TP 13203E

Thermographic Inspection of Tank-Car Thermal Insulation

for

Transport Canada
Safety and Security
Transportation Development Centre

by

A. M. Birk Engineering
Kingston, Ontario

March 1998

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This report reflects the views of the authors and not necessarily those of the Transportation Development Centre.

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16. Abstract

This project involved the development of an inspection procedure for finding insulation deficiencies on thermally protected or thermally insulated rail tank cars. The procedure uses thermography to see insulation defects under the steel jacket of the tank car.

The project started with a technology review of thermal imaging cameras. Based on this review, a low-cost 8-12 μm, uncooled focal plane array thermal imager was selected. This was followed by laboratory tests to study the feasibility of the inspection technique. Successful laboratory testing was followed by field testing and validation gained through several trips to rail yards and process plants.

Based on this work, it was concluded that the inspection method was effective, efficient and practical. Field data indicated that older tank cars may have significant insulation defects.

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16. Résumé

Ce projet consistait à mettre au point une procédure de détection des défectuosités dans l'enveloppe d'isolation ou de protection thermique des wagons-citernes. La procédure utilise la thermographie pour visualiser les faiblesses du revêtement isolant sous la jaquette en acier du wagon-citerne.

Dans un premier temps, les chercheurs ont passé en revue une gamme de caméras d'imagerie thermique. Au terme de cette évaluation, leur choix a porté sur un imageur thermique à cible focale non refroidi, fonctionnant dans la bande spectrale située entre 8 et 12 μm, d'un prix abordable. Des essais en laboratoire ont ensuite été réalisés pour établir la faisabilité de la technique d'inspection. Ces essais, concluants, ont été suivis d'essais de validation et d'essais poussés sur le terrain, lesquels ont comporté plusieurs visites à diverses cours de triage.

Les travaux ont permis de conclure que la thermographie constitue une technique de contrôle efficace, économique et commode. Les résultats des essais sur le terrain ont en outre révélé une détérioration parfois importante de l'enveloppe isolante des wagons-citernes âgés.

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Executive Summary

Over time, thermally protected and thermally insulated rail tank cars may develop insulation deficiencies due to continuous motion and vibrations. This thermal insulation is used on some (thermally protected) tank types to protect them from fire impingement while on other tanks the thermal insulation is used for both thermal protection in a fire and for maintaining product conditions.

Insulation deficiencies are generally not visible because of the protective outer steel jacket. This research project was undertaken to develop an inspection procedure to identify deficiencies in the thermal insulation of rail tank cars.

Thermography was selected as the most effective means of inspecting the thermal insulation because it is non-destructive, non-contact and economical. Thermography takes advantage of the fact that when a temperature difference exists between the contents of the tank car and the ambient conditions, insulation deficiencies can generate temperature gradients on the outer steel jacket of the tank car. These temperature gradients can then be identified using a thermal imager.

A series of laboratory and field tests were conducted to determine under what tank conditions and surroundings the inspection procedure is effective. The project involved the following major tasks:

- thermal imager technology review,
- laboratory tests,
- field validation and field tests,
- heat transfer analysis, and
- documentation of field test procedure.

A technology review of thermal imagers was undertaken. This review identified a number of camera manufacturers including Agema, FSI, Texas Instruments, Raytheon, Inframetrics, Mitsubishi and others. The cameras were compared based on price, performance and features. The thermal imagers came in a wide range of prices and capabilities. Because of budget constraints the least expensive camera was selected. This camera was not as sensitive as the more expensive cameras but it was considered adequate for this application.

The technology review was followed by a laboratory test program. The objective of these tests was to quantify the conditions under which the thermal imager could identify thermal insulation deficiencies. A full-scale, partial tank-car mock-up was constructed with a pattern of insulation deficiencies. A low-cost, uncooled 8-12 μm waveband thermal imager was used for thermal image generation. Using water to simulate the tank lading, thermal images of the tank were taken over a range of small temperature differences between the tank lading and the surroundings. It was found that the imager could resolve the thermal insulation pattern under temperature gradient conditions compatible with day-night cycle temperature variations. The method worked for both the 12 mm insulation thickness of thermally protected tanks and the 100 mm thickness of thermally insulated tanks. However, if thermal gradients were very small (the difference

between lading and ambient temperature less than 5°C) then the inspection method was not effective using the low-cost thermal imager.

The lab tests were followed by a limited field test and validation. The imager was taken into the field to view tank cars at sidings and industrial sites. The imager identified a number of tanks with severe insulation deficiencies. One of these tanks (a thermally protected 112-type car) was traced and when it was empty it was sent to a local repair yard. At the repair yard the tank was heated by flowing steam through the tank. This heating allowed the thermal imager to once again identify the deficiencies. At this point, a number of holes (approx. 10 cm x 10 cm) were made in the steel jacket. In those areas that showed the strongest indication of deficiency, it was found that no insulation was present in the gap between the tank shell and the steel jacket. In other areas that also showed some defect, the insulation was either crushed to a powder or there was no insulation at all. This test was used as a limited validation for the inspection procedure. Further validation is needed.

The limited validation was followed by a more extensive field test. The objectives of the field test were:

- to gain field experience with the inspection technique,
- to identify limitations of the inspection technique, and
- to obtain limited data on tank-car insulation deficiency statistics.

The field test involved over 200 tanks (Sarnia yard, Beauharnois PPG, Petromont Varennes, Varennes siding, Port of Montreal), of which 130 were analysed in detail. The analysis resulted in estimates of percent deficient area on the tank tops and bottoms. The field tests proved the inspection technique to be practical, efficient and effective when the conditions were correct for the inspection (i.e. minimal thermal gradients were present). As for limitations, the technique does not work on silver-painted or raw silver metal tanks due to the high reflection of the surface. The technique is very insensitive to tank surface condition for painted surfaces (glossy, flat, dirty, dusty, rusted, etc.) but it is degraded by a wet surface (once again because of the high reflection). It was also determined from these tests that the sun can greatly enhance the inspections when the lading is cool. It was found that some industrial practices enhance the inspection (i.e. unloading of tanks using hot vapours, steam heating of viscous lading in the winter, filling tanks with hot or cold lading, steam cleaning, etc.).

Based on the field trials it was concluded that the inspection method is viable. It was also concluded that older tanks may have severe insulation deficiencies.

The field test was followed by a heat transfer analysis. The objective of this analysis was to determine whether heat transfer considerations could be used to define an unacceptable defect size. The analysis showed that even small defects (20 cm wide strips) can reach high temperatures under fire exposure conditions. Further analysis is needed that considers both heat transfer and stress conditions resulting from insulation defects.

The final task involved the preparation of a field test manual based on the findings of this work. This manual includes basic background information, a description of the equipment used, limitations of the method, detailed procedures for conducting the inspection and analysis of the imagery. Charts are also included to help the inspector decide whether the inspection conditions are correct for an effective inspection.

In summary, the project was a complete success. The inspection method using a thermal imager for locating insulation deficiencies on tank cars was demonstrated to be effective, efficient and practical using a low-cost thermal imager. The method was validated using actual tank cars with field defects. Field studies have shown that older tank cars can have severe defects (up to 50 percent of the tank area is defective).

This report presents the results of all of the tasks performed in this study.

Sommaire

Avec le temps, l’enveloppe d’isolation ou de protection thermique des wagons-citernes peut se détériorer, sous l’effet des vibrations et du mouvement constants. Cette enveloppe a pour rôle, dans certains types de citernes (protégées thermiquement), de prévenir l’inflammation du contenu en cas d’incendie, tandis que dans d’autres, elle sert à la fois à protéger thermiquement le contenu et à en préserver les propriétés.

Mais les défectuosités de l’enveloppe isolante sont généralement cachées par la jaquette en acier qui sert de revêtement extérieur à la citerne. Ce projet avait pour objet de mettre au point une méthode d’inspection permettant de visualiser les faiblesses de l’enveloppe isolante des wagons-citernes.

La thermographie a été retenue comme étant la technique la plus efficace à cette fin, étant non destructive, sans contact et économique. La thermographie s’appuie sur le principe que, lorsqu’il existe un écart de température entre le contenu d’une citerne et l’air ambiant, toute défectuosité dans l’enveloppe isolante de la citerne produira une variation de température dans la jaquette extérieure en acier, variation que pourra révéler un imageur thermique.

Une série d’essais en laboratoire et sur le terrain ont été réalisés pour déterminer les conditions inhérentes à la citerne et les conditions environnementales les plus favorables à l’inspection par thermographie. Le projet comportait les tâches suivantes :

- revue technologique d’imageurs thermiques;
- essais en laboratoire;
- essais de validation et autres essais sur le terrain;
- analyse du processus de transfert thermique;
- documentation des essais sur le terrain.

Les chercheurs ont d’abord procédé à une évaluation technologique de divers imageurs thermiques, dont ceux offerts par Agema, FSI, Texas Instruments, Raytheon, Inframetrics et Mitsubishi. Le prix, les performances et les caractéristiques ont servi de critères de comparaison des imageurs. Tout l’éventail des prix et des fonctionnalités était représenté. Les contraintes budgétaires ont orienté le choix des chercheurs vers la caméra la moins chère, moins sensible que les caméras plus coûteuses, mais satisfaisante pour les besoins de l’étude.

Un programme d’essais en laboratoire a ensuite été entrepris. Ces essais devaient servir à définir quantitativement les conditions à remplir pour que l’imageur thermique puisse détecter des faiblesses dans l’enveloppe isolante. Une maquette grandeur réelle partielle d’un wagon-citerne a été construite, incorporant une enveloppe isolante défectueuse. Un imageur thermique bon marché, non refroidi et fonctionnant dans la bande spectrale située entre 8 à 12 μm a servi à la génération d’images thermiques. De l’eau simulait la charge de la citerne. Des images thermiques de la citerne ont été générées dans une gamme de faibles écarts de température entre le contenu du réservoir et l’air ambiant. L’imageur s’est montré apte à établir la carte des défectuosités de l’enveloppe isolante en vertu des écarts thermiques caractéristiques des variations cycliques de température entre le jour et la nuit. La méthode a permis d’obtenir des

images satisfaisantes tant de l'enveloppe de 12 mm d'épaisseur recouvrant les citernes protégées thermiquement que du revêtement de 100 mm d'épaisseur des citernes isolées thermiquement. Mais l'imageur bon marché a failli à la tâche, lorsque l'écart de température entre le contenu de la citerne et l'air ambiant était très faible (inférieur à 5 °C).

Aux essais en laboratoire ont succédé des essais limités de validation sur le terrain. L'imageur a été emporté pour l'examen *in situ* de wagons-citernes immobilisés dans des cours de triage. L'examen a mis au jour un certain nombre de citernes présentant de graves défectuosités d'isolation. Une de ces citernes (un wagon protégé thermiquement de type 112) a été vidée de son contenu et envoyée à un chantier de réparation local, qui l'a chauffée en y faisant circuler de la vapeur. Encore une fois, l'imageur a décelé les défectuosités. Des trous (d'environ 10 cm x 10 cm) ont alors été percés dans la jaquette en acier, ce qui a permis de constater que les zones présentant les défectuosités les plus graves, sur les images thermiques, coïncidaient effectivement avec les endroits où ne subsistait aucun matériau isolant dans l'espace entre le récipient intérieur et la jaquette en acier. Dans d'autres zones où l'imageur avait détecté des défectuosités, ou bien l'enveloppe isolante s'était pulvérisée, ou bien elle était totalement inexistante. Ces essais ont servi de validation partielle de la technique d'inspection. Une validation plus poussée s'impose.

Des essais sur le terrain ont été entrepris à la suite de la validation. Ils visaient à :

- acquérir une expérience pratique de la technique d'inspection;
- cerner les limites de la technique d'inspection;
- recueillir une information préliminaire sur les faiblesses de l'isolation des wagons-citernes.

Les essais sur le terrain ont porté sur plus de 200 citernes (triage de Sarnia, PPG Beauharnois, Pétromont Varennes, voies de garage du triage de Varennes, port de Montréal), dont 130 ont fait l'objet d'analyses poussées, qui ont débouché sur des pourcentages estimatifs de la superficie défectueuse du dessus et du fond des réservoirs. Au terme de ces essais, la technique d'inspection s'est révélée efficace, efficiente et commode, lorsqu'elle est utilisée dans les conditions voulues (en présence des écarts minimaux de température). Elle comporte toutefois des limitations : elle ne convient pas à l'inspection de citernes peintes couleur argent ou de citernes en acier non peintes, en raison de la forte réflectance de la surface. Elle est très peu sensible à l'état de surface du réservoir (brillant, mat, sali, poussiéreux, rouillé, etc.) lorsque celui-ci est revêtu de peinture, mais est moins efficace lorsque la surface est mouillée (là encore, en raison de la réflectance élevée). Les essais ont également révélé que des conditions ensoleillées sont de nature à faciliter grandement l'inspection lorsque la température de la charge est relativement basse. De même, certaines pratiques industrielles peuvent favoriser l'inspection par thermographie (p. ex., le déchargement des réservoirs au moyen de vapeurs chaudes, le chauffage à la vapeur de charges visqueuses en hiver, le remplissage des réservoirs avec des liquides chauds ou froids, le nettoyage à la vapeur).

Les essais sur le terrain ont permis de conclure à la faisabilité de la technique d'inspection par thermographie. Ils ont également mis en évidence la probabilité de graves défectuosités dans l'enveloppe isolante des citernes âgées.

Les chercheurs ont ensuite analysé le processus du transfert thermique, dans le but d'établir les dimensions au-delà desquelles la superficie d'une défectuosité doit être considérée inacceptable. Cette analyse a montré que même les zones de défectuosité de faible superficie (bandes de 20 cm de largeur) peuvent atteindre des températures élevées lorsque la citerne est exposée aux flammes. Des analyses plus poussées s'imposent, qui devront prendre en compte à la fois le transfert thermique et les contraintes résultant des défectuosités dans l'enveloppe thermique.

La dernière tâche consistait à préparer un guide d'essais *in situ*, à partir des résultats des travaux. Ce guide donne une information de base, avant de décrire le matériel utilisé, de poser les limites de la technique et d'exposer la méthode détaillée d'inspection et d'analyse de l'imagerie obtenue. Des tableaux sont annexés, qui aideront l'inspecteur à établir si les conditions sont remplies pour garantir la fiabilité de l'inspection.

En résumé, ce projet s'est soldé par une réussite totale. La méthode d'inspection faisant appel à la thermographie et utilisant un imageur thermique bon marché pour repérer les faiblesses de l'enveloppe isolante des wagons-citernes s'est révélée efficace, efficiente et commode. La méthode a été validée par des essais sur des wagons-citernes réels comportant des défectuosités acquises en service. Les études sur le terrain ont montré que les wagons-citernes âgés peuvent présenter des défectuosités graves (couvrant jusqu'à 50 p. 100 de la superficie de la citerne).

Le rapport présente les résultats de toutes les tâches exécutées dans le cadre de l'étude.

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1. Introduction

This report documents the development of an inspection procedure for using thermal imagers to detect thermal insulation deficiencies on rail tank cars.

1.1 Background

Over time, thermally protected and thermally insulated rail tank-cars may develop insulation deficiencies because of the continuous motion and vibrations. This thermal insulation is used on some tank types to protect them from fire impingement (these are thermally protected tanks) while on some tanks the thermal insulation is used for both thermal protection in a fire and for maintaining product conditions. In both cases the thermal insulation is covered by a steel jacket.

The insulation deficiencies are generally not visible because of the protective outer steel jacket. This research program was undertaken to develop an inspection procedure to identify deficiencies in the thermal insulation of rail tank cars.

Thermography was selected as the most effective means of inspecting the thermal insulation because it is non destructive, non contact and economical. Thermography takes advantage of the fact that when a temperature difference exits between the contents of the tank car and the ambient conditions, the presence of insulation deficiencies generate temperature gradients on the outer steel jacket of the tank car. These temperature gradients can then be identified using a thermal imager.

We expect to see temperature gradients in tanks for a number of reasons including:

- day night heating cooling cycles of tanks
- solar heating
- operations (hot/cold lading for loading/unloading, steam cleaning)

1.2 Objectives

The primary objective of this work was to develop a method of inspection that would find insulation deficiencies in thermally protected or thermally insulated rail tank cars. The inspection method was to be based on the use of a thermal imaging camera.

A secondary objective was to have the inspection method provide additional information to an emergency response team by assisting in the identification of accident features such as liquid levels in tanks.

1.3 Scope

The scope of the work was limited to the following:

- thermal imager technology review
- laboratory feasibility study
- field validation and testing

- preparation of a field inspection manual

This report presents the results of these activities.

1.4 Summary

The project involved the following major tasks:

- thermal imager technology review
- laboratory tests
- field validation and field tests
- heat transfer analysis
- documentation of field test procedure

A technology review of thermal imagers was undertaken. This review identified a number of camera manufacturers including Agema, FSI, Texas Instruments, Raytheon, Inframetrics and Mitsubishi and others. The cameras were compared based on price, performance and features. The thermal imagers came in a wide range of prices and capabilities. Because of budget constraints the least expensive camera was selected. This camera was not as sensitive as the more expensive cameras but it was believed that it would be adequate for this application.

The technology review was followed by a laboratory test program. The objective of these tests was to quantify the conditions under which the thermal imager could identify thermal insulation deficiencies. A full-scale, partial tank-car mock-up was constructed with a pattern of insulation deficiencies. A low cost, uncooled 8-12 μm waveband thermal imager was used for thermal image generation. Using water to simulate the tank lading, thermal images of the tank were taken over a range of small temperature differences between the tank lading and the surroundings. It was found that the imager could resolve the thermal insulation pattern under temperature gradient conditions compatible with day-night cycle temperature variations. The method worked for both the 12 mm insulation thickness of thermally protected tanks and the 100 mm thickness of thermally insulated tanks. However, if thermal gradients were very small (the difference between lading and ambient temperature less than 5°C) then the inspection method was not effective using the low cost thermal imager.

The lab tests were followed by a limited field test and validation. The imager was taken into the field to view tank-cars at sidings and industrial sites. The imager identified a number of tanks with severe insulation deficiencies. One of these tanks (a thermally protected 112 car) was traced, and when empty, was sent to a local repair yard. At the repair yard the tank was heated by flowing steam through the tank. This heating produced a thermal gradient that allowed the thermal imager to once again identify the deficiencies. At this point a number of holes (10 cm x 10 cm approx.) were made in the steel jacket. In those areas that showed the strongest indication of deficiency, it was found that no insulation was present in the gap between the tank shell and the steel jacket. In other areas that also showed some defect, the insulation was either crushed to a powder or there was no insulation. This test was used as a limited validation for the inspection procedure. Further validation is needed.

The limited validation was followed by a more extensive field test. The objectives of the field test were:

- to gain field experience with the inspection technique,
- to identify limitations of the inspection technique, and
- to obtain limited data on tank-car insulation deficiency statistics.

The field test involved over 200 tanks (Sarnia yard, Beauharnois PPG, Petromont Varennes, Varennes siding, Port of Montreal, etc.) of which 130 tanks were analysed in detail. The analysis resulted in estimates of percent deficient area on the tank tops and bottoms. The field tests proved the inspection technique to be practical, efficient and effective when the conditions were correct for the inspection (i.e. minimal thermal gradients were present). As for limitations, the technique does not work on silver painted or raw silver metal tanks due to the high reflection of the surface. The technique is very insensitive to tank surface condition for painted surfaces (glossy, flat, dirty, dusty, rusted, etc.) but it is degraded by a wet surface (once again due to the high reflection). It was also determined from these tests that the sun can greatly enhance the inspections when the lading is cool. It was found that some industrial practices enhance the inspection (i.e. unloading of tanks using hot vapours, steam heating of viscous lading in the winter, filling tanks with hot or cold lading, steam cleaning, etc.).

Based on the field trials it was concluded that the inspection method is viable. It was also concluded that older tanks may have severe insulation deficiencies.

The field test was followed by a heat transfer analysis. The objective of this analysis was to determine whether heat transfer considerations could be used to define an unacceptable defect size. The analysis showed that even small defects (20 cm wide strips) can reach high temperatures under fire exposure conditions. Further analysis is needed that considers both heat transfer and stress conditions resulting from insulation defects.

The final task involved the preparation of a field test manual based on the findings of this work. This manual includes basic background information, a description of the equipment used, limitations of the method, detailed procedures for conducting the inspection and analysis of the imagery. Charts are also included to help the inspector decide if the inspection conditions are correct for an effective inspection.

In summary, the project was a complete success. The inspection method using a thermal imager for locating insulation deficiencies on tank cars was demonstrated to be effective, efficient and practical using a low-cost thermal imager. The method was validated using actual tank cars with field defects. Field studies have shown that older tank cars can have severe defects (up to 50% of the tank area is defective).

This report presents the results of all of the tasks performed in this study.

2. Methodology

2.1 Overview of Thermography

Thermography is a method similar to photography, except that the "picture" taken is not of visible light, but rather it is thermal radiation. Visible light and thermal radiation are forms of electromagnetic radiation. In this application we limit our interest to thermal radiation falling in the 3-5 μm or 8-14 μm wavebands of the electromagnetic spectrum. This is because the available thermal imaging cameras fall in these wavebands. IR cameras use these wavebands because the atmosphere does not interfere (i.e. absorb radiation) strongly in these wavebands.

Several organizations offer thermography training (for example, see Academy of Infrared Thermography, 2955 Westsyde Road, Kamloops, B.C., V2B 7E7).

An object emits thermal radiation when it has a temperature above 0 K (-273^{o}C). Therefore, all objects we know emit thermal radiation. Low temperature objects radiate more in the 8-14 μm waveband and hot objects radiate more in the 3-5 μm waveband. For example, the sun radiates more in the 3-5 μm band then in the 8-14 μm band. Surfaces also reflect thermal radiation from surrounding objects such as the ground, sky, sun and other nearby structures. When viewing an object using a thermal imager the viewer will see both emitted and reflected radiation.

The temperature of an object depends on many factors such as internal heat sources, external convection and thermal radiation. An object sitting in the sun will heat up due to solar radiation. An object will cool down at night due to heat loss by convection and radiation.

In this specific application, i.e. inspection of thermal insulation deficiencies, the method of thermographic inspection relies on the fact that the object to be inspected has temperature variations on its surface that are caused by variation in thermal insulation. In this case the thermal gradients are caused by high or low lading temperatures relative to ambient. These temperature differences may be due to the filling or unloading temperatures used for a specific commodity or to the natural day/night or seasonal temperature fluctuations.

2.2 Infrared Thermal Image

For a given thermal imager, the image obtained will be a function of the following:

- temperature of object
- surface finish of object
- view angle to the object surface
- other sources of radiation surrounding the object including the background (i.e. ground, sky, solar, etc.)

The following sections discuss each of these important factors.

Temperature

The temperature of an object should be different from its surroundings for it to be effectively resolved from the background. The larger the temperature difference, the easier it will be to resolve the object. Current thermal imagers can resolve temperature differences of less than 0.5°C.

Surface Finish

Most tank cars are painted black or white. This paint may be new and glossy or old and flat. They may be rusty or dirty and some may have patches of new paint with patches of old. This means that surface radiative properties will vary, which in turn will cause a variation in the image.

It should be noted that white paint and black paint look almost the same in the 3-5 and 8-14 µm wavebands. However, they absorb and reflect solar radiation very differently and this strongly affects surface temperature and thermal image. A white surface reflects most of the solar radiation whereas the black surface absorbs most. This is why black surfaces get much hotter in the sun than white surfaces.

Wet surfaces also reflect differently than dry. Therefore rain has two effects on a surface; it will cause a cooling or warming effect which will change temperatures and it will also change the way the surface reflects its surroundings.

View Angle

The view angle is important because it affects the viewed image. If an imager is pointed at a curved surface (such as a rail tank car or tank truck) it will see a variation in surface radiance due to the effect of angle. A painted surface becomes more reflective as the view angle becomes more oblique. Therefore if a tank is viewed from the side, the top of the tank will look different from the side due to view angle differences.

Other Radiation Sources

Other sources of radiation will be reflected off the surface. If the tank is sitting in the sun then the sun will strongly influence the viewed image. This is due both to solar heating and reflection.

If there are nearby objects that radiate strongly (cold or hot) then you may see their reflection in the tank surface. Examples of these kinds of sources are:

- flames
- hot pipes, vessels
- smoke stacks and plumes
- welders
- snow, ice

2.3 Insulation Deficiencies

Insulation deficiencies will be detectable only if there is a temperature gradient from the tank inside to the outside. Laboratory testing has shown that gross deficiencies (i.e. insulation is not present in spots) can be detected for both 13 mm and 102 mm insulation thicknesses provided there is a temperature difference between the lading and the surroundings of at least 5-10°C.

3. Technology Review

A technology review was conducted to identify available thermal imagers that could be used for this work. The complete technology review report can be found in Appendix A.

The cameras of interest operate in the 3-5 or 8-12 μm waveband of the electromagnetic spectrum. This was done so that the cameras will be sensitive to relatively low temperatures and small temperature gradients.

3.1 Imager Requirements

The basic imager hardware requirements for this project were:

- person portable (hand-held or cart-mounted)
- video output for monitor and/or VCR storage,
- simple to operate (auto gain, auto focus, etc.)
- high spacial resolution image (TV quality image).
- minimum resolvable temperature difference < 0.5°C over desired temperature range
- operate in a range of environmental conditions (-20 to 40°C)
- take an image of the entire tank or large part of the tank (one side at a time).
- ability to accurately image a surface with temperature ranging from -20 to + 130°C.
- affordable (i.e. < $35000. Including all support equipment)

The following requirements were identified as desirable:

i) gray scale or false colour images
ii) zoom lens 35-100 mm or electronic zoom
iii) fast image (e.g. 30-60 images/s, fast shutter speed for moving train)
iv) temperature output
v) digital image storage on medium compatible with IBM PC or compatible

In the technology review the following features of the candidate hardware were reviewed:

- sensitivity (MRTD – minimum resolvable temperature differences, etc.)
- resolution (typically 256 x 256 pixels in field of view (FOV))
- portability (durability) Usually the equipment can be mounted on a cart with wheels for easy transport in the back of a car or van. The camera head is usually mounted on a tripod.
- special requirements (some imagers need cryogenic coolers that need continuous filling, etc.)

- calibration (this is only needed when actual temperatures are to be determined and may not be necessary here)
- ease of use (menu-driven, push buttons, complex gain settings, etc.)
- - training required
- ease of interface to PCs (data on floppies, interface card required, standard format for images, etc.)
- data storage capacity (how many images can be stored for later analysis, VHS or SVHS tapes, etc.)
- image speed (some imagers must integrate over time and cannot handle a moving train)
- built-in analysis capabilities (image enhancement, false colour, etc.)
- cost (rental, lease, buy, service, etc.)

During this survey, every attempt will be made to obtain the equipment for a demonstration of its capabilities.

3.2 Thermal Imagers

The thermal imagers being evaluated for this study can be organized into two types:

- scanners
- focal plane arrays (FPAs)

Scanners are devices that use a single sensing element or a linear array of elements and the field of view (FOV) is scanned using a suitable mechanism. The FPA is a two-dimensional array of elements that view the entire FOV.

FPAs have the advantage of being faster and usually more sensitive because each element does a single job whereas for the scanning type each element must view a larger part of the FOV.

Imagers also operate in different spectral ranges. The most important ranges for this application are the 3-5 μm and 8-14 μm wavebands. As the temperature of an object increases more and more of the radiated energy falls at shorter wavelengths.

The sensing elements in thermal imagers usually must be cooled to very low temperatures (e.g. 80 K) for them to work effectively. This requires small cryogenic coolers and this adds cost to the imagers. Some cooled cameras need liquid nitrogen for cooling and this adds complexity to the process. Recent developments have allowed the introduction of uncooled FPA cameras that are much less expensive. These cameras may be less sensitive than some cooled cameras.

3.3 Imager Manufacturers

The following manufacturers of thermal imagers were contacted and literature was obtained from each.

- Agema
- Inframetrics
- Texas Instruments
- Mitsubishi
- Compix
- Electrophysics
- Kodak
- FSI
- Amber (Raytheon)

All of these manufacturers make cameras that give produce images. However, some cameras were not intended for field use. From these a short list was prepared which included FSI, Amber, TI, Agema and Inframetrics. This list was based on a number of factors including image quality, image speed, cost, portability, etc. Cameras from each of these manufacturers were obtained for demonstration.

3.4 Imager Selection

In the end the uncooled FPA TI cameras were selected (i.e. the TI Nightsight and the Palm IR 250 – note by the end of this contract TI was purchased by Raytheon-Amber). This selection was based primarily on cost. These were by far the least expensive cameras while at the same time having image quality that was consistent with the objectives of this work.

The complete technology review report can be found in Appendix A. The reader is cautioned that this review is already dated. There have been several developments in the thermal imager industry that are not included in the report. For example, FSI and Agema have merged and the thermal imager division of TI has been taken over by Raytheon (Amber). Several imager manufacturers are now offering the low-cost uncooled FPA technology that was eventually selected for this project.

4. Laboratory Tests

A series of laboratory tests were conducted to study the feasibility of using a thermal imager to find insulation deficiencies in tanks. Thermography has been used for many years to find insulation deficiencies in systems that have large temperature gradients. For example, thermal imagers can be pointed at the roofs of buildings during winter months to detect heat loss. In the case of an insulated tank car there may not be any large thermal gradients because the lading may be at ambient temperature. However, there will usually be a small gradient due to the day-night hot-cold cycles that a tank will normally experience. In North America the temperature varies by about 10^{o}C from day to night. If the tank lading takes up an average temperature then there will usually be some difference between the lading temperature and the current air temperature. The question was – is a gradient of the order of 5^{o}C large enough to see insulation deficiencies.

The laboratory tests were conducted to answer this question. The full laboratory report can be found in Appendix B.

4.1 Objective

The objectives of the laboratory testing of the thermal imager was:

- to determine, under controlled conditions, the capabilities and limitations of using a thermal imager in detecting insulation deficiencies.
- to determine whether a thermal imager could be used to detect the liquid level in uninsulated, thermally protected, and thermally insulated tanks.

It should be noted that since a TI NightSight thermal imager was used to perform all tests, the results reflect the capabilities of the NightSight in the detection of insulation deficiencies, not necessarily thermal imagers in general.

4.2 Test Procedure

To determine the effectiveness of using a thermal imager for detecting insulation deficiencies, thermal images were taken of a simulated tank car with different of levels of insulation deficiencies, ambient conditions, tank lading conditions, and tank surface conditions. The tests were carried out in the laboratory on an apparatus designed to accurately represent actual heat transfer conditions in full-size tank cars. This approach was used rather than using actual tank cars so that the variables could be carefully controlled and a wide range of test conditions could be studied quickly.

4.3 Test Variables

For the laboratory tests, the following parameters were kept constant:

- tank geometry – representative of a full-size tank car. (see Figure 1).
- tank material – only carbon steel tanks were used in the laboratory tests.
- liquid and vapour thermal properties – in all cases the test vapour was air and the test liquid was water.
- ambient radiation – all tests conducted in the laboratory were conducted in a dark room with exterior windows blinded shut.

The variables studied during the laboratory testing were :

- temperature gradients – the difference in temperature between the tank lading and the surroundings was varied over a range likely to be found in the field.
- surface finish – all inner surfaces including the outer tank surface and the steel jacket inner surface, were painted with a flat black enamel paint over a red oxide paint. The effect of surface radiating properties was studied by varying the finish of the outer steel jacket. This included several different paints, flat and gloss white, flat and gloss black; and surface coatings of water, oil, and dust.
- insulation materials – both thermally protected and thermally insulated insulation configurations both dry and wet were studied. Limited testing was done simulating foam in place insulation.
- insulation deficiencies – a pattern of different sized and shaped insulation deficiencies was investigated.

4.4 Test Apparatus

The test apparatus was designed to simulate a tank car incorporating the following features:

- tank surface curvature
- correct wall thicknesses and thermal properties (thermal capacities, thermal conductivities, etc.)
- variable fill level
- controlled liquid and vapour temperatures
- ability to change thermal insulation configuration easily (including jacket gap dimension).

The apparatus, shown in Figure 1, consists of a 2.1 m long quarter section of a full-scale tank car. The main tank wall is plain carbon steel and has a thickness of 16 mm and the outer tank shell has a thickness of 3 mm. The outer steel jacket can be placed in two positions to allow the gap for insulation between the main tank wall and the outer

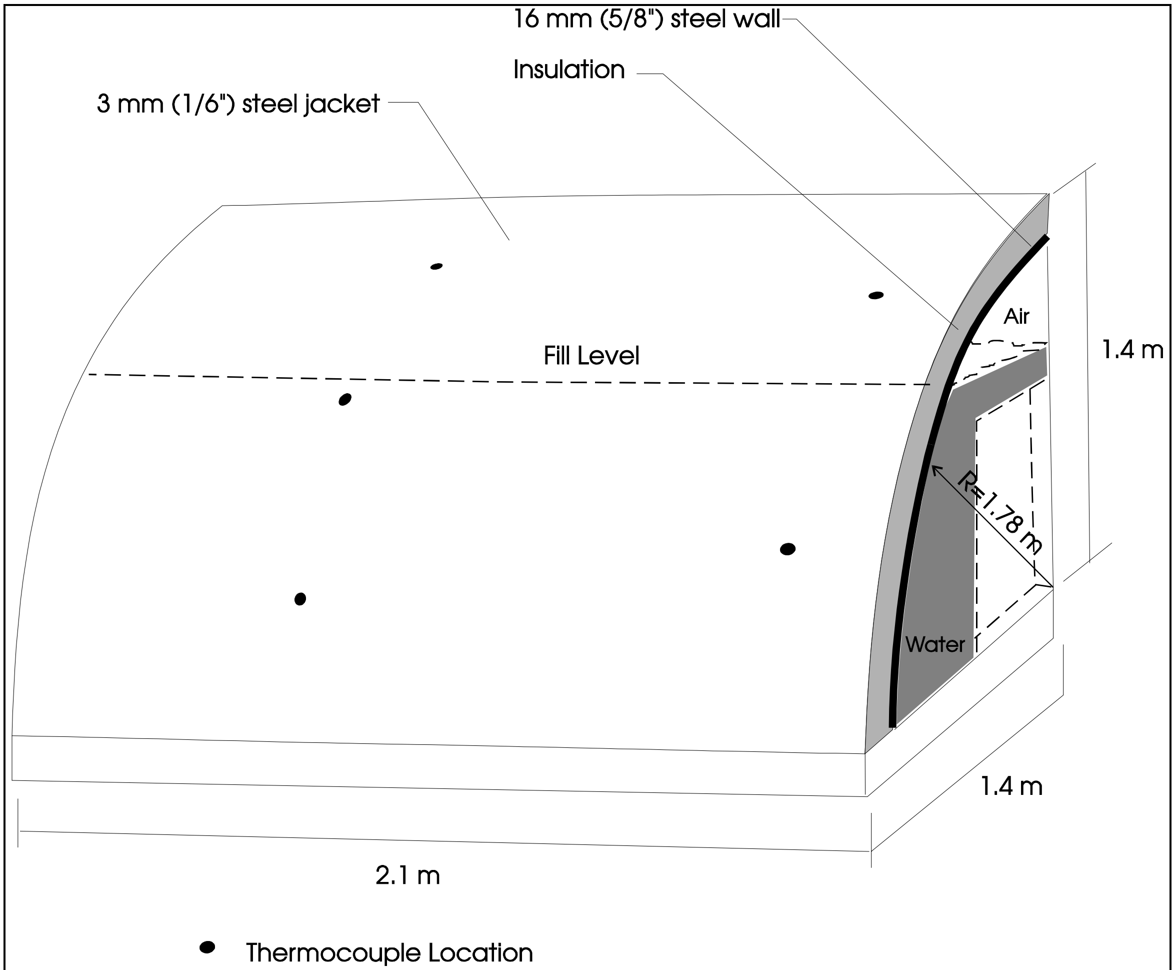

Figure 1: Tank mock-up

tank shell to be either 13 mm simulating thermally protected or 102 mm thermally insulated.

4.5 Insulation Test Pattern

To evaluate the effectiveness of using a thermal imager to detect insulation deficiencies, a pattern of insulation deficiencies was developed. The pattern, shown in Figure 2, was designed to simulate closed cells and convective paths formed by deficiencies. The placement of diamonds of insulation and varying widths of deficiencies allowed the spatial resolution of the technique to be evaluated. The large triangular sections of insulation created by the convective path also allowed the effect of the distance between adjacent deficiencies to be observed. The pattern was repeated in both the upper and lower halves of the apparatus so that the pattern could be observed in both the liquid and vapour space.

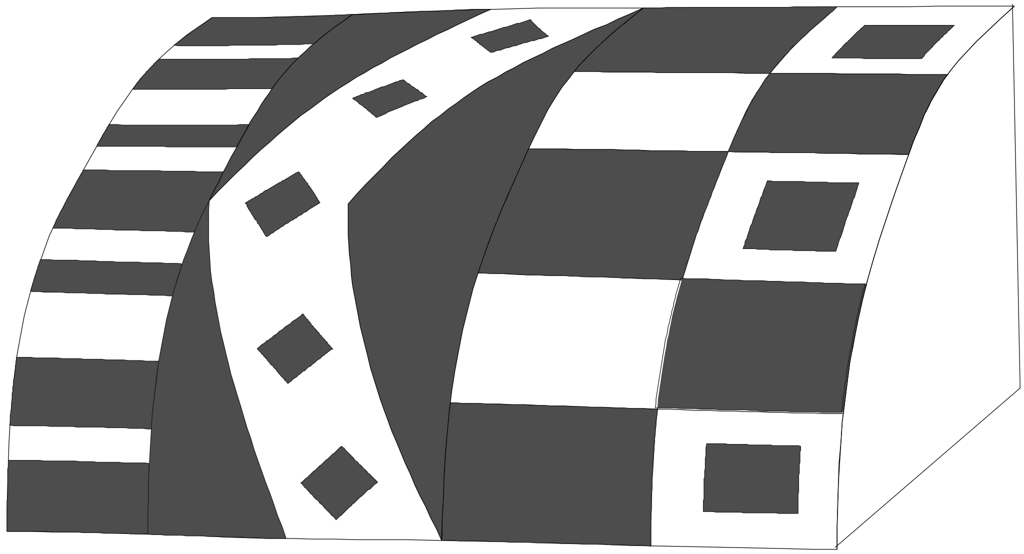

Figure 2: Insulation test pattern

4.6 Test Instrumentation

The test instrumentation consisted of the TI NightSight thermal imager video camera for visually recording the tests when required, and thermocouples for measuring the temperature differences between the tank lading and inner wall, and the outer tank steel jacket to the ambient air.

Type K thermocouples were mounted on the outer surface of the tank wall. The temperatures at the same location but on the outside of the outer tank steel jacket were measured using a hand-held temperature probe. The thermocouple locations were selected to allow the temperature differences across the gap to be measured at insulated and uninsulated locations in both the liquid and vapour regions. Surface temperature measurements were taken at additional locations during some tests if greater spatial resolution of the temperature measurement was required.

4.6.1 TI NightSight Thermal Imager

The Texas Instruments NightSight thermal imager used in the laboratory testing is an uncooled 8-12 μm focal plane array (FPA). It is intended principally for law enforcement use and is therefore designed to be rugged and easy to use. The specifications of the imager are given in Table 1.

Table 1: Technical Specifications of TI NightSight

Property	Value
Spectral range	8-12 μm
Sensing element	uncooled BST
Field of view	27° X 18°
Resolution	328 X 200 pixels
MRTD	0.2°C quoted (more like 0.5°C in practice)
Depth of field	6 m (20') to infinity
Image control	automatic gain and level
Output	standard video
Weight	7.6 kg (16 lb.)
Power consumption	50 W peak, 6 W steady state, 12 VDC
Features	roof mount, tilt and pan drive, weather proof

The technology that allows the NightSight to be affordable also results in a poorer quality image compared to more expensive imagers. The type of sensing elements used in the TI NightSight require a chopper, which is similar to a propeller, that spins and periodically blocks the sensors' view of the object being imaged. Due to the optical set-up in the TI NightSight and imperfections in the chopper, a "false" image is always overlaid on top of the real image adding overall noise to the image of interest. The false image, consisting of alternating dark and light horizontal bands, can be viewed by placing a surface of uniform temperature over the entire field of view of the image. The image is constant over the short term and varies slightly over the long term depending on ambient conditions and length of time the imager has been operating. This allows the error introduced by the false image to be partially corrected for, using image processing.

4.7 Test Results

The complete lab test results can be found in Appendix B.

The laboratory tests showed that the TI Nightsight could indeed identify thermal insulation deficiencies in tanks (both the thermally protected and the thermally insulated) with small thermal gradients. If the thermal gradients were very small (temperature difference between lading and ambient less than 5°C) then image processing was necessary to reduce image noise. The image noise was related to the specific imager used for these tests. The TI Nightsight was the least expensive and the least sensitive of the cameras considered and therefore if the Nightsight could identify the deficiencies then more sensitive cameras could also.

5. Field Tests

The laboratory tests proved that it was feasible to identify thermal insulation deficiencies in tanks with small thermal gradients present. The laboratory tests were then followed by a series of field tests. The field tests were conducted for the following reasons:

- validation of the inspection method
- further development of the inspection procedure
- to gain field experience with the method
- to quantify the effects of the sun
- to obtain baseline tank data

Several field trips were taken. The following is a summary of the documented field tests:

- Varennes Siding
- Petromont Varennes
- Procor Repair Shop – Montreal
- Sarnia Yard
- Beauharnois PPG
- Petromont Varennes
- Varennes Siding
- Port of Montreal

The details of these various field trips can be found in the individual field test reports in Appendix C.

5.1 TI Palm IR 250

At the time of the field trials, a new low-cost thermal imager was available that had a greater sensitivity than the NightSight. The TI Palm IR 250 (Texas Instruments) is based n the same technology as the NightSight but uses improved optics to achieve greater sensitivity. The Palm IR 250 was used for most of the filed tests

5.2 Validation

The lab tests were followed by a limited field test and validation. The NightSight was taken into the field to view tank cars at sidings and industrial sites. The imager identified a number of tanks with severe insulation deficiencies. One of these tanks (a thermally protected 112 car) was traced, and when empty, was sent to a local repair yard.

At the repair yard the tank was heated by flowing steam through the tank. This heating introduced a thermal gradient that allowed the thermal imager to once again identify the deficiencies. At this point, a number of holes (10 cm x 10 cm approx.) were made in the steel jacket. In those areas that showed the strongest indication of deficiency, it was found that no insulation was present in the gap between the tank shell and the steel jacket. In other areas that also showed some defect the insulation was either crushed to a powder or there was no insulation. This test was used as a limited validation for the inspection procedure.

Appendix C contains the full validation report.

5.3 Field Experience

As noted earlier a series of field tests were carried out. These are fully documented in the field test reports contained in Appendix C. The field tests showed that the inspection procedure is practical and highly effective. However, care must be taken by the inspector to ensure that the conditions are good for inspections. The method of recording the images on a VCR for later analysis proved to be very effective. The following are some important observations from the field tests.

5.3.1 Correlation of Visual and IR image

It is critical that the inspector compare the visual image of the tank to the thermal image. In this way they will be able to eliminate false indications of insulation deficiencies that may be caused by shadows, changes in paint colour, etc.

5.3.2 Solar Effects

The tank inspections were greatly enhanced by solar heating of the dark coloured tanks. Dark coloured tanks will heat up much more due to solar radiation than white, metallic or light coloured tanks. The tank lading was cool and therefore any solar heating made the temperature gradient between the lading and tank outer shell very large. This means that insulation deficiencies would appear as cool areas on the tank outer surface. These were clearly visible when the tank sides were uniformly solar heated. However, shadows also appeared as cool areas and for this reason care must always be taken to compare the visual and thermal image. Also, white lettering on a dark tank will also appear as cool areas, but these are usually obvious.

5.3.3 Effects of Time of Day

The inspection technique was not as effective early in the morning before the solar heating had taken effect. During this field trial the temperature gradient between the lading and the ambient temperature was small and therefore inspections would have been difficult without the solar heating. For this reason inspections of the shaded sides of the tanks were not carried out. There is a second reason for this – inspection of the tank shaded side would mean the thermal imager would be pointed towards the sun and this is not a good procedure due to the extreme solar radiation levels and the possibility of solar reflection of the top of the tanks.

5.3.4 View Angles

During the tests it was observed that inspections should be carried out from the tank side with the camera pointed at a right angle to the tank axis. If the camera is pointed with glancing angles to the tank then the surface reflection stands out and the thermal images are severely affected. This also means that if the tank is inspected from the side, then the camera angle results in reflection from the tank top and bottom regions. Care must be taken to account for this when the thermal images are interpreted.

The camera view angle made it very difficult to walk up to the tank and carry out close-up inspections. When standing a few metres from the tank, the camera only sees a few metres of tank and the observer can become disoriented. The best inspection distance is around 20-30 m where a large part of the tank can be seen in the field of view. For close-up inspections a thermal imager with a very wide angle lens is needed.

5.3.5 Field Logistics

Due to the limitations of the field of view of the current imager (TI NightSight or Palm IR 250) as described above, the thermal images must be taken 20-30 m from the tank cars. This limitation basically eliminates the possibility of the inspector walking between lines in a rail yard. Therefore the inspections will be most effectively carried out from a vehicle since this eliminates the need for the inspector to carry large amounts of equipment including a VCR and battery packs (the equipment can be powered by the vehicle battery using an 120 V inverter).

The equipment required for vehicle-based inspection would be:

- thermal imager
- video camera
- VCR (for recording thermal imager output)
- small TV monitor
- dual-head tripod
- 120 V inverter
- thermocouple probe (optional)

The most effective installation of the thermal imager and video camera would be a roof mount since this would allow for easy adjustment and a 360° view. If this is not possible, the use of a van with a sliding side door is suitable. As was done during the field trials, the video camera and thermal imager can be mounted on a dual head tripod with the video camera adjusted to give the same field of view as the thermal imager. The tripod is then positioned in the van to look out of the open side door.

The field trials were conducted by two people, one operating the thermal imager and video camera, and the second recording the tank car data and driving the vehicle. With this arrangement approximately 20 tank cars could be inspected per hour. If the inspection was being performed by a lone inspector, it is estimated that the rate of inspection would be 5-10 cars per hour.

5.3.6 Analysis

Experience from the field trials suggests that the best procedure for analysis is to record the thermal and video images at the time of inspection but complete the analysis of the images at a later time. The analysis of the images required approximately 50% of the person-days required for the inspection. During the field trials the tank information was recorded on data sheets by hand and later summarized in a database for analysis. Some time could be saved during the analysis if the tank data was entered directly into a database on a laptop computer at the time of inspection.

The equipment needed for image analysis is:

- VCR
- TV monitor
- video printer

Ideally the analyst would have two VCRs and two monitors (one for IR one for visual).

5.4 Tank Insulation Deficiency Data

During the field testing it became clear that there are significant numbers of tanks with insulation deficiencies. As a result the test objectives were expanded to include the collection of tank insulation deficiency data. Some typical field test data is shown in the following pages. These plots are from the Sarnia field trip. (All of the field trip reports can be found in Appendix C.)

The test results clearly show that older tanks may have severe deficiencies. As can be seen from the data plots, a large fraction of the tank population have some deficiencies. Early on in this test program there was a concern that it would be difficult to verify the effectiveness of the inspection method since it may be difficult to find tanks with deficiencies. This has not been the case in practice.

The condition of insulation in each age division is summarized in the Figures 3-7 showing the Sarnia data. Generally the results indicate that the condition of the insulation deteriorates with age. Up to an age of 20 years the deficiencies are relatively minor, but for tank cars greater that 20 years old, the number and severity of insulation deficiencies greatly increase.

A comparison of Figure 3 and Figure 4 shows that on average the area of insulation deficiencies on the top half of the tank cars is approximately twice as large as that on the bottom half of the tank car. This pattern of deficiencies would be expected, since at the top of the tank car the insulation would be more susceptible to:

- insulation crushing from the weight of the jacket resting on the shell
- insulation settling – the weight of the lower insulation pulling on the upper insulation
- damage form lading spillage or water penetration at the manway

Figures 2-5 show that there is an trend of larger deficiencies with age but there is a wide scatter in the range of insulation deficiency areas at all ages. This is emphasized by Figure 7 which shows that the average values in each age group is substantially less than the peak values in the age group and the standard deviation is on the same order as the average value of the deficiency area. This shows that even in the older tank cars where large deficiencies occur, there is a large number of older tank cars with only minor or no insulation deficiencies. However, older tank cars are more likely to have a large insulation deficiency.

Figure 6 shows the area of insulation deficiency by age for the three models of tank car viewed: 112, 111, and 105. No distinction was made between the various sub-models of each tank car model. No 111's or 105's were found with large defects, but this is most likely due to their age since all 111's and 105's were less than 20 years old. When the ages of the tank cars are taken into consideration, there does not seem to be any significant difference in the quality of the insulation between tank car models. This suggests that considering all tank car models as one group is a valid assumption.

If tank cars greater that 20% deficient in insulation are considered to be critical, Figure 8 shows that approximately 20% of tank cars greater that 30 years old have greater than 20% areas of deficiency, 10% of tank cars 20-30 years old have this level of deficiency, and very few tank cars younger than 20 years have levels of deficiency this great.

For further details of the field test data, see Appendix C.

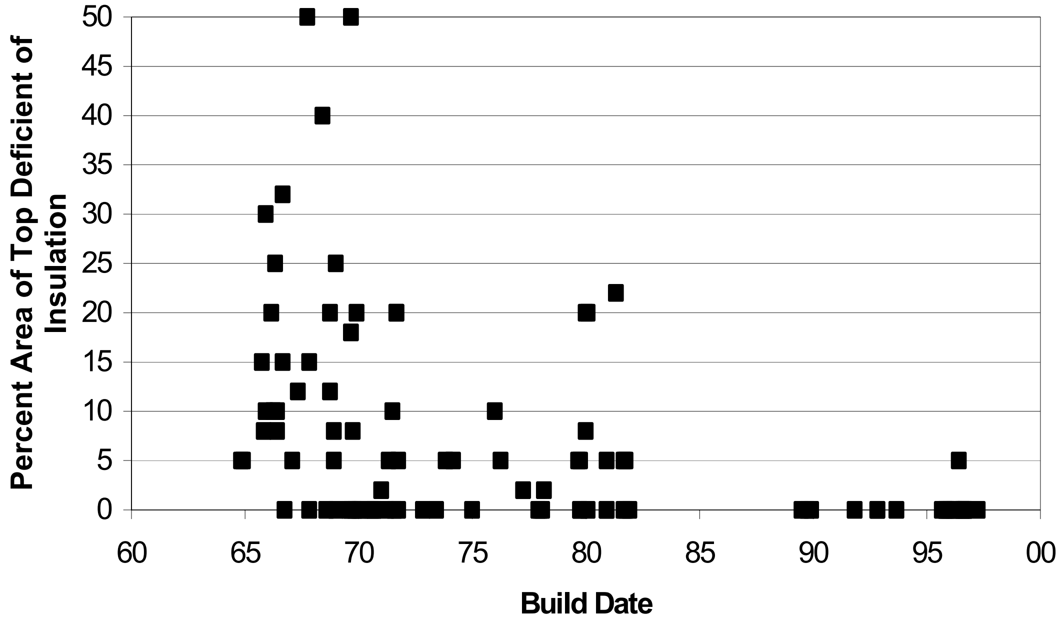

Figure 3: Area of insulation deficiencies on top half of tank cars, one side, by tank car age (Sarnia field test)

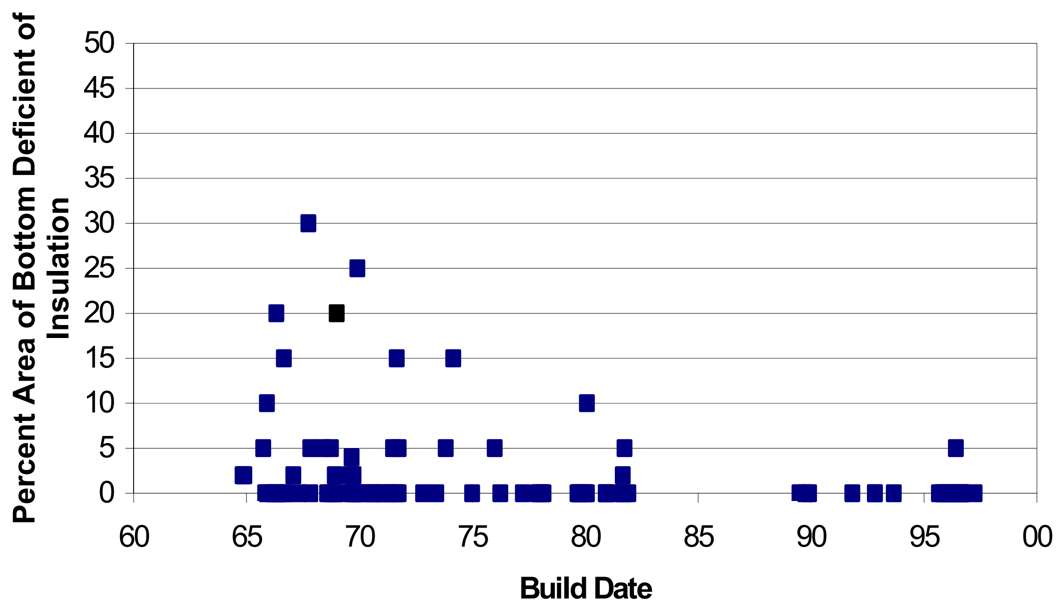

Figure 4: Area of insulation deficiencies on bottom half of tank cars, one side, by tank car age (Sarnia field test)

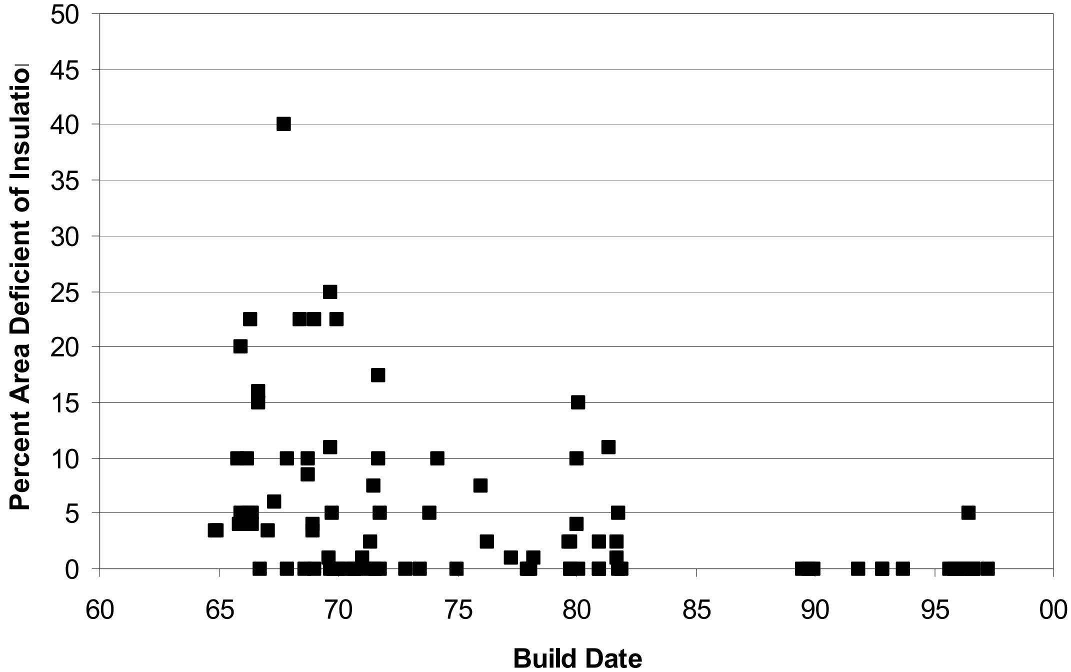

Figure 5: Area of insulation deficiencies on one complete side of tank cars by tank car age (Sarnia field test)

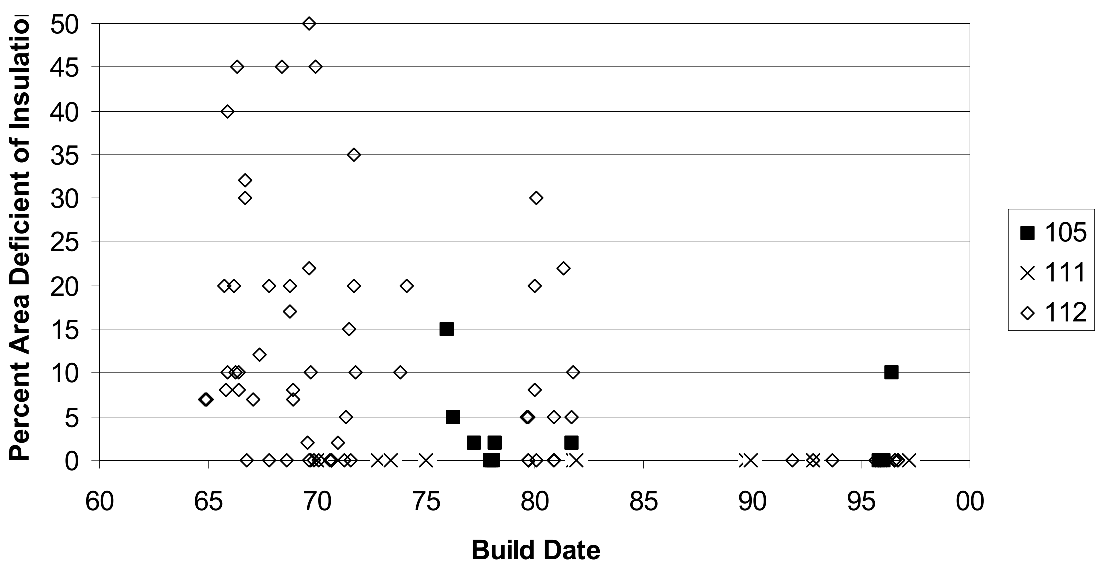

Figure 6: Total area of deficiency tank car side by model (Sarnia data)

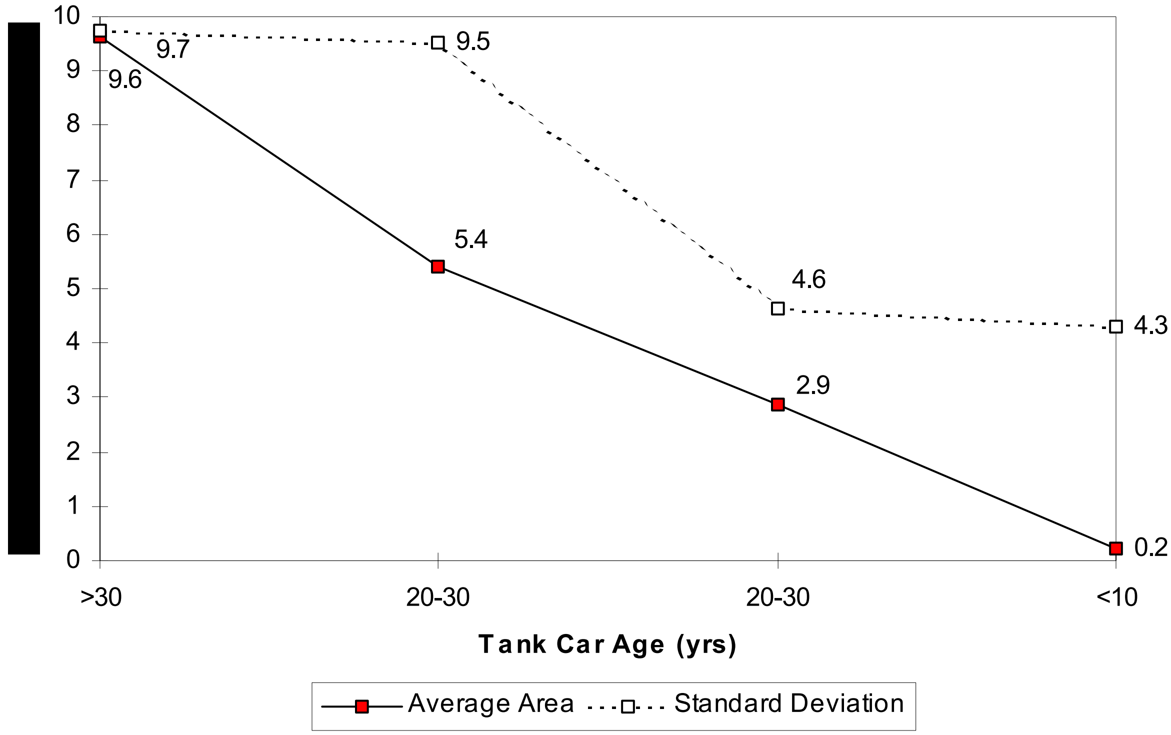

Figure 7: **Average level of insulation deficiency on complete tank car side by age (Sarnia Data)**

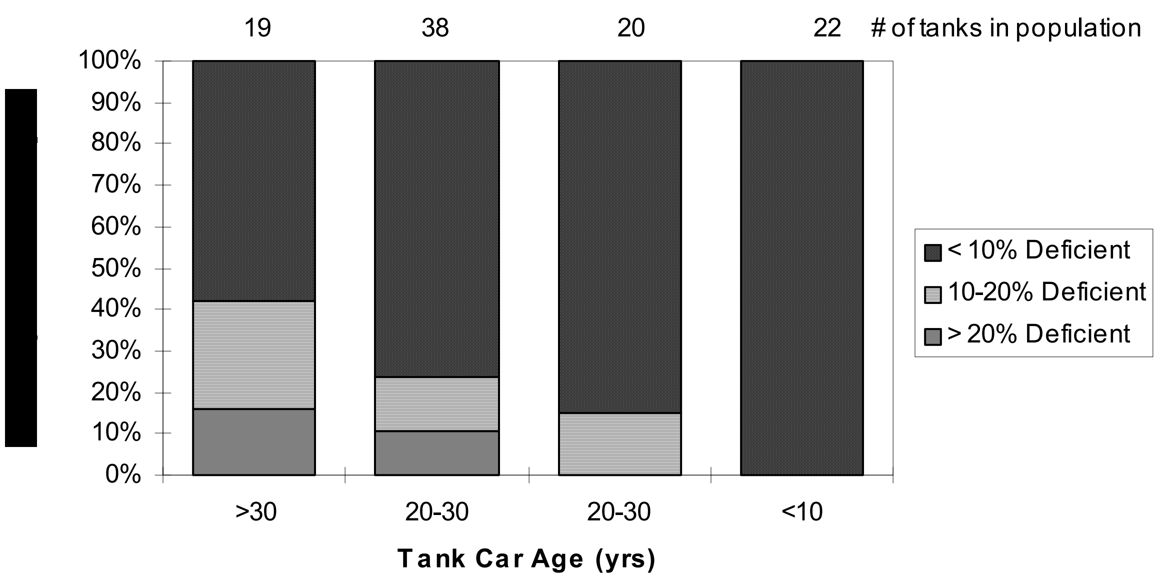

Figure 8: Distribution of severity of defects in the tank car population by age (Sarnia data)

5.5 Field Experience Summary

The field tests showed that the inspection procedure is practical and highly effective under good inspection conditions. However, care must be taken by the inspector to ensure that the conditions are good for inspections.

Based on this field test the following conclusions have been made for the inspection procedure:

1. The inspection procedure proved to be highly effective under good test conditions (i.e. clear sunny day – cool lading).
2. Solar heating greatly enhances inspection, but care must be taken to account for shadows, reflection, differences in paint colours, etc.
3. Inspection of the shaded tank side may be difficult if thermal gradients are small.
4. The thermal imager should not be pointed towards the sun during inspections.
5. Glancing camera angles should be avoided because of surface reflections.
6. The method of recording the images on a VCR for later analysis proved to be very effective.

For the collection of tank data:

1. Tank cars were inspected for insulation deficiencies and the data was analysed.
2. Based on the age distribution of the sample, it appears that the sample is a reasonable representation of the general tank car population.
3. In general the state of the insulation usually deteriorates with tank car age.
4. Tank cars less than 20 years old generally only have minor defects and tank cars older than 20 years may have major defects. In the current sample, 3% of the sample population had more than a 20% insulation deficiency.

6. Heat Transfer Considerations

Through laboratory and field testing, it was demonstrated that a thermal imager could be used to reliably identify areas of insulation deficiency on rail tank cars. However, it remains to be determined what size an insulation deficiency must be before it significantly reduces the level of thermal protection on the tank car.

The presence of an insulation deficiency alone does not mean that the tank car is not sufficiently protected, since even when a deficiency exists, there is still significant thermal protection provided by the steel jacket. The outer steel jacket acts as a radiation shield, reducing the temperature of the vessel shell on the order of 100°C in typical fire conditions when compared to a totally unprotected tank. Furthermore, heat conduction in the tank wall to areas that are still insulated will also limit the temperature of the shell. However, at some point the size of the deficiency will result in there being a large enough area of the shell at an elevated temperature to make the vessel susceptible to a thermally induced rupture. For maintenance purposes, it must be established at what size an insulation deficiency requires repair.

The purpose of this heat transfer study was to numerically predict how the temperature of the shell wall changes with the size of the insulation deficiency. This analysis was limited to heat transfer alone. No attempt was made to account for stresses in the tank wall or creep of the wall due to these stresses and the elevated temperatures that are predicted.

The analysis suggests that for defects larger than 0.2 m across, the wall temperature is no longer affected by the size of the defect. The steel jacket reduces the maximum wall temperature by about 200°C when compared to a wall not covered by a steel jacket.

The following pages present an overview of the analysis and its results. For further details, see Appendix D.

6.1 Heat Transfer Model

The wall of a thermally protected tank car consists of a 16 mm tank shell (pressure vessel wall) 1.2 -10 cm of fibreglass and/or mineral wool insulation, and an outer 3 mm steel jacket. A cross section of a tank car wall is shown in Figure 9. The portion of the tank most susceptible to thermal weakening is the portion of the tank wall in the vapour space since the portion of the shell in contact with the liquid will be efficiently cooled by the liquid (the convective heat transfer coefficient is much greater for a liquid than a gas). Therefore, the heat transfer analysis is limited to the portion of the shell in the vapour space.

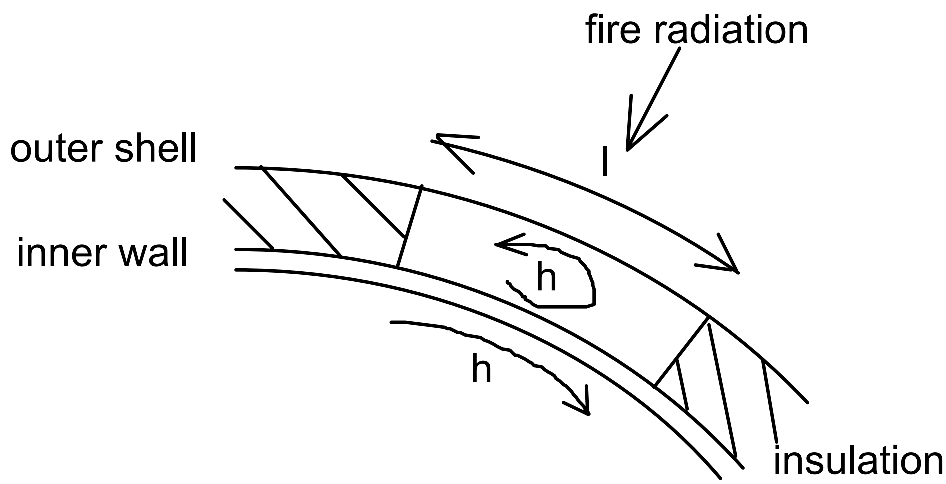

Figure 9: Cross section of tank car wall

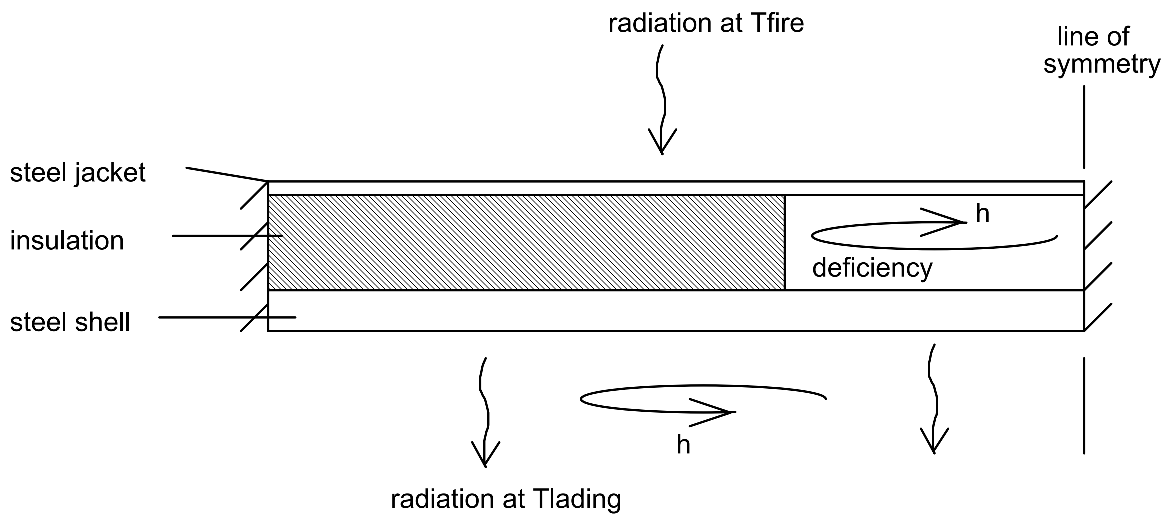

Figure 10: Heat transfer model of tank car wall

To simplify the analysis, the tank car wall was modeled as a finite 2-D planar wall as shown in Figure 10. The 2D assumption means that the analysis is considering a strip of defect that runs the length of the tank. The defect was assumed to be symmetrical and only one-half of the wall/defect was considered in the analysis.

For further details about the model and its solution, see Appendix D.

6.2 Validation

To validate the model, limiting cases were solved analytically and compared to the numerical result. The numerical results did not completely represent the analytical solution since for example the width of the wall must be finite. In this case, the width of the wall was increased until it was essentially infinite. The cases used and the analytical and numerical results are given in Table 2.

Table 2: Validation of Numerical Results

Validation Case	Analytical Result		Numerical Result	
	jacket	shell	jacket	shell
two infinite plates between two infinite constant temperature sources at 1100 K and 330 K	1001	828.5	1001.1	828.5
an infinite composite wall made up of a layer of insulation with steel plates on both sides exposed to black body sources of 1100 K and 330 K on either side of the wall	1096	425.7	1096	425.8

6.3 Results

The temperature distribution through the wall was calculated for insulation thicknesses of 1.3 and 10 cm for deficiency widths of 0.002 to 1.0 m. The remaining tank properties are given in Table 3. Grid sensitivity studies showed that a 93 node grid was suitable for calculating the temperatures. Eight nodes were used through the thickness of the wall and 13 along the length of the wall.

The maximum shell temperature (at the defect centre) for the two insulation thicknesses is shown in Figure 11. This shows, as expected, that as the size of the deficiency increases the maximum temperature on the shell increases. For small

Table 3 : Parameters for numerical runs

Parameter	Value
steel conductivity	40 W/m K
insulation conductivity	0.04 W/m K
steel emissivity	0.9
insulation emissivity	0.3
jacket thickness	3 mm
shell thickness	16 mm
width of insulated section	2 m
convective heat transfer coefficient	8
fire temperature	1100 K
lading temperature	330 K

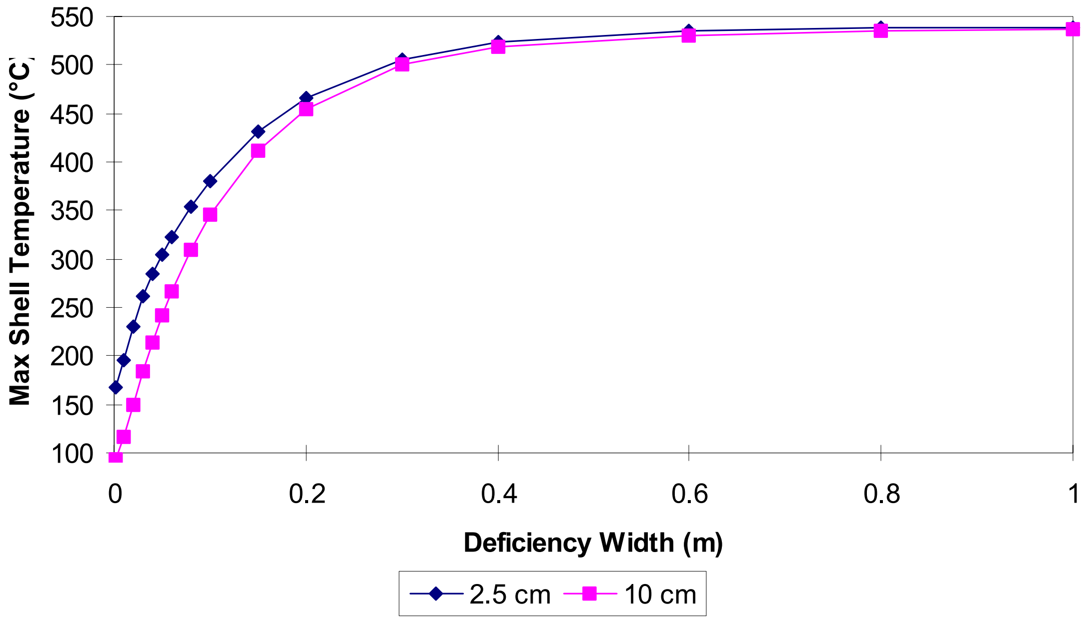

Figure 11: Variation of maximum inner shell temperature with width of deficiency for fire temperature of 1100 K

deficiencies, the temperature is that of the insulated wall and as the size of the deficiency grows, the temperature approaches the value of that for infinite parallel radiating plates. The analysis shows that for a width of 1 m, the shell temperature is approximately that of infinite parallel plates. The figure also shows that there is some difference in the wall temperature for 1.3 cm and 10 cm thick wall insulation at small deficiency widths, but for deficiencies greater than 20 cm the thickness of the insulation does not have an effect on the shell temperature.

Figure 13 shows the temperature profile along the inner shell surface for several widths of deficiencies. The deficiencies extend from 0 to their respective half widths – the remaining length being insulated. The figure shows that the temperature jumps dramatically at the transition between the insulated and uninsulated portions, with the temperature in each portion being relatively constant.

The temperature of the shell can be reduced by introducing a low emissivity surface on one or more of the radiating surfaces (i.e. jacket inner surface and tank outer surface). Figure 12 shows the variation of maximum shell temperature for a range of emissivities applied to outer surface of the tank shell (one surface) and to both the outer surface of the tank shell and the inner surface of the tank jacket (two surfaces). As can be seen, the temperature of the shell can be decreased by 150°C.

Figure 14 shows how the maximum shell temperature increases with increasing fire temperature. The increase in the wall temperature is approximately 50% of the increase in the fire temperature.

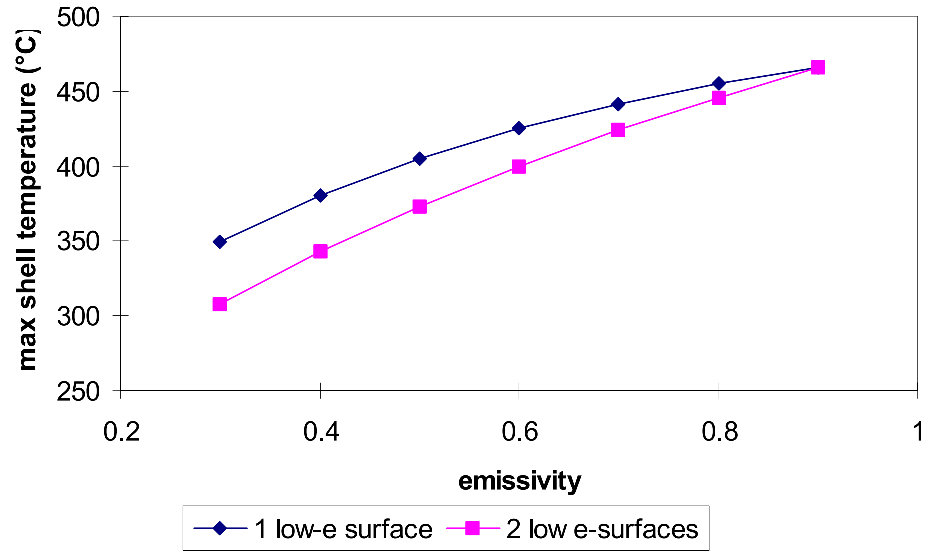

Figure 12: Effect of emissivity on maximum shell temperature, total deficiency width = 20 cm, fire temperature = 1100 K, insulation thickness = 1.3 cm

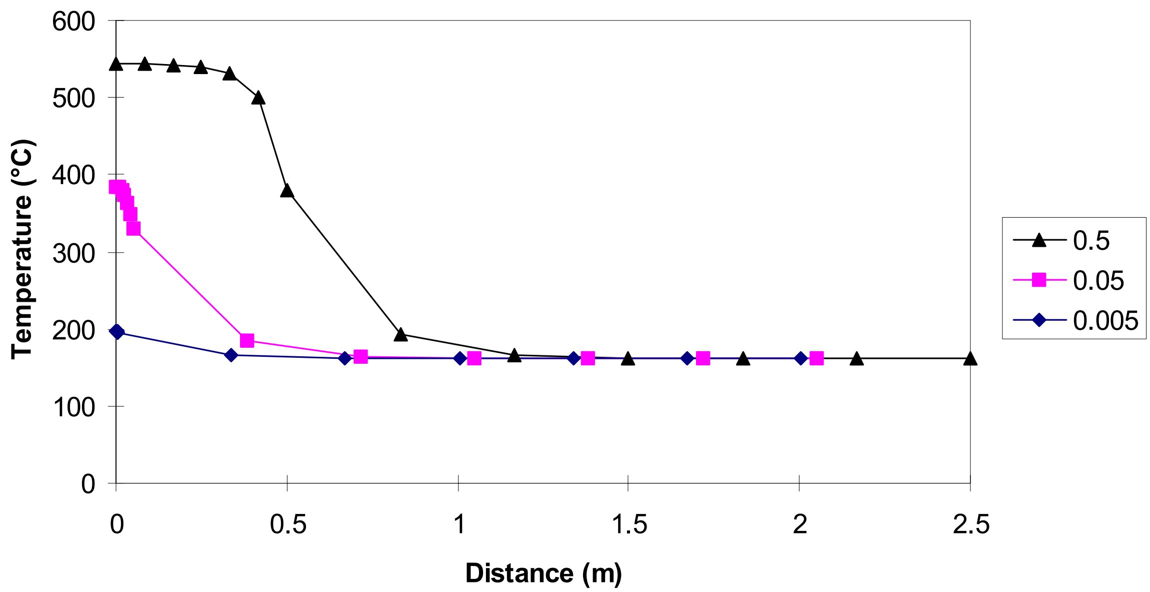

Figure 13: Temperature profile along outer surface of shell, for fire temperature of 1100 K, insulation thickness 1.3 cm

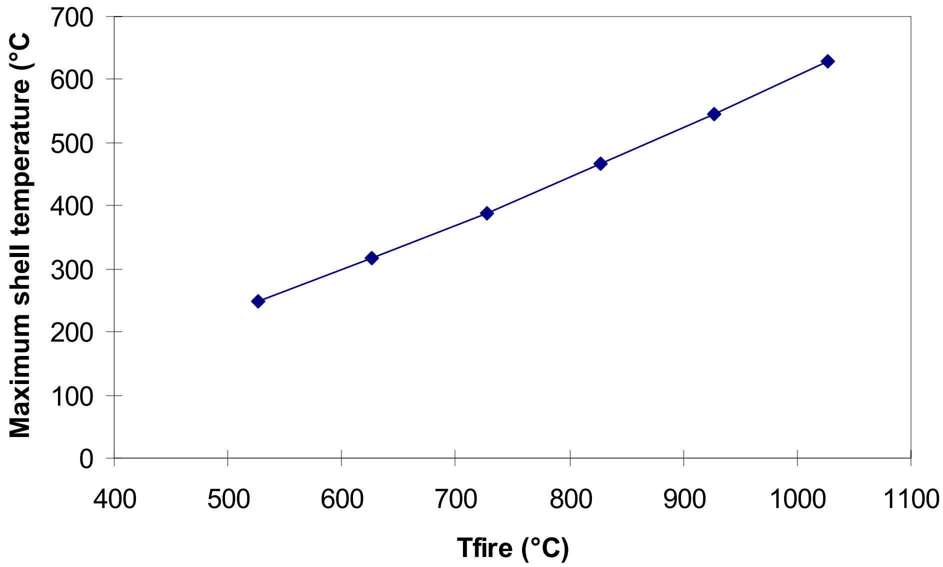

Figure 14: Change of maximum shell temperature with fire temperature; total defect width = 20 cm, insulation thickness=1.3 cm

6.4 Discussion

A pressure tank can fail if wall temperatures cause material degradation and local weakening of the shell. This weakening can lead to local creep, bulging and wall thinning which in turn leads to higher stresses and more thinning, etc. At some point the wall thinning results in the formation of a small hole which may grow resulting in the catastrophic failure of the tank.

The analysis suggests that defect size has a strong effect on the maximum wall temperature up to a defect size of about 0.2 m. For defects larger than this the temperature does not vary much with the defect size.

If we select a temperature limit then we can specify a limiting defect size. For example we know that tank-car steels start to loose strength at temperatures above 300°C (see Figure 15). The strength drops rapidly after 400°C. At 600°C the tank has lost 60% of its strength.

Based on the results here, if we allow a temperature limit of 400°C and assume a fire temperature of 1100 K then the limiting defect size is about 10 cm. If the fire temperature increases then the allowable defect size would go down. This shows that if we base the allowable defect size only on temperature considerations then even small defects are not acceptable. In our opinion, such a small defect alone would not likely result in a tank failure unless the defect had a very critical shape – for example:

- a 10 cm wide strip running along the top of the tank length, or
- a 10 cm wide strip running around the circumference of the tank

Either of these defects could severely reduce the structural integrity of the tank. The longitudinal strips could allow the tank to unzip along its length while the circumferential defect could result in the tank separating into two end tubs.

A small heated area may not lead to failure because of the supporting effect of the surrounding material. However, a large heated area may result in tank failure. At some defect size the surrounding tank material cannot take up the extra burden.

In other words, the size, shape and location of the defect and the temperature work together in the failure process. The question is, how do wall temperature, area of heated wall and tank pressure factor together to result in tank failure? The answer to this requires more than a heat transfer analysis and is beyond the scope of this report.

The heat transfer in a tank car wall containing insulation deficiencies was modeled as a planar 2-D composite wall. A finite difference numerical technique has been used to solve the heat transfer equations. The numerical solution was verified using limiting cases; however, further verification is needed.

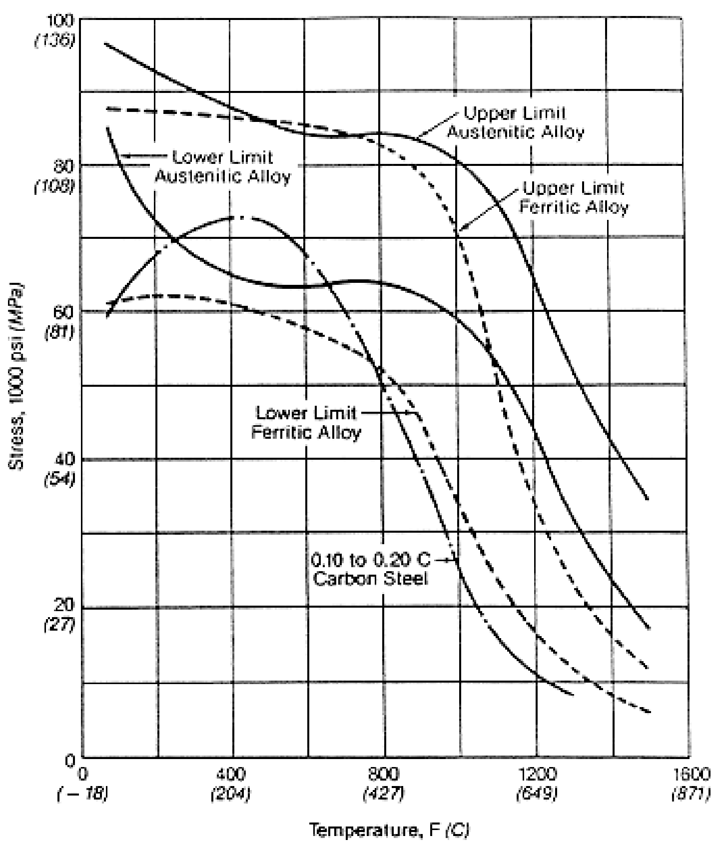

Figure 15: Strength of carbon steel [3]

7. Conclusions

A thermal imager can be used to find thermal insulation deficiencies on a tank when a thermal gradient is present. This technique applies to both thermally insulated and thermally protected tanks. The method applies to a wide range of insulation types. The method does not work effectively on highly reflective surfaces (raw stainless steel, aluminum, silver paint).

Small thermal gradients are present due to natural day-night heating-cooling cycles. Large thermal gradients may be present during filling or off-loading of tanks or under solar-heated conditions. Inspections can be performed on empty tanks by using heat injection (steam or hot air) techniques.

For large thermal gradient testing, the results are easy to interpret – i.e. deficiencies will be obvious. For small thermal gradients, care must be taken to ensure that indications of thermal deficiencies are real and not simply reflection effects, solar effects or surface finish effects.

For uninsulated tanks it is possible to observe the liquid level provided small thermal gradients are present.

A field test manual has been prepared based on the results of this work. A copy can be found in Appendix E.

References

1. Siegel,R., Howell, J, *Thermal Radiation Heat Transfer,* Taylor and Francis, Washington, 1992.

2. Incropera, F., DeWitt, D, Fundamentals of Heat and Mass Transfer, John Wiley and Sons, New York, 1996.

3. Steam: Its Generation and Use, 40th edition, Babcock and Wilcox, Barbertion, Ohio, 1992.

Appendix A: Technology Review Report

(Not available in electronic format/
Non disponible en format électronique)

Appendix B: Laboratory Test Report

(Not available in electronic format/
Non disponible en format électronique)

Appendix C: Validation and Field Trial Reports

(Not available in electronic format/
Non disponible en format électronique)

Appendix D: Heat Transfer Analysis

(Not available in electronic format/
Non disponible en format électronique)

Appendix E: Field Test Manual

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