TP 13955E

DEVELOPMENT OF A TRAILER-MOUNTED LIGHTWEIGHT CONTAINER MODULE FOR COMPRESSED GAS VEHICLE FUEL

Prepared for
Transportation Development Centre
Transport Canada

by
Powertech Labs Inc.

December 2002

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by

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December 2002

This report reflects the views of the authors and not necessarily those of the Transportation Development Centre of Transport Canada or the sponsoring organization.

Un sommaire français se trouve avant la table des natières.

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 13955E	2. Project No. 9967-68	3. Recipient's Catalogue No.
4. Title and Subtitle Development of a Trailer-Mounted Lightweight Container Module for Compressed Gas Vehicle Fuel		5. Publication Date December 2002 6. Performing Organization Document No.
7. Author(s) Craig Webster		8. Transport Canada File No. ZCD2450-D-726
9. Performing Organization Name and Address Powertech Labs Inc. 12388 88th Avenue Surrey, British Columbia Canada V3W 7R7		10. PWGSC File No. MTB-0-01184 11. PWGSC or Transport Canada Contract No. T8200-000525/001/MTB
12. Sponsoring Agency Name and Address Transportation Development Centre (TDC) 800 René Lévesque Blvd. West Suite 600 Montreal, Quebec H3B 1X9		13. Type of Publication and Period Covered Final 14. Project Officer R. Nishizaki

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

Co-sponsored by the Program of Energy Research and Development (PERD) of Natural Resources Canada (NRCan)

16. Abstract

The lightweight carbon fibre-reinforced high-pressure cylinders developed by Dynetek Industries could be used for the large-volume transportation of compressed hydrogen and natural gas fuels. This report details the development of a lightweight transport unit for compressed fuel gases, and the work involved in preparing an application to the Transport Dangerous Goods Directorate of Transport Canada for a permit. Carbon fibre cylinder designs have never before been used in transportation applications.

Work activities included consultation with Transport Canada regarding permit requirements, construction of a demonstration trailer unit at Powertech Labs using lightweight Dynetek cylinders for the transportation of compressed hydrogen fuel, and design qualification testing per Transport Canada requirements on a Dynetek cylinder design. These design qualification tests included hydraulic pressure cycling of cylinders under ambient and extreme temperature conditions, hydraulic burst testing, bonfire testing of pressurized cylinders, and gunfire testing of pressurized cylinders. An application has been prepared for Transport Canada consideration in granting a permit for equivalent level of safety to use the Dynetek carbon fibre cylinder design for transporting compressed hydrogen and compressed natural gas fuels.

17. Key Words Lightweight cylinder, carbon fibre-reinforced cylinder, Dynetek, compressed hydrogen, natural gas fuels	18. Distribution Statement Limited number of copies available from the Transportation Development Centre

19. Security Classification (of this publication) Unclassified	20. Security Classification (of this page) Unclassified	21. Declassification (date) —	22. No. of Pages x, 14, apps	23. Price Shipping/ Handling

Transports Canada / Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. N° de la publication de Transports Canada TP 13955E	2. N° de l'étude 9967-68	3. N° de catalogue du destinataire
4. Titre et sous-titre Development of a Trailer-Mounted Lightweight Container Module for Compressed Gas Vehicle Fuel		5. Date de la publication Décembre 2002 6. N° de document de l'organisme exécutant
7. Auteur(s) Craig Webster		8. N° de dossier - Transports Canada ZCD2450-D-726
9. Nom et adresse de l'organisme exécutant Powertech Labs Inc. 12388 88th Avenue Surrey, British Columbia Canada V3W 7R7		10. N° de dossier - TPSGC MTB-0-01184 11. N° de contrat - TPSGC ou Transports Canada T8200-000525/001/MTB
12. Nom et adresse de l'organisme parrain Centre de développement des transports (CDT) 800, boul. René-Lévesque Ouest Bureau 600 Montréal (Québec) H3B 1X9		13. Genre de publication et période visée Final 14. Agent de projet R. Nishizaki

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

Coparrainé par le Programme de recherche et développement énergétiques (PRDE) de Ressources naturelles Canada (RNCan)

16. Résumé

Les bouteilles haute pression renforcées de fibre de carbone mises au point par Dynetek Industries pourraient servir au transport en grand volume de carburants gazeux, comme l'hydrogène et le gaz naturel comprimé. Le rapport relate les étapes de la mise au point d'un système de stockage léger pour le transport de gaz comprimés, et les travaux préalables à la présentation d'une demande de permis à la Direction générale du transport des marchandises dangereuses de Transports Canada. Car jamais, jusqu'ici, des bouteilles en fibre de carbone n'avaient été utilisées dans des applications de transport.

Le projet comportait les tâches suivantes : consultations avec Transports Canada concernant les permis exigés; construction par Powertech Labs d'une remorque porte-tubes de démonstration équipée de bouteilles légères fabriquées par Dynetek pour le transport d'hydrogène comprimé; essais de validation du concept de bouteille Dynetek, menés conformément aux exigences de Transports Canada. Ces essais comprenaient la variation cyclique d'une charge hydraulique dans des conditions de température ambiante et de températures extrêmes, des essais d'éclatement, des essais à la flamme vive et des essais de tir sur des bouteilles sous pression. Une demande de permis de niveau équivalent de sécurité a été déposée auprès de Transports Canada en vue de l'utilisation de la bouteille en fibre de carbone Dynetek pour le transport d'hydrogène comprimé et de gaz naturel comprimé utilisés comme carburants.

17. Mots clés Bouteille légère, bouteille renforcée de fibre de carbone, Dynetek, hydrogène comprimé, gaz naturel utilisé comme carburant	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

19. Classification de sécurité (de cette publication)	20. Classification de sécurité (de cette page)	21. Déclassification (date)	22. Nombre de pages	23. Prix
Non classifiée	Non classifiée	—	x, 14, ann.	Port et manutention

CDT/TDC 79-005
Rev. 96

Canada

ACKNOWLEDGEMENT

The patience and support of Roy Nishizaki from the Transportation Development Centre of Transport Canada is gratefully acknowledged.

EXECUTIVE SUMMARY

Advanced lightweight cylinder designs using carbon fibre composite reinforcement have been developed by Dynetek Industries for the high-pressure storage of compressed gases. These designs are currently used on board vehicles for the storage of compressed hydrogen and compressed natural gas as engine fuel. However, these cylinder designs are not yet used for the large-scale transportation of compressed gas fuel, a commodity that is currently only transported in heavy steel tube trailer units of limited capacity.

Transport Dangerous Goods regulations enforced by Transport Canada do not cover the use of carbon fibre-reinforced cylinder designs for transportation purposes; however, Transport Canada has recently issued a Permit for Equivalent Level of Safety to several cylinder manufacturers to use carbon fibre cylinders primarily in air breathing (i.e. class 2.2 dangerous goods) applications. The Dynetek design (model V260) to be used for the transportation of flammable fuel gases is significantly larger that the carbon fibre designs that were granted permits by Transport Canada. In addition, it is intended for the Dynetek design to be used for carrying class 2.1 (flammable) dangerous goods.

To demonstrate the safety of using relatively large carbon fibre cylinders to transport compressed hydrogen fuel, Powertech Labs constructed a small trailer unit using Dynetek cylinders. This unit was used in the U.S. under local approvals to refuel hydrogen vehicles. Powertech also reviewed the performance of Dynetek cylinders used in compressed hydrogen service elsewhere. This information is being used to support the introduction of carbon fibre cylinder designs into relevant Canadian Standards Association (CSA) standards.

Powertech performed design qualification testing of the Dynetek model V260 cylinder design according to Transport Canada requirements. These tests included hydraulic pressure cycling under extreme temperature conditions, bursting, bonfire exposure and gunfire testing. To obtain a permit for equivalent safety from Transport Canada, Dynetek Industries has prepared a design submission using the data provided by Powertech. The design submission addresses how the Dynetek design deviates from the standards requirements and how an equivalent level of safety is maintained. To eliminate the future need for Transport Canada permits of equivalent safety, Powertech has formed a CSA working group to adopt carbon fibre cylinder designs into relevant CSA standards.

SOMMAIRE

Dynetek Industries a mis au point un modèle perfectionné de bouteille légère, renforcée de fibre de carbone pour le stockage haute pression de gaz comprimés. Ces bouteilles sont présentement utilisées à bord des véhicules pour le stockage de carburants gazeux comprimés (hydrogène et gaz naturel). Mais elles ne sont pas encore utilisées pour le transport en grand volume de gaz comprimé. À ce jour, seules des remorques porte-tubes en acier lourd de capacité limitée servent à cette fin.

Le Règlement sur le transport des marchandises dangereuses appliqué par Transports Canada est muet sur l'utilisation de bouteilles renforcées de fibre de carbone à des fins de transport; mais Transports Canada a récemment délivré un permis de niveau équivalent de sécurité à plusieurs fabricants pour que des bouteilles en fibre de carbone puissent servir au stockage d'air comprimé (marchandises dangereuses incluses dans la classe 2.2, Gaz ininflammables). Or, la bouteille de Dynetek (modèle V260) qui servira au transport de carburants gazeux inflammables est beaucoup plus grosse que les bouteilles en fibre de carbone pour lesquelles Transports Canada a délivré des permis. De plus, la bouteille de Dynetek est conçue pour le transport de marchandises dangereuses incluses dans la classe 2.1 (Gaz inflammables).

Pour démontrer qu'il n'est pas dangereux d'utiliser des bouteilles en fibre de carbone relativement grosses pour transporter de l'hydrogène comprimé, Powertech Labs a construit une petite remorque porte-tubes équipée des bouteilles de Dynetek. Cette remorque a été utilisée aux États-Unis, conformément à des approbations locales, pour le ravitaillement de véhicules mus à l'hydrogène. Powertech a également examiné les performances de bouteilles Dynetek utilisées pour le stockage d'hydrogène comprimé dans d'autres applications que le transport. Ces données sont présentement utilisées pour appuyer l'intégration des bouteilles en fibre de carbone au champ d'application des normes pertinentes de l'Association canadienne de normalisation (CSA).

Powertech a réalisé les essais de validation du concept du modèle de bouteille V260 de Dynetek, conformément aux exigences de Transports Canada. Ces essais comprenaient la variation cyclique d'une charge hydraulique dans des conditions de température ambiante et de températures extrêmes, des essais d'éclatement, l'exposition à une flamme vive et des essais de tir sur des bouteilles sous pression. Dans le but d'obtenir un permis de niveau équivalent de sécurité de Transports Canada, Dynetek Industries a préparé un dossier sur son modèle de bouteille V260, en s'appuyant sur les données fournies par Powertech. Le fabricant explique comment, même si sa bouteille ne répond pas aux normes, elle répond quand même au niveau équivalent de sécurité. Pour éviter que Transports Canada ait à étudier d'autres permis de niveau équivalent de sécurité dans l'avenir, Powertech a formé un groupe de travail avec la CSA pour l'intégration des bouteilles en fibre de carbone au champ d'application des normes pertinentes de la CSA.

CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

1.1 Background

Increasing interest in the use of hydrogen fuel cell vehicles and natural gas vehicles has resulted in the need to develop a large-scale road transport system for supplying vehicle filling stations with compressed hydrogen and natural gas fuels. Transport Canada regulations for the transportation of dangerous goods currently limits existing compressed gas tube trailer transport designs to the use of steel tubes of thick-walled construction. The road weight (and restricted storage capacity) of steel tube trailers severely limits the economics of transporting compressed gas. In addition, in some areas there are seasonal weight restrictions on roads that prevent the use of heavy steel tube trailers.

The introduction of pressure vessels manufactured using high-strength carbon fibre reinforcement provides an attractive alternative to steel pressure vessels. In addition to providing a significant reduction in the weight-to-volume ratio, carbon fibre also allows significantly higher storage pressures to be used. Because of the high strength of carbon fibre, the wall thickness of these lightweight pressure vessels is significantly less than steel cylinders and thus a greater amount of gas can be stored for a given external volume.

Several tens of thousands of carbon fibre high-pressure compressed gas fuel storage cylinders have been used on board vehicles since 1992. This successful application of lightweight cylinders in road service indicates that this new technology could be safely used as lightweight container units to carry relatively large volumes of compressed gas fuel. For this to come into practice, it is necessary to obtain approval of the carbon fibre design from the Transport Dangerous Directorate of Transport Canada.

The concept of using composite-reinforced cylinders for the large-scale transportation of compressed gas was recently introduced in Germany. Mannesmann Cylinder Systems received approval from the Technischer Ueberwachungsverein (the German safety and standards institution) for cylinder trailers composed of steel cylinder liners hoop-wrapped with Kevlar composite reinforcement. These road trailers are currently being used in Germany for the transportation of compressed hydrogen.

1.2 Dynetek Industries

Dynetek Industries Ltd. of Calgary, Alberta is a world leader in the design and manufacture of lightweight carbon fibre-reinforced cylinders. Dynetek supplies most automotive manufacturers worldwide with compressed gas fuel storage cylinders for natural gas vehicles and prototype hydrogen fuel cell vehicles. The Dynetek design comprises a thin aluminum alloy liner that is fully wrapped with carbon fibre reinforcement. Dynetek manufactures cylinders up to 3 m long, up to 610 mm in diameter, and with water capacities up to 350 L.

Dynetek cylinder designs are registered in Canada under the Canadian Standards Association (CSA) B51 standard for compressed natural gas use. The CSA B51 standard covers the requirements for cylinders used for compressed natural gas service on board vehicles and for stationary ground storage. Dynetek designs are also registered in British Columbia for compressed hydrogen service, using the CSA B51 standard as a reference.

1.3 Regulatory Requirements

The transportation of compressed gases not used on board a vehicle as an engine fuel is covered by Transport Dangerous Goods regulations. The Transport Dangerous Goods Directorate of Transport Canada is responsible for enforcing regulations covering compressed gases that may be transported across provincial borders.

The requirements for transporting compressed gases are described in the CSA B340 standard "Selection and Use of Cylinders, Spheres, Tubes, and Other Containers for the Transportation of Dangerous Goods, Class 2". The design specifications for the pressure vessels listed in CSA B340 are detailed in the CSA B339 standard "Cylinders, Spheres, and Tubes for the Transportation of Dangerous Goods".

While the CSA B339 standard includes specifications for composite-reinforced cylinder designs, these composites are limited to the use of glass fibres. CSA B339 has no provision for cylinder designs that use carbon fibre reinforcement simply because this is a relatively new material compared to fibreglass. The TC-3FCM cylinder specification in the CSA B339 standard most closely describes the Dynetek design, except that the specification only allows for glass fibre composite reinforcement, not carbon fibre. In addition, the TC-3FCM specification has the following limits:

- Clause 9.1.1 specifies a maximum water capacity of 91 L, and a service pressure up to 34.5 MPa.
- Clause 4.2.6 specifies that TC-3FCM composite containers shall be used only for gases in Classification 2.2, or compressed natural gas.

Despite the absence of carbon fibre specifications in the CSA B339 standard, the Transport Dangerous Goods Directorate may issue permits for an equivalent level of safety. This requires the applicant to demonstrate - using drawings, plans, calculations, procedures, and test results - how the proposed manner of transport will "ensure a level of safety at least equivalent to that achieved by complying with the Regulations". The following manufacturers have received from Transport Canada a Permit for Equivalent Level of Safety for their carbon fibre cylinder designs in general accordance with the TC-3FCM specification:

- Structural Composites Industries for transporting Class 2.2 (inert) gases.

- Luxfer Gas Cylinders for transporting Class 2.2 (inert) gases.

However, an application by Dynetek Industries to Transport Canada for a Permit for Equivalent Level of Safety for a carbon fibre-reinforced cylinder design must also consider the following additional restrictions in the CSA B340 standard for transporting compressed hydrogen:

- Clause 5.2.1 specifies that compressed hydrogen can only be filled in certain cylinder designs of either steel or aluminum construction.
- Clause 5.2.2.2 specifies that compressed hydrogen can only be filled in tubes of certain steel designs.
- Clause 4.6.2 specifies that cylinders of composite construction can only be used to transport classification 2.2 (non-flammable) gases or compressed natural gas - this classification prevents the use of TC-3FCM specification cylinder designs for compressed hydrogen transportation.

It is therefore necessary to demonstrate the safety of using large-volume carbon fibre-reinforced cylinder designs for the transportation of compressed hydrogen and natural gas fuels.

2.0 APPROACH

Dynetek has been funded under a separate contract through Natural Resources Canada to construct a trailer unit for the transportation of compressed natural gas fuel. This trailer unit would then be used as the basis for demonstrating the safety of using lightweight cylinder designs for the transportation of compressed fuel gases. Each of the three separate container units mounted on the trailer will be composed of 39 large-volume lightweight cylinders of 230 bar working pressure (see Figure 1). Each model V260 lightweight cylinder will have a water volume of 260 L, and will measure 381 mm in diameter by 2,800 mm in length. The completed trailer with the three container units will consist of a total of 117 cylinders, providing a storage capacity of 30,420 L (water volume).

For this project, Powertech was to perform the necessary design work on the trailer to ensure compliance with the regulatory requirements for a Transport Canada permit; however, delays in initiating the Natural Resources Canada contract has caused the trailer unit construction at Dynetek to be significantly behind the schedule of this project. As a result, a lightweight trailer design was constructed at Powertech using Dynetek cylinders for the transportation of compressed hydrogen. The trailer is being used to provide service experience with carbon fibre-reinforced cylinders for the transportation of compressed gas fuels.

Powertech efforts in this project focused on supporting the development of a design submission by Dynetek to Transport Canada for a permit to use the carbon fibre reinforced cylinder designs. This support was provided in the following activities:

- Consultation with regulatory authorities regarding the requirements for demonstrating that carbon fibre designs could provide a level of safety equivalent to cylinder designs already specified in standards.
- Working with the Canadian Standards Association to update existing standards regarding the use of carbon fibre cylinders.
- Testing the condition of Dynetek cylinders that have been used in compressed hydrogen service for several years.
- Collecting experience operating the Powertech lightweight trailer unit for the transportation of compressed hydrogen.
- Performing design qualification testing of the Dynetek V260 design to the CSA B339 TC-3FCM specification for Transport Canada.

Figure 1 Completed Dynetek container unit for Natural Resources Canada

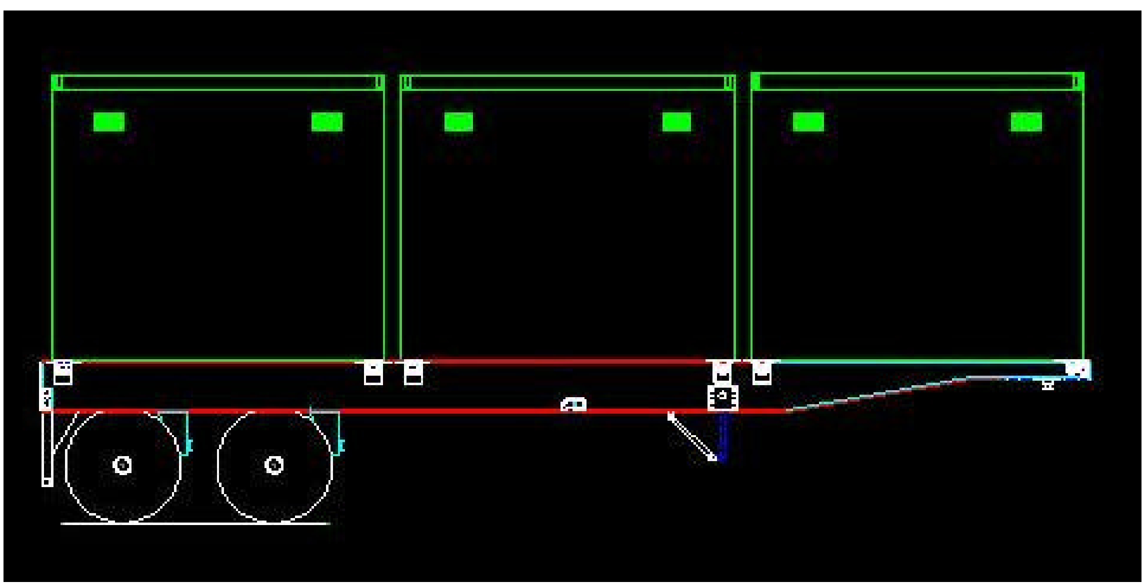

Figure 2 Schematic of three Dynetek container units mounted on a trailer

3.0 WORK PROGRAM

3.1 Information Gathering

Discussions were held with Transport Canada personnel to determine the requirements for the approval of lightweight carbon fibre cylinder designs for transportation uses.

Transport Canada Transport Dangerous Goods personnel stated that if the Dynetek design application duplicated the design requirements of previous carbon fibre cylinder design applications by other manufacturers, such as SCI and Luxfer, that had received a Permit for Equivalent Level of Safety, then there would be no problem in Dynetek also receiving approval. However, if the design varied from designs that had been previously provided with a Permit, then an argument would have to be presented to justify why the design differences would still provide an equivalent level of safety. The typical timing for approval is three to four months, provided the application duplicates the requirements of previous applicants who have already received permits [1].

Discussions were also held with Transport Canada Transport Dangerous Goods personnel regarding permissible deviations in the design qualification test requirements listed in the TC-3FCM specification in the CSA B339 standard for the Dynetek design. These deviations were necessary due to the fact that the Dynetek design exceeded the size limits for the TC-3FCM specification, thus changing several test parameters. It was determined that changes in the test procedures could be accepted, provided that a rationale was provided to explain how an equivalent level of safety was achieved by the changes [1].

Transport Canada Transport Dangerous Goods advised that to expedite approval, it would be preferable to issue a permit rather than wait for the CSA standards to be changed and then recognized by Transport Canada regulations. It was also advised that the carbon fibre design type should be introduced to the relevant CSA committee at the same time to initiate inclusion into the CSA B339 standard, thus removing any future requirement to apply for a permit to approve a carbon fibre cylinder design [2].

The Transport Canada Road Safety Directorate said that while Transport Dangerous Goods is responsible for enforcing hazardous materials regulations, it was the responsibility of this group to ensure the road safety and the load rating of the trailer unit [3].

Following the advice of Transport Canada, contact was established with the CSA and Powertech became a member of the CSA B339/340 standards group. A CSA B339/340 meeting in Toronto in March 2001 was attended by Powertech. At that meeting, a CSA Working Group was formed, with Powertech as the Chair, to consider the introduction of carbon fibre cylinder designs into the standard.

3.2 Technical Support on Detailed Design

Initially, efforts concentrated on developing a trailer structure for supporting the Dynetek cylinders that would provide equivalent safety to existing steel tube trailer designs. Clause 4.5 of the CSA B340-00 standard has several specific requirements for steel tube trailer designs. Because of their wall thickness and strength, steel tubes are typically installed in an exposed position on transport trailers. For the lightweight container trailer design, it was proposed that multiple cylinders be manifolded together within a protective frame or container. This container module could then be placed in an enclosed transport trailer unit for transportation. The protective framework, combined with the transport trailer covering, would provide the necessary protection from collision damage.

Upon careful review of the CSA B340-00 standard, however, it was determined that the definition of a "tube" was a container with a water capacity greater than 450 L. A "cylinder" is defined as having a water capacity of less than 450 L. The Dynetek cylinders have a water capacity of 260 L. As a result, the specific requirements under clause 4.5 for tubes attached to trailers would not apply to Dynetek, since it has cylinders and not tubes. Instead, it is believed that the Dynetek design would fall under clause 4.4 for "Manifolded Containers". The only structural requirement for manifolded containers is for the cylinders to be "….supported and held together as a unit by structurally adequate means". There are also the following additional requirements for manifolded containers of compressed gas:

- Valves and pressure relief devices (PRDs) must be protected from impact.
- Each container shall be equipped with a PRD.
- PRDs on horizontal cylinders filled with Class 2.1 (flammable) gas shall vent upwards.
- Each cylinder shall have a shut-off valve.

In accordance with the above requirements for a manifolded container unit, a demonstration trailer was constructed at Powertech Labs using internal funding. It consisted of a manifolded container of 16 Dynetek model W292 carbon fibre cylinders mounted in a protective structural framework of steel. The manifolded container was then mounted on a trailer to make it transportable (see Figure 3). The unit was designed for the transportation of compressed hydrogen at 250 bar. To date, it has only been used in the United States under local approvals for fuel hydrogen vehicles involved in a rally from Los Angeles to Las Vegas (see Figure 4).

One of the purposes of the trailer unit was to demonstrate that carbon fibre cylinder designs could be safely used to transport compressed hydrogen. The trailer unit also demonstrated that significant quantities of compressed gas fuel could be transported in a lightweight package that could be towed by a light-duty vehicle. The trailer can carry 82 kg of hydrogen with a trailer weight of just over 4,000 kg. This compares favourably to a steel tube trailer unit that has 10 times the road weight and only 3 times the hydrogen capacity.

Figure 3 Support framework for transportable container unit of Dynetek cylinders

Figure 4 Complete transportable container unit being used to refuel a fuel cell vehicle

3.3 Permit to Use Dynetek Cylinder Design for Compressed Hydrogen

Currently, the CSA B340-00 standard does not allow the use of type TC-3FCM cylinder designs to carry hydrogen. Type TC-3FCM designs are, however, allowed to carry natural gas, which is a flammable gas with very similar properties to hydrogen. It is therefore necessary to get the CSA B340 standard to recognize that type TC-3FCM designs can also be used to safely transport compressed hydrogen.

The CSA Working Group formed by Powertech to address the issues involving the introduction of carbon fibre cylinder designs into the CSA B339/B340 standards will also address the issue of using TC-3FCM specification designs to transport compressed hydrogen.

While changes to the standards are being pursued, Dynetek has prepared a design application to Transport Canada for a Permit for Equivalent Level of Safety to use the carbon fibre reinforced cylinder design for the transportation of compressed hydrogen and compressed natural gas fuels.

3.4 Performance of Tests

Discussions with Transport Canada indicated that the Dynetek cylinder design, and not the entire trailer unit, would require a permit from Transport Canada. As a result, the performance tests portion of this project focused on the qualification testing of the Dynetek cylinder design in accordance with the CSA B339 standard for a TC-3FCM specification design. All design qualification tests were performed at Powertech Labs and observed by an authorized inspector from Arrowhead Inspection representing Transport Canada.

Originally, the proposal was to perform design qualification tests on a Dynetek model W292 cylinder design. However, the Dynetek trailer design was changed to meet Natural Resources Canada specifications and the cylinder design was changed to a model V260. The following tests were therefore conducted on the V260 model per clause 9.2 of the CSA B339 standard:

- Ambient temperature cycling test of two cylinders per clause 9.13.3(a).
- Environmental cycling test of two cylinders per clause 9.13.3(b).
- Burst test of two cylinders per clause 9.13.4.
- Gunfire test of one cylinder per clause 9.13.5.
- Bonfire test of two cylinders per clause 9.13.6.

The test reports are included in Appendix A.

3.5 Permit to Operate in Canada

Dynetek is in the process of preparing an application to the Transport Dangerous Goods Directorate of Transport Canada for a permit to use the Dynetek design under the TC-3FCM specification for transporting compressed hydrogen and compressed natural gas. The application requires an explanation for deviations from the CSA B339 and B340 standard, including:

- Use of the design for transporting compressed hydrogen.
- Use of carbon fibre composite reinforcement.
- Design exceeding 91 L limit.
- The fact that bonfire testing could not be performed in the vertical position due to the length of the oversize design.

The application will include a description of the successful use of the Dynetek design in compressed hydrogen and compressed natural gas service, and the use of the Powertech demonstration trailer for fuelling hydrogen vehicles.

4.0 CONCLUSION

The operation of the Powertech lightweight trailer unit, the review of cylinders removed from compressed hydrogen service, and the performance of thousands of Dynetek cylinders in compressed natural gas vehicle service worldwide have demonstrated that the Dynetek carbon fibre-reinforced cylinder design is suited for the transportation of compressed fuel gas. This conclusion is further reinforced by the fact that the Dynetek design successfully completed design qualification testing in general accordance with the requirements for a TC-3FCM specification design in the CSA B339 standard.

5.0 RECOMMENDATION

The development of compressed gas fuel types should be promoted by supporting the updating of standards to recognize advances in technologies that improve the economics of using alternative fuels.

REFERENCES

1. Discussions with Amy Park, Senior Specialist – Cylinders, Transport Dangerous Goods, Transport Canada

2. Discussion with Doug Dibble, Chief – Research and Governmental Activities, Transport Dangerous Goods, Transport Canada

3. Discussion with Dan Davis, Chief – Standards and Regulations, Road Safety Directorate, Transport Canada

APPENDIX A

CSA B339 TEST REPORTS

**(*not available in electronic format/
pas disponible en format électronique*)**

APPENDIX B

DYNETEK CONTAINER UNIT
STRUCTURAL ANALYSIS

General Hydrogen

Mechanical Engineering Investigation Report

Number: 02-03
Subject: FE Analysis of Mobile Hydrogen Storage System Frame
Author: Matthew Harper
Project: Customer Projects: Hydrogen Storage
Date: June 28, 2002

1. Objective

To determine whether the MHSS frame (GH Part # 001638) is strong enough to sustain impact loads.

2. Methodology

First, the production Pro/Engineer model was modified to ensure continuity between parts, and to simplify the model so as to reduce analysis time. This assembly was then imported into DesignSpace FE Analysis software. The results were captured as .jpg images showing the more highly-stressed areas; those images are presented below. Three separate load cases were analyzed: Front and side impacts, and vertical load. The masses of the cylinders and frame were the only applied loads. Then, the stresses induced in the structure were evaluated to make sure they did not exceed the safety factor specified by DOT standards (see §3).

3. Assumptions and Data Sources

Requirements for the strength of structures in gas transportation systems are outlined in US DOT Hazardous Materials Regulations and Procedures Codes. Chapter 1, Subchapter C, Part 178.255-11 states that frames for transportable tanks shall "be designed with a safety factor of four, and built to withstand loadings in either direction of two times the weight of the tanks and attachments", or an effective safety factor of 8 on a 1-g load.

4. Results

The results of the analysis are shown in Figures 1 through 6, below. It is important to note that, when quantifying the maximum stresses in a particular member, it is necessary to discount localized stress concentrations found in some of the sharp corners. The magnitude of these concentrations is exaggerated by the FE model for two reasons. First, in the actual model, there are thick weld beads holding the member together. These have the effect of distributing the load, but are difficult to model quantitatively. Second, the stress concentrations are higher due to the linear behaviour of the finite element solver. In a real part, the material would deform and thus spread the load over a greater area. Linear FEA, however, does not take account of changes in part geometry, and thus the force-distributing characteristic of these deformations are not taken into account.

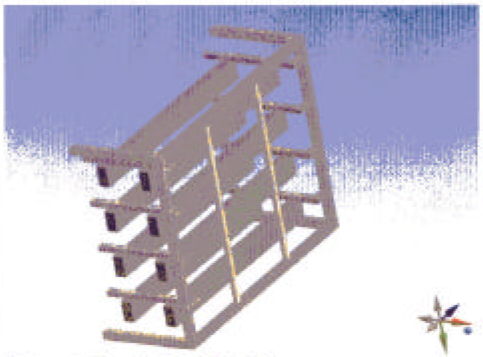

Figure 1: Meshed FE Model

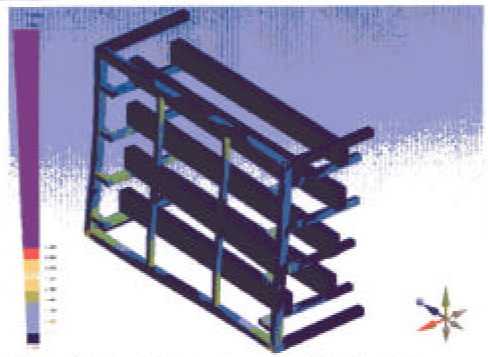

Figure 2: Model showing von-Mises stresses

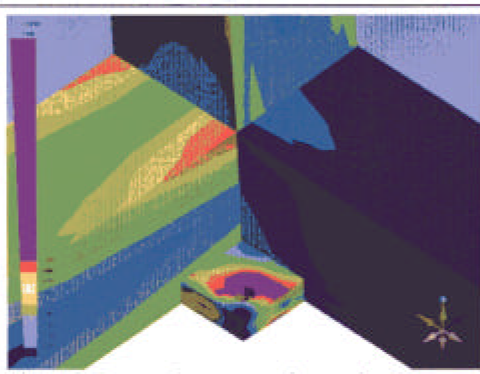

Figure 3: Stresses in corner and mounting lug

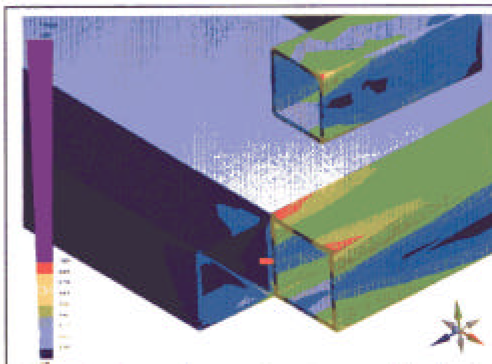

Figure 4: Corner beams w/ post removed for clarity

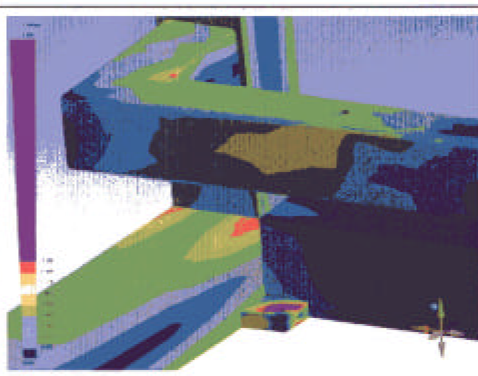

Figure 5: Stress concentrations

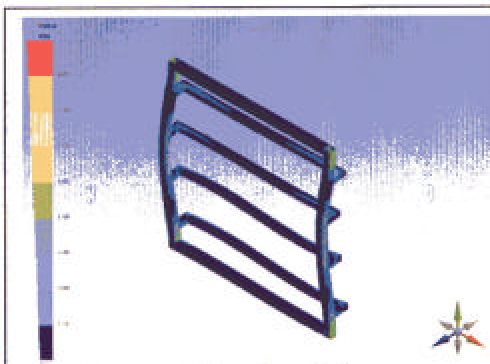

Figure 6: Stresses induced by side impact.

4. Results (Continued)

The models showed that the highest stresses on the structure were for the front impact case, with moderate stresses in the side impact and vertical load cases. Graphical representations of these results are shown in figures 1-5. Maximum combined (von-Mises) stresses were found to be in the region of 8 kpsi, neglecting local stress concentrations as noted above. The maximum horizontal deflection at the top of the assembly for the applied 1-g load was 0.165". Stresses for the side impact case (figure 6) were approximately 2 kpsi (again neglecting localized stress concentrations). As these figures are all more than a factor of 8 smaller than the material's ultimate tensile strength (80 kpsi for 304L stainless steel), it can be concluded that the frame is strong enough for the intended application.

The stresses in the mounting lugs were found to be quite high. However, the lug is being compressed against one of the main support members, which makes a failure unlikely. Also, the model does not account for the distributing effect that the bolt pre-load will have on transferring reaction forces. Thus, yielding of the lug is not seen as a likely failure mode.

5. Conclusion

It has been concluded that the structure is sound, and meets the DOT specification for support frames for transportable tanks.

6. References

All relevant documents have been stored in the following directory:
G:\Technical Development\Technical Library\Mechanical Engineering Investigation Reports\Supporting Documents

- 001638 Front Impact.dsdb
- 001638 Side and Vertical Impact.dsdb
- 001638 side impact detail.jpg
- 001638 corner post removed.jpg
- 001638 corners and lugs.jpg
- 001638 corners.jpg
- 001638 mesh.jpg
- 001638 overall stress.jpg