subroutine failuretime(walltemp,stress,dtime,
        & stressratio,yieldratio,damage,delay)
c
c
c
c
        common/failtime/ temp(100),sigult(100),sigyld(100),slope(100),
        &timerange(100),ndata
c
        do 100 i=1,ndata-1
c
        if(walltemp.ge.temp(i).and.walltemp.le.temp(i+1)) then
        theslope =
        & (slope(i+1)-slope(i))/(temp(i+1)-temp(i))*(walltemp-temp(i))
        & + slope(i)
        thesigult =
        & (sigult(i+1)-sigult(i))/(temp(i+1)-temp(i))*(walltemp-temp(i))
        & + sigult(i)
        thesigyld =
        & (sigyld(i+1)-sigyld(i))/(temp(i+1)-temp(i))*(walltemp-temp(i))
        & + sigyld(i)
        thetimerange =
        & (timerange(i+1)-timerange(i))/(temp(i+1)-temp(i))*
     & (walltemp-temp(i)) + timerange(i)
```

```
c
        go to 200
        else
        endif
 100    continue
 200    continue
c
        stressratio = stress/thesigult
        yieldratio = stress/thesigyld
        failtime = theslope*(1-stressratio)
        if(yieldratio.lt.1.0) failtime = 99999.
        if(failtime.lt.0.0) failtime = 0.0
        delay = thetimerange
c
        if(failtime.eq.0.0) failtime = 0.0001
        damage = dtime/failtime
c       cummdamage = cummdamage + damage
c
c       write(2,*)      walltemp,stressratio,yieldratio,failtime,delay
c
 300    continue
c
        return
        end
```