Conformable Tank for Compressed Natural Gas (CNG) Program
Final Report
1 Aug 02

Submitted to fulfill Reporting Requirements of Part III, Section J, of Contract No. DE-AC02-99CH10981

Prepared By:

Mr. Andrew C. Haaland
Program Manager
Thiokol Propulsion

Submitted To:

Dr. Jim Wegrzyn
Deputy, Energy Science Technology Division
Department of Applied Science
Brookhaven National Laboratory
Building 815
Upton, New York 11973-5000

And

Ms. Patrice Brewington
U.S. Department of Energy
Chicago Operations Office
Environmental Programs Group
9800 South Cass Avenue
Argonne, Il 60439

DOE Patent Clearance Granted
M P Dvorscak 2·19·03
Mark P. Dvorscak Date
(630) 252-2393
E-mail mark.dvorscak@ch.doe.gov
Office of Intellectual Property Law
DOE Chicago Operations Office

ATK
ALLIANT TECHSYSTEMS

THIOKOL PROPULSION
P.O. Box 0707, Brigham City, Utah 84302-0707

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1.0 Introduction

Thiokol Propulsion has been successfully involved with the design, development, and fabrication of storage tanks for alternative fuel vehicles. Brookhaven National Laboratory (BNL) has supported much of this effort relating to compressed natural gas (CNG) conformable storage tanks by providing funding and technical oversight for Thiokol's activities. Past efforts have led to the successful completion of design, fabrication, and risk reduction testing of a two-cell conformable tank for storage of CNG at a nominal pressure of 3,600 psi. Thiokol Propulsion has completed additional development and testing of the CNG tanks using funding under contract DE-AC02-99CH10981BNL. The intent of this effort is to further develop and certify the two-cell CNG tank for use in commercial vehicles. Certification will be in accordance with the accepted industry NGV2-2000 (ANSI/IAS NGV2-2000) standard, and will allow Thiokol to pursue efforts that will lead to successful commercialization of the two-cell tank for use in CNG fueled vehicles.

As part of a previous contract with BNL, a total of six tanks were built and subjected to selected NGV2 tests to assess the feasibility of obtaining NGV2 certification of the baseline CNG tank design. The tests that were conducted were selected on the basis of being the most difficult to pass. Of the six NGV2 tests that were conducted by an independent testing company, Powertech, the tanks passed five tests. Table 1.1 includes a summary of the test matrix and obtained results. Thiokol conducted the burst tests and the result reported is the average of tests conducted on three separate tanks. The test that was not successfully completed was the drop test.

Table 1.1. Risk Reduction NGV-2 Testing of CNG Conformable Tank

NGV-2 Test	Success Criteria	NGV-2 Test Result
Burst Test	8,100 psig minimum	8,980 psig average
Ambient Cycle Test	15,000 cycles to 4,500 psig	1st Tank: 60,126 cycles 2nd Tank: 37,082 cycles
Hot Cycle Test	3,760 cycles to 4,500 psig	Testing stopped after 12,107 cycles
Cold Cycle Test	3,760 cycles to 2,880 psig	Testing stopped after 12,193 cycles
Flaw Tolerance	15,000 cycles to 4,500 psig	53,975 cycles
Drop	15,000 cycles at ambient temperature after six foot drop	Tank dropped six times. Survived nine cycles

This document has been prepared to satisfy the final reporting requirement defined in Part III, Section J, of Contract No. DE-AC02-99CH10981. The primary objective of this document is to provide a complete summary of activities conducted by Thiokol to complete items outlined in the contract statement of work (SOW). The two major tasks to be completed were additional tank testing and a market survey of heavy duty CNG vehicles.

2.0 Summary of Tank Testing

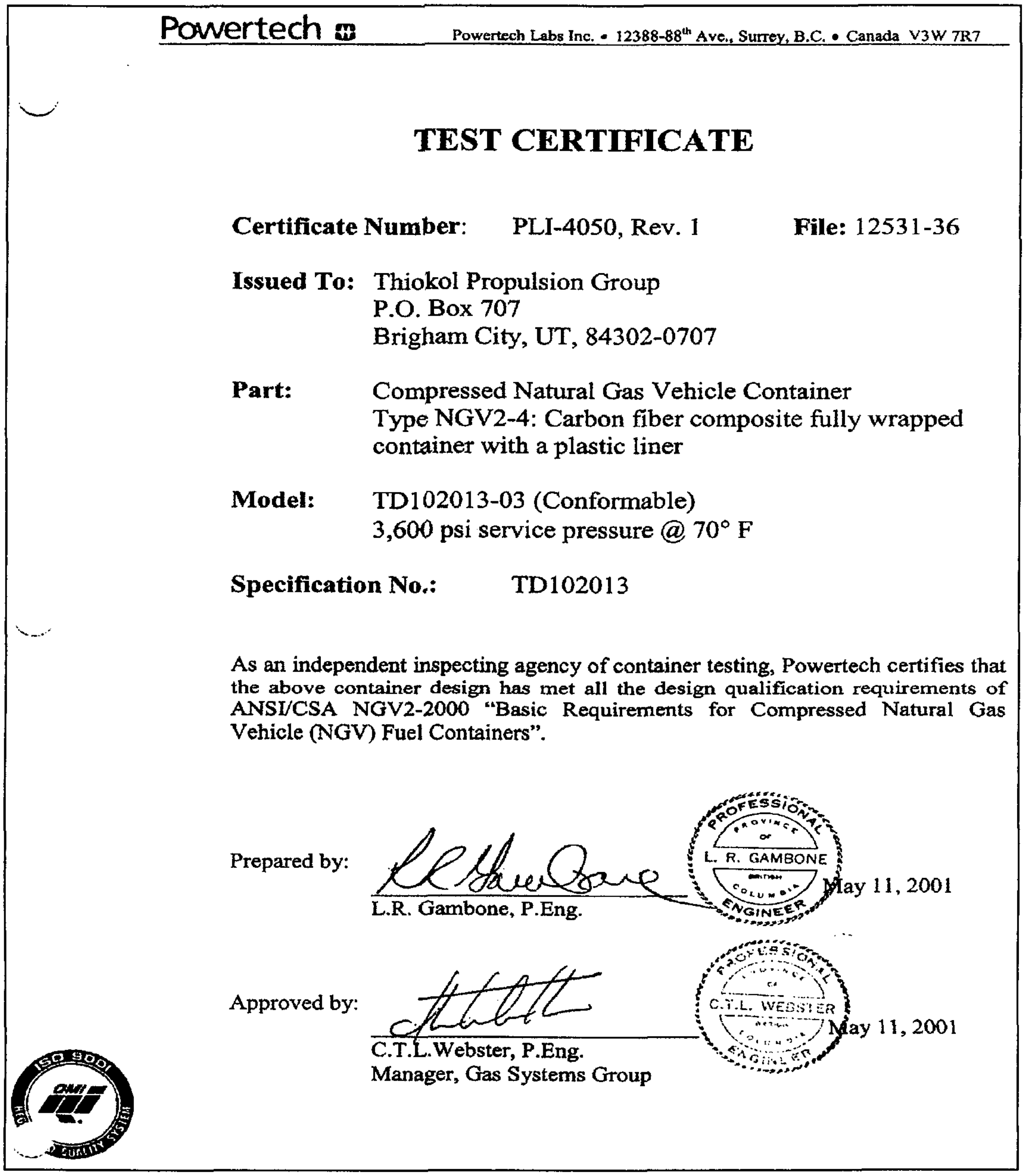
Tank testing activities have been directed towards completion of the remaining NGV2-certification tests. All tanks used for additional testing were fabricated at Thiokol Propulsion using contract funding. In addition to the remaining NGV2-2000 tests, an additional bonfire test was conducted at 25 % of the tank maximum service pressure to also satisfy the requirements of federal motor vehicle safety standard (FMVSS) 304. Certification to the FMVSS304 standard is required by the U.S. Department of Transportation (DOT) prior to allowing the tanks to be used in vehicles that travel on public roadways. A copy of the Thiokol Propulsion internal report that documents all FMVSS304 testing and compliance issues is presented in Appendix 1. All of the tests contained in the FMVSS304 specification are very similar to the expanded number of tests contained in the NGV2-2000 standard with the exception of the additional bonfire test at 25 % service pressure. NGV2-2000 paragraph 18.8.5 (b) indicates that a bonfire test at 25 % of service pressure is "not required if a thermally activated device is used." This statement for not requiring a test at 25 % of service pressure if a thermally activated pressure relief device is used is not included in the FMVSS304 standard. In accordance with the contract SOW, all tank testing has been completed to satisfy the requirements of both standards. A summary of all test results is shown in Table 2.1 below, while all test certifications are presented in Appendix 2:

Table 2.1. CNG Tank Testing Summary

Test	Criteria for Successful Test	Result
Burst	Safety Factor 2.25 x 3,600 psig = 8,100 psig	Pass
Ambient Cycle	15,000 cycles without failure: 45,000 cycles without rupture to 1.25 safety factor x 3,600 psig = 4,500 psig	Pass
Environmental Cycling	Subject to fluid exposure, pendulum impact, gravel impact, high low, ambient temperature cycling, burst above 6,480 psig	Pass
Flaw Tolerance	Machined flaws followed by cycling (15,000 cycles to 4,500 psig)	Pass
Drop	A total of 6 drops from a height of 6 feet followed by ambient cycling of 15,000 cycles to 4,500 psig	Pass
Penetration	Bullet penetration of tank pressurized to 3,600 psig with CNG. Tank must not fragment	Pass
Permeation	Specified maximum leak rate for CNG of 0.25 scc/hr/l	Pass. Leak Rate = 0.015 scc/hr/l.
Bonfire	Must safely vent at 100 % of service pressure (3,600 psig) Must safely vent at 25 % of service pressure (900 psig)	Pass Pass
CNG Cycling	1,000 cycles with CNG to 3,600 psig, followed by leak test and	Pass

Test	Criteria for Successful Test	Result
	destructive inspection	
Accelerated Stress Rupture	Tank pressurized to 4,500 psig and held at pressure for 1,000 hours at 149 F. At conclusion, tank must burst above 6,075 psig	Pass

At the conclusion of this testing, Thiokol Propulsion had Powertech Labs complete an independent review of all test data to determine if all testing criteria of the NGV2-2000 specification had been satisfied. As a result of this review, Powertech Labs determined that the tank did meet all test criteria and issued a certificate of compliance shown in Figure 2.1 below;



Powertech Powertech Labs Inc. • 12388-88th Ave., Surrey, B.C. • Canada V3W 7R7

TEST CERTIFICATE

Certificate Number: PLI-4050, Rev. 1 **File:** 12531-36

Issued To: Thiokol Propulsion Group
P.O. Box 707
Brigham City, UT, 84302-0707

Part: Compressed Natural Gas Vehicle Container
Type NGV2-4: Carbon fiber composite fully wrapped container with a plastic liner

Model: TD102013-03 (Conformable)
3,600 psi service pressure @ 70° F

Specification No.: TD102013

As an independent inspecting agency of container testing, Powertech certifies that the above container design has met all the design qualification requirements of ANSI/CSA NGV2-2000 "Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers".

Prepared by: L. R. GAMBONE May 11, 2001
L.R. Gambone, P.Eng.

Approved by: C.T.L. WEBSTER May 11, 2001
C.T.L.Webster, P.Eng.
Manager, Gas Systems Group

Figure 2.1. Certificate of Compliance Issued by Powertech Labs for Conformable Tank

A formal process has also been initiated to complete the necessary administrative requirements of the NGV2-2000 standard. This process is being supported using Thiokol discretionary funding. Activities that are a part of this process include completion of a manufacturing plan, a quality plan, and formal documentation of all completed test activities. Once these activities have been completed, the entire package of certification data will be subjected to Thiokol's technical review board (TRB), which will complete an independent, formal review of all certification issues. Once all concerns of the TRB have been addressed, Thiokol will certify that the tanks meet all criteria established by the NGV2-2000 specification. Work on the manufacturing plan and quality plan is progressing as expected and will result in a formal, documented method for tank fabrication, tank proof testing, and record retention.

As part of the review of the test specifications and test results obtained to date, Thiokol engineers have discovered the need to resolve three additional technical issues. These issues include UV exposure testing of the exterior of a completed CNG conformable tank, resolution of a liner softening issue, and the method that Thiokol has used to determine the volumetric expansion of the tank during hydro proof testing. Resolution of all of these technical issues is being pursued in conjunction with the Natural Gas Vehicle Coalition (NGVC), of which Thiokol is a member.

3.0 Market Study for Heavy Duty CNG Vehicles

3.1 Introduction

A market study was performed to support additional tank development and to determine the commercial potential of conformable tanks for heavy-duty vehicles. Heavy-duty vehicles were defined as class 3-8 trucks, with each truck class defined by a specific range of gross vehicle weight. Table 3.1.1 below summarizes the weight ranges and gives examples of vehicles in each class;

Table 3.1.1. Gross Vehicle Weight Ranges

Vehicle Class	Gross Vehicle Weight Range, Lbs	Vehicle Example
1	0-6,000	***Class 1-3:*** Minivans, Utility Van, Multi Purpose, Pick-ups, Mini Bus, Step Van
2	6,001-10,000	
3	10,001-14,000	
4	14,001-16,000	***Class 4-6:*** City Delivery, Large Walk-in, Bucket, Landscaping
5	16,001-19,500	
6	19,501-26,000	
7	26,001-33,000	***Class 7-8:*** Refuse, Tow Trucks, Refrigerated, Dump Trucks, Furniture, Fuel, Fire Engine,
8	33,001-150,000	

Gross vehicle weight (GVW) is the maximum allowable fully laden weight of a vehicle and its payload.

CNG vehicles in the class 3-8 range were chosen as the focus of a market study for several reasons. These reasons are listed below;

1.) Class 3-8 vehicles primary rely on diesel power for their operation and because of this configuration will have a difficult time meeting the EPA standards for emissions that will take effect in calendar years 2004 and 2007.
2.) The use of CNG fuel in class 3-8 vehicles in conjunction with existing technologies allows class 3-8 vehicles to meet proposed EPA requirements.
3.) Approximately 14 million vehicles from these classes are currently on the road performing critical functions such as mass transportation and material delivery. It is estimated that heavy duty trucks transport as much as 80 % of the total quantity of goods in the United States.[1] These vehicles are projected to increase their fuel usage by 25 % in the years 2000-2010 according to the 21st Century Truck Initiative.
4.) Of all of the alternative fuel technologies, CNG is the most mature and has the most infrastructure available for fleet and personal vehicle use. The U.S. Energy Information Administration (EIA) estimates that approximately 21,000 heavy duty natural gas vehicles were in operation in the U.S. in calendar year 2000.
5.) As with all alternative fuels, CNG vehicle range when compared to traditional fuels is an issue. CNG has less BTU storage on a per gallon equivalent basis than either gasoline or diesel fuel, making the use of a more volumetrically efficient storage technology such a conformable tanks attractive.
6.) The capacity for CNG tank manufacturing is not currently sufficient to meet projected demand for heavy-duty vehicles on a world wide basis.

To address the reasons for conducting a market study of CNG tanks, the following topics will be addressed in subsequent sections of this document; status of the CNG tank manufacturing capability, summary of EPA regulations affecting the heavy duty vehicle market, market forces affecting heavy-duty CNG vehicles, and opportunities for heavy duty vehicle CNG storage using conformable tanks.

3.2 CNG Tank Manufacturing Capabilities

CNG tanks are made world wide by a small number of niche firms that sell their products to OEM and aftermarket conversion firms. Four types of tanks are manufactured and are more specifically defined in the NGV2-2000 specification. The four tank types are shown below in Table 3.2.1.

Table 3.2.1. CNG Tank Types

Tank Type	Description
I	All metal fabrication
II	Structural metal liner with composite hoop overwraps

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[1] Bradley, Ron et.al. "Technology Roadmap for the 21st Century Truck Program, A Govenrment-Industry Research Partnership," Oak Ridge National Laboratory. 21CT-001 December 2000

Tank Type	Description
III	Thin metal liner with structural composite overwrap
IV	Non metallic liner with structural composite overwrap

Estimated production volume for calendar year 2001 of the major tank manufacturers was obtained from interviews with marketing managers, from company brochures, and from electronic sources specific to each firm. Only estimated data was available because this information is held as competitive and strategic information by industry firms. This data is shown in Table 3.2.2 and represented graphically Figure 3.2.1 below;

Table 3.2.2. Estimated World Wide CNG Tank Production for CY 2001

Tank Producer	Annual Volume	Market Share	Principal Product	Location
Lincoln Composites	14,000	14%	Type IV	USA
Ullit	6,000	6%	Type IV	France
SCI	4,000	4%	Type II, III	USA
Dynetek	4,500	5%	Type III	Canada
Faber	30,000	30%	Type I, II	
InFlex	20,000	20%	Type I	
Luxfer	1,000	1%	Type I	
Others	20,000	20%	Type I,II,III	
Quantum	500	1%	Type IV	USA
Totals	**100,000**	100%		

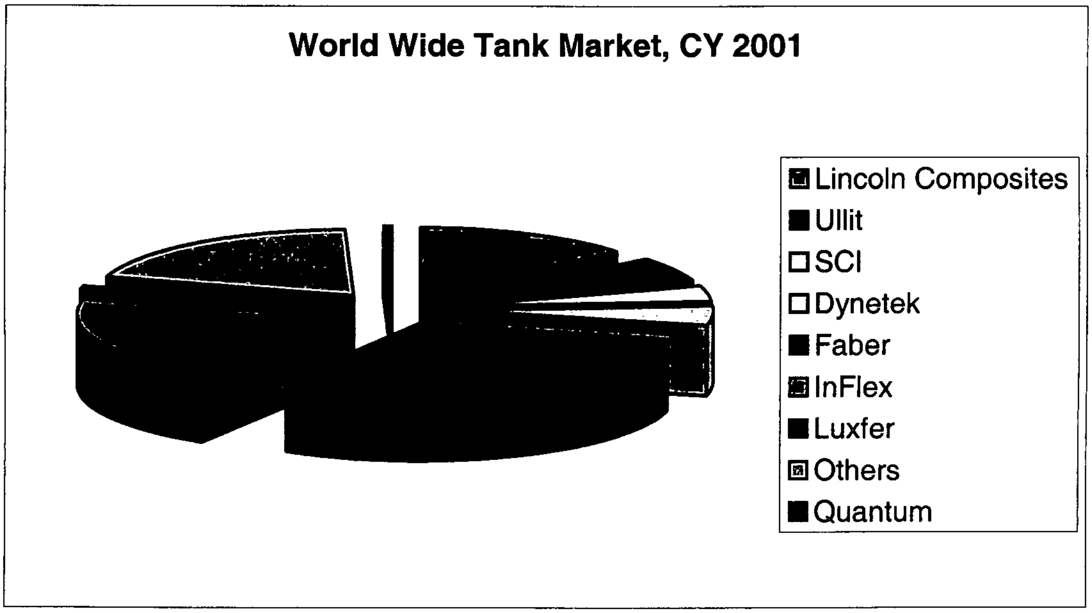


Figure 3.2.1. Estimated Word Wide Tank Market, CY 2001

The firms shown in Table 3.2.2 and Figure 3.2.1 are not expected to increase dramatically in the next few years. The two primary reasons for this are the high costs associated with entering the market create a significant barrier to entry, and the overall demand for CNG vehicles is not expected to increase at a rate that will require significant additional manufacturing capability in the next few years. Table 3.2.3 below summarizes some of the costs that create the high entry barrier for firms looking to enter the CNG tank business. It is important that the design and certification costs are on a per tank basis.

Table 3.2.3. Costs Associated with Entering the CNG Tank Business

Investment Category	Cost		Lead Time	Justification
Development	**$200,000**			
Design		$125,000	3 Months	Actuals from BNL Contract
Initial Fabrication and Testing		$75,000	3 Months	Actuals from BNL Contract
Certification	**$95,000**			
Tank Fabrication		$20,000	2 Months	Actuals from BNL Contract
Testing at Independent Lab		$75,000	4 Months	Actuals from BNL Contract
Facilities & Tooling				
Production Tooling	**$75,000**			
Liner Molds		$25,000	2 Months	Vendor Quote
Winding Tooling		$25,000	2 Months	Estimate
Curing Tooling		$25,000	3 Months	Estimate
Facilities	**$850,000**			
Winding Machines		$500,000	6 Months	Estimate
Curing Ovens		$100,000	6 Months	Estimate
Hydroproof Testing		$125,000	6 Months	Teaming Partner Experience
PermeationTesting		$125,000	6 Months	Teaming Partner Experience
Additional Activities	**$170,000**			
MRP & Quality		$85,000	6 Months	Thiokol Actuals
Training		$85,000	6 Months	Thiokol Actuals
Total		**$1,390,000**		

3.3 Regulations Affecting Heavy Duty CNG Vehicles

Emissions from heavy-duty vehicles are regulated at both the federal and state level. The primary regulatory agency at the federal level is the U.S. Environmental Protection Agency (EPA), while local air quality boards do most regulation at the state level.

The primary federal legislation that allows the EPA to regulate air quality is the U.S. Clean Air Act. The Clean Air Act attempts to governing bodies to maintain a basic level of air quality that allows for minimal environmental and public health impacts.

The EPA sets clean air standards for threshold concentrations of key pollutants called National Ambient Air Quality Standards (NAAQS). These standards attempt to set maximum levels of six key pollutants as measured in parts per million per volume of air.

The key pollutants that are regulated by these standards are carbon monoxide, nitrogen dioxide, ozone, lead, particulate matter with a diameter of 10 microns or less as well as particulate matter with a diameter of 2.5 microns or less, and sulfur dioxide. Under the Clean Air Act, each state must provide the EPA with a State Implementation Plan that outlines what actions will be taken to improve air quality in areas that do not meet the NAAQS. The Federal Government attempts to force states to meet the NAAQS for all measured areas through the treat of loss of federal highway funds or the treat of requirements for air quality that exceed the NAAQS for specific areas.

The EPA used its power to enact challenging air quality emissions standards for heavy duty vehicles that must be met incrementally in 2004 and 2007 (Code of Federal Regulations (CFR) 40 part 86). The standards set for 2004 are generally thought to be attainable by the heavy duty vehicle community, but no clear roadmap has been shown that gives confidence that the industry will meet the increased 2007 emissions standards. This challenge is one of the major drivers that will force the heavy duty vehicle industry to consider and implement engines and fuel management systems that utilize CNG.

3.3 Market Forces Affecting Heavy-Duty CNG Vehicles

Several firms currently manufacture diesel engines that use CNG as a fuel. A list of these manufacturers and their products are shown in Table 3.3.1 below;

Table 3.3.1. CNG Heavy Duty Engines

Manufacturer	Engine Type
Caterpillar	3126;C-10;C-12
Cummins	B5.9;C8.3
Deere Power Systems	6.8L;8.1L
Detroit Diesel	50G ;60G
Mack	E7G
AFT	N466 Navistar
Crusader	4.3L;7.0L

These engines are used in heavy duty vehicles manufactured by Athey, Crane Carrier, Elgin, Freightliner, Mack, Peterbilt, Ottawa, SISU, and Volvo. These vehicles are designed to accomplish both on and off road activities such as construction, freight hauling, and industrial manufacturing. In addition to these vehicles, Table 3.3.2 shows the manufacturers of Busses that use CNG fuel systems;

Table 3.3.2. Bus Manufacturers Offering CNG Vehicles

Bus Type	Manufacturers
Transit Busses	Orios, Neoplan, El Dorado, North American Bus, New Flyer, NOVA, TransTeq
School Busses	Blue Bird, Thomas Built

Bus Type	Manufacturers
Shuttles	El Dorado, Blue Bird, Champion, Goshen, Metrotrans, North American, Transit, Orion

In addition to offering solutions to heavy duty vehicle use that address regulatory issues, manufacturers of CNG heavy duty vehicles tend to focus on high fuel use fleets located primarily in urban markets. These fleets are not limited to busses, and include refuse trucks, delivery trucks, sweepers, and other industrial vehicles used in manufacturing. The high fuel use of these fleets shortens the payback period associated with CNG capital expenditures, leads to reduced vehicle wear and maintenance costs, and allows fleet operators to realize fuel cost savings due to the lower cost of CNG vs. gas when compared on a BTU equivalent basis.

Currently there are 21,000 medium and heavy duty CNG fueled vehicles on US roads and approximately 1,600 fueling sites according to the Natural Gas Vehicle Coalition.

3.4 Opportunities for Heavy-Duty CNG Conformable Tanks

Conformable CNG tanks are suited for use in heavy duty vehicles. Use of conformable tanks would significantly increase the range of the vehicle due to the increased fuel storage. While the exact amount of increase in fuel range is difficult to quantify, Figure 3.4.1 shows the calculated increase in volume that may be obtained through the use of conformable tanks;

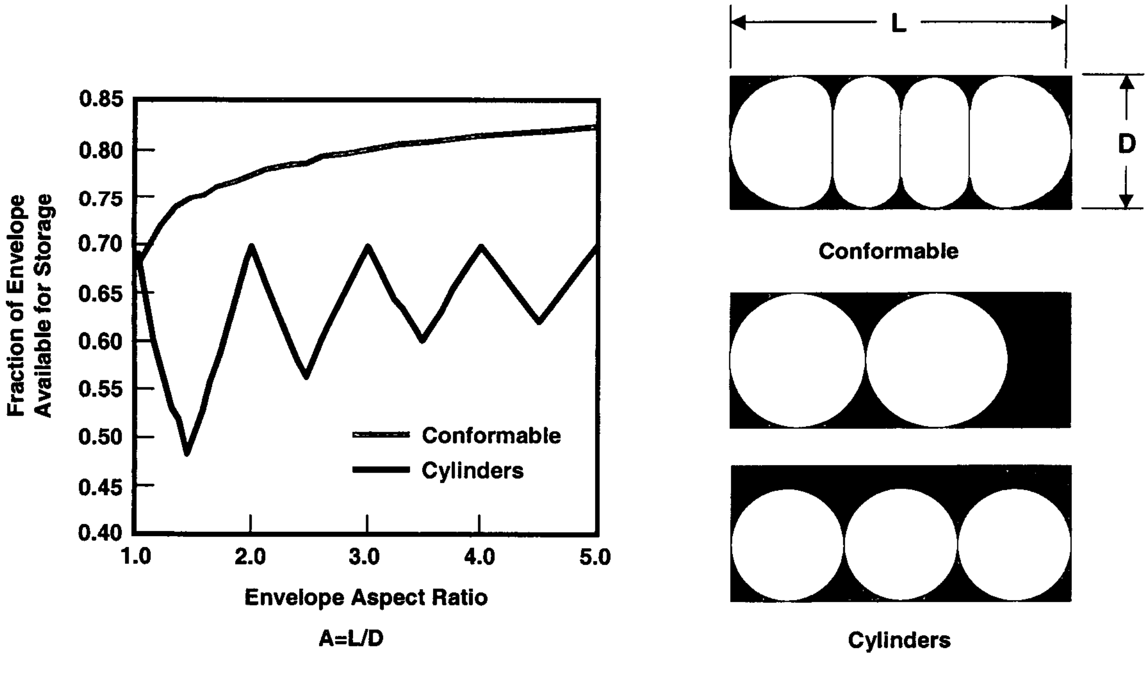


Figure 3.4.1. Increase Fuel Storage Allowed by Conformable Tanks

To investigate the application of conformable tanks to heavy duty CNG vehicles, Thiokol did complete several designs for use in hauling applications. The results of this effort are shown below;

Table 3.4.1. Tank Designs for Heavy Duty Vehicles Operating at 3,600 PSIG

	Envelope (without fittings or valves)	Number of Cells	**Weight**		**Internal Volume**		**Equivalent Capacity**		
			lbs	kg	in^3	Liter	SCF	Gasoline	Diesel
12" - M30S	12.5 X 20.7 X 27	2	60	27	4,150	68	710	5.7	5.1
12" - T700	12.6 X 20.8 X 27	2	65	29	4,150	68	710	5.7	5.1
	12.6 X 29.1 X 27	3	93	42	5,800	95	990	8.0	7.2
18" - T700	17.3 X 29.4 X 46.5	2	167	76	14,680	241	2,510	20	18
	17.3 X 41.6 X 46.5	3	242	110	20,830	341	3,570	29	26
24" - T700	24.1 X 40 X 76	2	456	207	47,340	776	8,100	65	59
	24.1 X 55.9 X 76	3	657	298	66,600	1,091	11,400	92	83
	24.1 X 71.8 X 76	4	858	389	85,860	1,407	14,700	118	106

Table 3.4.2 Tank Designs for Heavy Duty Vehicles Operating at 5,000 PSIG

	Envelope	Number of Cells	**Weight**		**Internal Volume**		**Capacity CH_2**	
			lbs	kg	in3	Liter	Lbs	kg
12" - M30S	12.68 X 21.04 X 27	2	71	32	4,150	68	3.5	1.6
12" - T700	12.8 X 21.25 X 27.	2	78	35	4,150	68	3.5	1.6
	12.8 X 29.71 X 27.	3	112	51	5,800	95	4.9	2.2
18" - T700	17.6 X 30.02 X 46.5	2	212	96	14,680	241	12.4	5.6
	17.6 X 42.45 X 46.5	3	306	139	20,830	341	17.5	8.0

The viability of these tank designs was explored though a review with representatives from Questar Gas. Questar is a regional supplier of CNG and has been involved in the initial conversion of heavy duty diesel trucks to CNG. These trucks have an equivalent fuel capacity of 40-60 gallons of diesel. The installation completed by Questar and an independent conversion house is shown in figure 3.4.3 below;

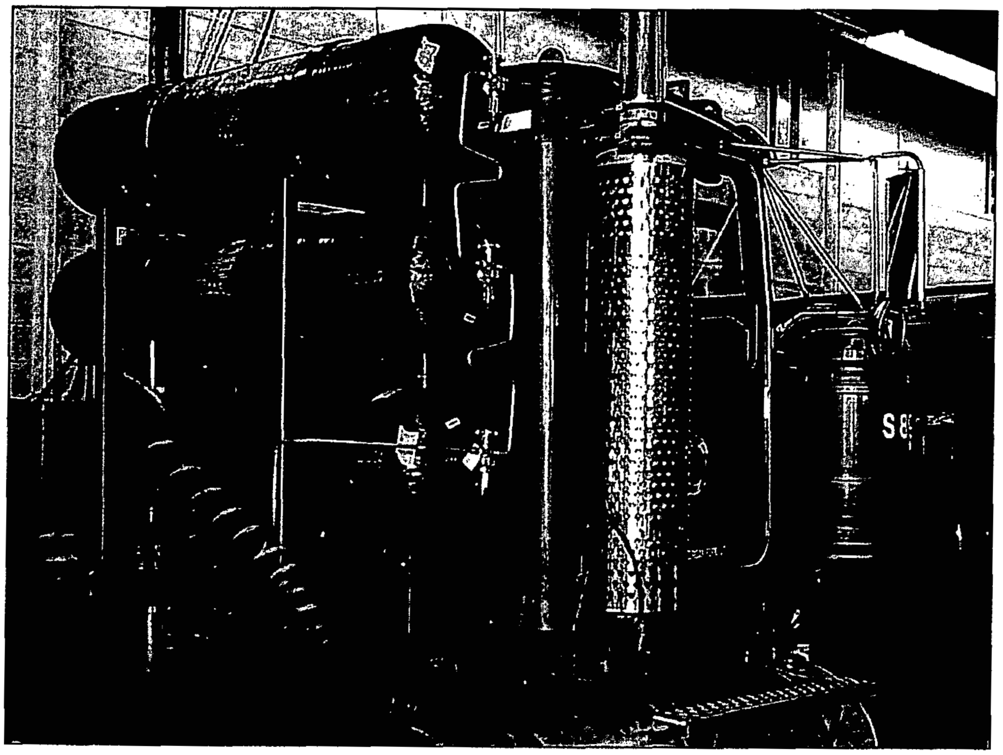
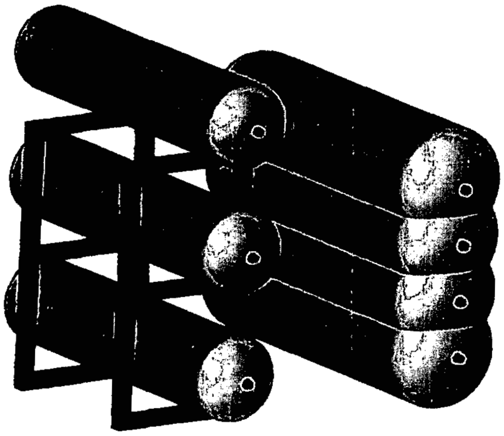


Figure 3.4.3. CNG Conversion of Heavy Duty Vehicle Using CNG Cylinders

Based on data supplied by Questar, a tank design was completed for this specific application. This design is shown in Figure 3.4.4 below;



Envelope	Number of Cells	Tank Configuration	Weight		Internal Volume		Fuel Capacity		Engineering Estimate of Production Tank Costs*		
			lbs	kg	in^3	Liter	SCF	Diesel (US gal)		Cost per SCF	Cost per Diesel
24.1 X 40.0 X 78 612mm X 1,016mm X 1,981mm	2		465	212	48,760	800	8,350	60	$10,500	$1.26	$175
24.1 X 55.9 X 78 612mm X 1,420mm X 1,981mm	3		675	306	68,610	1,125	11,740	85	$14,750	$1.26	$174
24.1 X 71.8 X 78 612mm X 1,824mm X 1,981mm	4		880	400	88,450	1,450	15,140	110	$19,000	$1.25	$173

*Projected cost numbers after development and substantial orders.

Figure 3.4.4. Conformable CNG Tank Designs for Questar Application

The specific tank proposed for the Questar application is the three cell tank described kin Figure 3.4.4. The cost estimates for storage of CNG at 3,600 psig and cost per diesel gallon BTU equivalent storage were based on tank production volumes of 10,000 per year. The primary obstacle to production of this tank is the high cost of tank certification as well as the lack of a market for 10,000 tanks/year.

4.0 Conclusions

1.0) Thiokol did complete the certification of the 65 liter conformable CNG tank to both the FMVSS304 and NGV2-2000 standards.

2.0) The market for heavy duty CNG vehicles is largely driven by federal and state regulations in the US.

3.0) The market has not reached a level of maturity that would support the high volumes of conformable tank manufacturing necessary to offset the costs of certifying the tank and establishing initial production.

Appendix 1: FMVSS304 Testing Summary

DOC NO.: TR12515 VOL: REV: N/C

TITLE: Qualification of CNG Conformable Tanks to FMVSS 304 Requirements

12 APRIL 2001

Prepared by:

Original signed by George Berkley

G. A. Berkley
Ballistics/Insulation

Original signed by David J. Son

D. J. Son
Case Design/Analysis

Approved by:

Original signed by C. Paul Pulver

C. P. Pulver, Supervisor
Case Design/Analysis

Original signed by A. C. Haaland

A. C. Haaland, Program Manager
Technical Programs

Original signed by David K. Dorius

D. K. Dorius
DLV Quality Engineering

Released by:

Original signed and released by J. F. Jensen 2 May 2001

Data Management:

ALCOA Thiokol Propulsion

P. O. Box 707 Brigham City, UT 84302-0707 (435) 863-3511

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INTRODUCTION

This report details the requirements contained in the Code of Federal Regulations, Title 49, Part 571—Federal Motor Vehicle Safety Standards (FMVSS), Standard No. 304—Compressed Natural Gas Fuel Container Integrity.

FMVSS 304 was revised on October 1, 2000. An amendment was issued to this revision on October 24, 2000. This standard identifies four separate requirements that a fuel container must meet in order to be considered acceptable for use on motor vehicles in the USA when filled with compressed natural gas (CNG). Those requirements are (1) pressure cycle testing, (2) hydrostatic burst testing, (3) bonfire testing, and (4) container marking.

According to the marking requirement in S7.4 (d) "The symbol DOT, constituting a certification by the CNG container manufacturer that the container complies with all requirements of this standard."

It is the intent of this document to summarize the testing that shows that the container design shown on drawing TD102013-03, "Tank, 12-inch High, 2-cell, 3,600 psi", has successfully passed the testing required by FMVSS 304 as amended on October 24, 2000. This container configuration is now considered to be DOT qualified and approved for usage in the USA when properly marked according to the requirements of S7.4.

CONFIGURATION

The container configuration that was tested is shown in Figure A1-1. This tank configuration was protected against handling damage by the addition of foam protection dome caps as shown in Figure 2. For the bonfire test, a manual valve and pressure relief device (PRD) were added. The valve that was used on the bonfire test was GFI Control Systems, Inc, valve model T1-100, which is rated for 3,600 psig, with a temperature rating of –40 C (-40 F) to 125 C (257 F). The pressure relief device was a GFI PRD P1750-30W, rated for 3,600 psig, which is a CGA CG9 device rated for 217 F. The same valve and PRD designs are required for all tanks that are used with the "DOT" label based on the testing documented in this report.

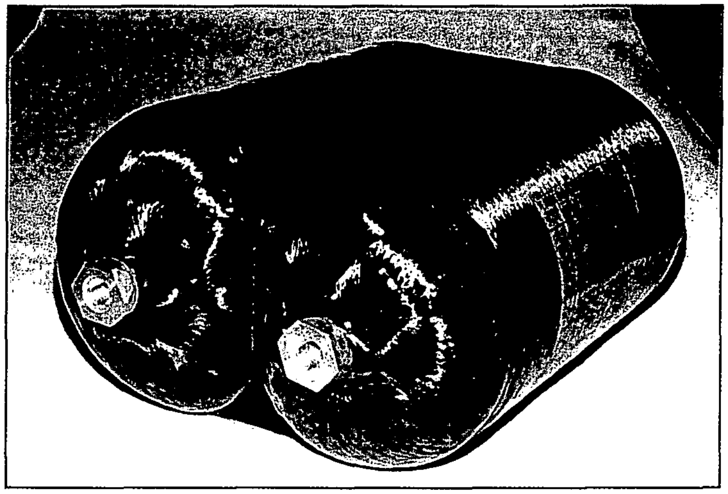

Figure A1-1: Conformable Two-cell Tank

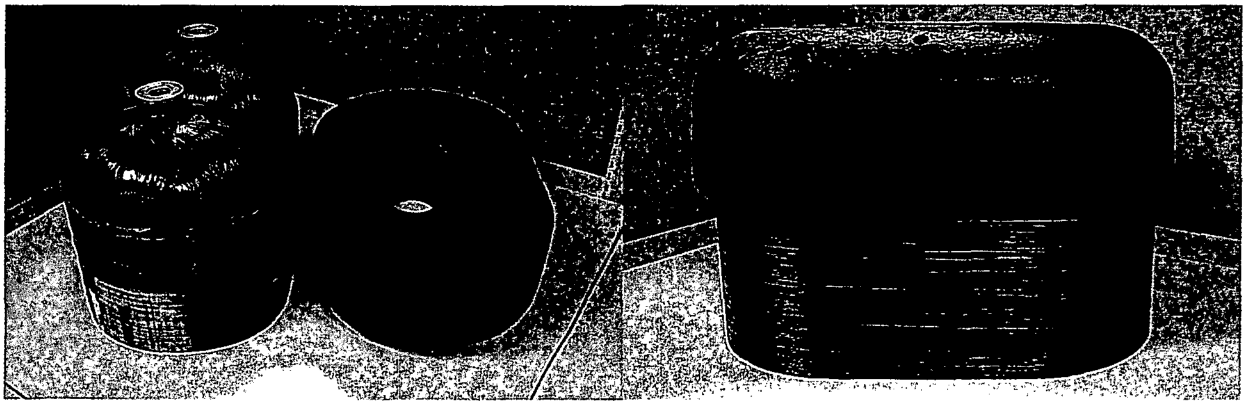

Figure A1-1: Pre-fabricated Dome Cap

Tests

The following table shows compliance of this fuel storage tank design to all of the requirements of FMVSS 304. It is a summary of the requirements of FMVSS 304 along with the testing that has been conducted to demonstrate compliance to those requirements. Testing was conducted by an independent testing facility, Powertech Gas Systems Engineering, referred to hereafter as "Powertech". Appendix A contains Powertech's test reports. Table I shows that this container configuration meets all testing requirements and is qualified to be marked with "DOT", per section S7.4 (d) of FMVSS 304.

Table I. Requirements and Compliance

FMVSS 304 Requirements (Revised Oct 1, 2000, and amendment issued Oct 24, 2000)	METHOD OF VERIFICATION	COMPLIANCE AND/OR JUSTIFICATION
S1. Scope. This standard specifies requirements for the integrity of compressed natural gas (CNG), motor vehicle fuel containers.	None.	Yes. General note.
S2. Purpose. The purpose of this standard is to reduce deaths and injuries occurring from fires that result from fuel leakage during and after motor vehicle crashes.	None.	Yes. General note.
S3. Application. This standard applies to each passenger car, multipurpose passenger vehicle, truck, and bus that uses CNG as a motor fuel and to each container designed to store CNG as motor fuel on-board any motor vehicle.	Examination of intended use.	Yes. The requirements of this standard apply to this tank design since it is intended that this tank design will be used for CNG fuel storage on motor vehicles.
S4. Definitions….	None.	Yes. General information.
S5. Container and material requirements. S5.1.4 Type 4—Composite non-metallic full wrapped container means resin impregnated continuous filament with a non-metallic liner "full wrapped."	Examination of design.	Yes. The tank design includes an inner plastic liner that is fully wrapped with resin impregnated continuous carbon fibers.
S6 General requirements. S6.1 Each passenger car, multipurpose passenger vehicle, truck, and bus that uses CNG as a motor fuel shall be equipped with a CNG fuel container that meets the requirements of S7 through S7.4. S6.2 Each CNG fuel container manufactured on or after March 27, 1995 shall meet the requirements of S7 through S7.4.	Examination of all test results.	Yes. See S7 and S8 sections below. All tanks of this design will be manufactured after March 27, 1995.
S7 Test requirements. Each CNG fuel container shall meet the applicable requirements of S7 through S7.4.	Examination of test reports.	Yes. See S7 and S8 sections below.
S7.1 Pressure cycling test at ambient temperature. Each CNG fuel container shall not leak when tested in accordance with S8.1.	Examination of test report.	Yes. See S8.1 below.
S7.2 Hydrostatic burst test. S7.2.1 Each Type 1 CNG ….	Examination of test report.	Yes. See S8.2 below.

FMVSS 304 Requirements (Revised Oct 1, 2000, and amendment issued Oct 24, 2000)	**METHOD OF VERIFICATION**	**COMPLIANCE AND/OR JUSTIFICATION**
S7.2.2 Each … Type 4 CNG fuel container shall not leak when subjected to burst pressure and tested in accordance with S8.2. Burst pressure shall be not less than 2.25 times the service pressure.		
S7.3 Bonfire test. Each CNG fuel container shall be equipped with a pressure relief device. Each CNG fuel container shall completely vent its contents through a pressure relief device or shall not burst while retaining its entire contents when tested in accordance with S8.3.	Examination of tests and drawings.	Yes. See S8.3 below. Each tank that is used for storage of CNG in a motor vehicle will be equipped with a PRD of the same design as used in the bonfire tests.
S7.4 Labeling. Each CNG fuel container shall be permanently labeled with the information specified in paragraphs (a) through (h) of this section. Any label affixed to the container in compliance with this section shall remain in place and be legible for the manufacturer's recommended service life of the container. The information shall be in English and in letters and numbers that are at least 6.35 mm (\1/4\inch) high. (a) The statement: "If there is a question about the proper use, installation, or maintenance of this container, contact ________________," inserting the CNG fuel container manufacturer's name, address, and telephone number. (b) The statement: "Manufactured in ___________," inserting the month and year of manufacture of the CNG fuel container. (c) The statement: "Service pressure ________ kPa, (______ psig)." (d) The symbol DOT, constituting a certification by the CNG container manufacturer that the container complies with all requirements of this standard. (e) The container designation (e.g., Type 1, 2, 3, 4). (f) The statement: "CNG Only." (g) The statement: "This container should be visually inspected after a motor vehicle accident or fire and at least every 36 months or 36,000 miles, whichever comes first, for damage and deterioration. (h) The statement: "Do Not Use After ______" inserting the month and year that mark the end of the manufacturer's recommended service life for the container.	Examination of drawings.	Yes. The specification requires the following labeling information that will be permanently applied to each tank that will be used for storage of CNG in a motor vehicle. All letters and numbers will be at least ¼ inch high. "If there is a question about the proper use, installation, or maintenance of this container, contact Thiokol Propulsion, P. O. Box 707, Brigham City, UT 84302-0707, (435) 863-3511. Manufactured in Month Year. Service pressure 24,800 kPa, (3,600 psig). DOT Type 4 CNG Only. This container should be visually inspected after a motor vehicle accident or fire and at least every 36 months or 36,000 miles, whichever comes first, for damage

FMVSS 304 Requirements (Revised Oct 1, 2000, and amendment issued Oct 24, 2000)	**METHOD OF VERIFICATION**	**COMPLIANCE AND/OR JUSTIFICATION**
Note: for tanks that are designed and tested according to the requirements of The Natural Gas Vehicle Coalition, the following additional information is required by standard ANSI/CSA NGV2-2000. "NGV2-xx" (where "xx" denotes the year of this standard to which the container is designed) The manufacturer's part number, and batch number or serial number. The statement "For Use Only With The Container Manufacturer's Approved Pressure Relief Devices and Valves".		and deterioration. Do Not Use After MM YYYY" The following marking is required by NGV2-1998 and NGV2-2000 specifications and will also be part of the label information on each tank once considered qualified. "NGV2-xx Part number Serial number For Use Only With The Container Manufacturer's Approved Pressure Relief Devices and Valves". Note: the appropriate months, years, part numbers, and serial numbers of the tank will be inserted on each label.
S8.1 Pressure cycling test. The requirements of S7.1 shall be met under the conditions of S8.1.1 through S8.1.4. S8.1.1 Hydrostatically pressurize the CNG container to the service pressure, then to not more than 10 percent of the service pressure, for 13,000 cycles. S8.1.2 After being pressurized as specified in S8.1.1, hydrostatically pressurize the CNG container to 125 percent of the service pressure, then to not more than 10 percent of the service pressure, for 5,000 cycles. S8.1.3 The cycling rate for S8.1.1 and S8.1.2 shall be any value up to and	Tests.	Yes. The requirement is to pressure cycle at ambient temperature from not more than 360 psi to 3,600 psi for 13,000 cycles, then from not more than 360 psi to 4,500 psi (3,600 X 1.25) for 5,000 cycles at not more than 10 cycles per minute. Powertech conducted a more severe test per NGV2-1998, Clause 18.3 Ambient Temperature Cycling

FMVSS 304 Requirements (Revised Oct 1, 2000, and amendment issued Oct 24, 2000)	METHOD OF VERIFICATION	COMPLIANCE AND/OR JUSTIFICATION
including 10 cycles per minute. S8.1.4 The cycling is conducted at ambient temperature.		Test. Two tanks, TD102013 SN 5 and 8, were cycle tested from not more than 300 psi to not less than 4,500 psi (greater than 1.25 times service pressure) for 45,000 cycles without any leakage. The testing was conducted at ambient temperature and the cycling rate was between 4 to 5 cycles per minute.
S8.2 Hydrostatic burst test. The requirements of S7.2 shall be met under the conditions of S8.2.1 through S8.2.2. S8.2.1 Hydrostatically pressurize the CNG fuel container, as follows: The pressure is increased up to the minimum prescribed burst pressure determined in S7.2.1 or S7.2.2, and held constant at the minimum burst pressure for 10 seconds.	Tests.	Yes. For a service pressure of 3,600 psi, and a safety factor of 2.25, the minimum burst pressure is 8,100 psi. Powertech conducted more severe hydrostatic burst tests per NGV2-1998, Clause 18.5 Hydrostatic Burst Test. Two tanks, TD102013 SN 4 and 5, were tested. Tank SN 4 burst at 11,330 psi and tank SN 5 was pressurized to 9,380 psi before a leak occurred at the closed end fitting. The Powertech report states that each tank was pressurized at a rate of 100 psi per second. A hold for 10 seconds at the

FMVSS 304 Requirements (Revised Oct 1, 2000, and amendment issued Oct 24, 2000)	**METHOD OF VERIFICATION**	**COMPLIANCE AND/OR JUSTIFICATION**
		minimum burst pressure was not performed. However, with a minimum burst or leak occurring at 1,280 psi above the minimum acceptable burst level, the tanks were above the minimum burst pressure for at least 12 seconds. Most tanks of this design fail at a pressure of about 11,000 psi, which would require about 29 seconds after reaching the minimum burst pressure of 8,100 psi.
S8.2.2 The pressurization rate throughout the test shall be any value up to and including 1,379 kPa (200 psi) per second.		The pressurization rate for the hydroburst testing at Powertech is shown in Figure 3. This figure includes pressure-time traces of the actual data for tank TD102013 SN 5, as well as other similar Thiokol tanks that have been tested at Powertech. Also included in the figure are two lines which depict a slope for a pressurization rate of 200 psi/second (10,000 psi/50 seconds). The maximum pressurization rates for the testing at Powertech at the lower pressures are close to the limit of 200 psi/second maximum. Between 10,000 and 12,000 psi, the pressurization rates, as shown in

FMVSS 304 Requirements (Revised Oct 1, 2000, and amendment issued Oct 24, 2000)	METHOD OF VERIFICATION	COMPLIANCE AND/OR JUSTIFICATION
		Figure 3, are less than 100 psi/second.
S8.3 Bonfire test. The requirements of S7.3 shall be met under the conditions of S8.3.1 through S8.3.7. S8.3.1 Fill the CNG fuel container with compressed natural gas and test it at: (1) 100 percent of service pressure; and (b) 25 percent of service pressure. S8.3.2 Container positioning. (a) Position the CNG fuel container in accordance with (b) and (c) of S8.3.2. (b) Position the CNG fuel container so that its longitudinal axis is horizontal and its bottom is 100 mm (4 inches) above the fire source. (c) (1) Position a CNG fuel container that is 1.65 meters (65 inches) in length or less and is fitted with one pressure relief device so that the center of the container is over the center of the fire source. (2) Position a CNG fuel container that is greater than 1.65 meters (65 inches)…. (3) Position a CNG fuel container that is fitted with pressure relief devices at more than one location…. (4) Test a CNG fuel container that is greater than 1.65 meters (65 inches) in length…. S8.3.3 Number and placement of thermocouples. To monitor flame temperature, place three thermocouples so that they are suspended 25 mm (one inch) below the bottom of the CNG fuel container. Position thermocouples so that they are equally spaced over the length of the fire source or length of the container, whichever is shorter. S8.3.4 Shielding. (a) Use shielding to prevent the flame from directly contacting the CNG fuel container valves, fittings, or pressure relief devices. (b) To provide the shielding, use steel with 0.6 mm (.025 in) minimum nominal thickness. (c) Position the shielding so that it does not directly contact the CNG fuel container valves, fittings, or pressure relief devices.	Test.	Yes. Bonfire testing was conducted on one tank at 100% of service pressure and on another tank at 25% of service pressure. An amendment issued against 49 CFR Part 571.304 was issued October 24, 2000. This change is found in the October 30, 2000 NHTSA amended standard's bonfire test procedures (65 FR 64624). This amendment states that the National Highway Traffic Safety Administration (NHTSA)… " has decided to amend the bonfire test procedures to be consistent with the ANSI/NGV2 industry standard published in June 1998". It was still not clear if a bonfire test was required in the vertical orientation for a container less than 1.65 meters (65 inches) in length. Mr. Henry E. Seiff, PE, Director of Technology, The Natural Gas Vehicle Coalition, requested a clarification. Mr. John Womack, Acting Chief Counsel, National Highway Traffic Safety

FMVSS 304 Requirements (Revised Oct 1, 2000, and amendment issued Oct 24, 2000)	**METHOD OF VERIFICATION**	**COMPLIANCE AND/OR JUSTIFICATION**
S8.3.5 Fire source. Use a uniform fire source that is 1.65 meters long (65 inches). Beginning five minutes after the fire is igniter, maintain an average flame temperature of not less than 430 degrees Celsius (800 degrees Fahrenheit) as determined by the average of the two thermocouples recording the highest temperature over a 60 second interval: $\frac{1}{2}[(T_{High1} + T_{High2})/2$ @ time 30 sec + $(T_{High1} + T_{High2})/2$ @ time 60 sec] shall be greater than or equal to 430 deg C. If the pressure relief device releases before the end of the fifth minute after ignition, then the minimum temperature requirement does not apply. S8.3.6 Recording data. Record time, temperature, and pressure readings at 30 second intervals, beginning when the fire is ignited and continuing until the pressure release device releases. S8.3.7 Duration of exposure to fire source. The CNG fuel container is exposed to the firer source for 20 minutes after ignition or until the pressure release device releases, whichever period is shorter. S8.3.8 Number of tests per container. A single CNG fuel container is not subjected to more than one bonfire test. S8.3.9 Wind velocity. The average ambient wind velocity at the CNG fuel container during the period specified in S8.3.6 of this standard is not to exceed 2.24 meters/second (5 mph).		Administration, U.S. Department of Transportation, provided the following response: "Thus, taken together, paragraphs (b) and (c) of S8.3.2 specify that a CNG fuel container that is 1.65 meters in length or less is positioned so that its longitudinal axis is horizontal, its bottom is 100 mm above the fire source, and its center is over the center of the fire source. The new bonfire test procedures do not specify that a CNG fuel container that is 1.65 meters in length or less is tested in the vertical position." Powertech conducted one test per NGV2-1998, Clause 18.8 Bonfire Test. Tank TD102013 SN 7 was tested while pressurized at 3,600 psi. The tank included a GFI Control Systems manual valve and PRD. The tank was pressurized with compressed natural gas and centered horizontally over a 65-inch long propane burner unit such that the bottom of the container was 4 inches above the fire source. Metallic shielding was used to protect the PRD from direct flame

FMVSS 304 Requirements (Revised Oct 1, 2000, and amendment issued Oct 24, 2000)	METHOD OF VERIFICATION	COMPLIANCE AND/OR JUSTIFICATION
		impingement. Three thermocouples were suspended in the flame approximately one inch below the bottom of the container. A fourth thermocouple was attached to the PRD itself. Three thermocouple temperatures exceeded 800 F within 31 seconds of burner ignition. The pressure relief device activated after 1 minute 2 seconds. The container vented down to less than 100 psi in 2 minutes 22 seconds after the PRD activated. The valve that was used on the bonfire test was GFI Control Systems, Inc, valve model T1-100, which is rated for 3,600 psig, with a temperature rating of –40 C (-40 F) to 125 C (257 F). The pressure relief device was a GFI PRD P1750-30W, rated for 3,600 psig, which is a CGA CG9 device rated for 217 F. Powertech conducted a second bonfire test on 16 March 2001. Tank TD102013 SN 13, was bonfire tested while pressurized at

FMVSS 304 Requirements (Revised Oct 1, 2000, and amendment issued Oct 24, 2000)	**METHOD OF VERIFICATION**	**COMPLIANCE AND/OR JUSTIFICATION**
		900 psig (25% of the 3,600 psig service pressure). This tank included the same valve and PRD designs as used in the previous bonfire test conducted at 3,600 psig. Two thermocouples exceeded 800 F within 7 seconds of burner ignition. The PRD started to vent 45 seconds after initiation of the heat source. The PRD had vented the tank pressure to less than 100 psig in 44 seconds after the PRD started to vent, or 89 seconds after initiation of the heat source.

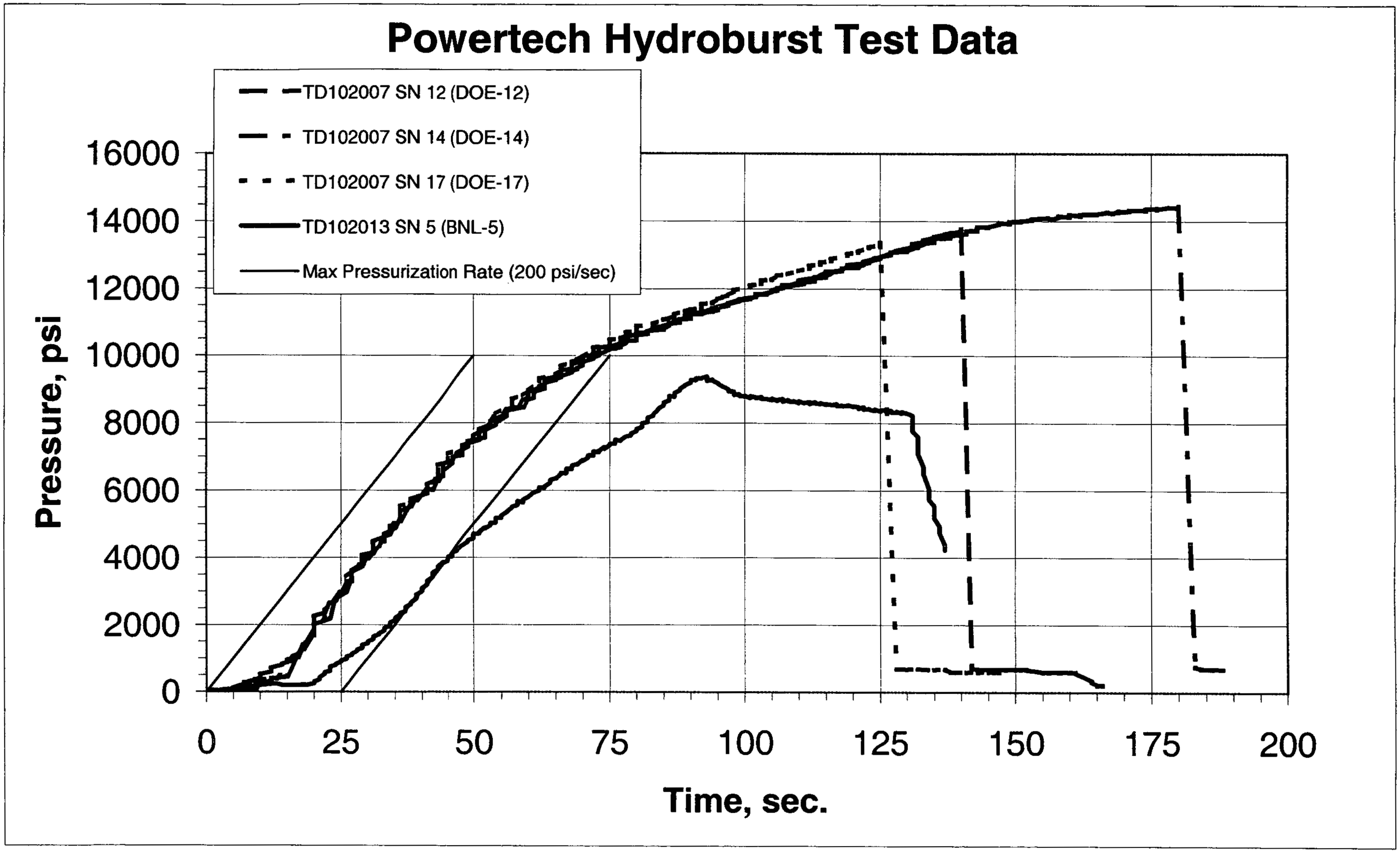

Figure 3. Hydroburst Test Data and Maximum Rise Rate

APPENDIX 2:
Powertech Gas Systems Engineering Test Reports

ANSI/IAS NGV2-1998 Clause 18.3 Ambient Temperature Cycling Test

Powertech
Gas Systems Engineering

12388 - 88th Avenue
Surrey, B.C. CANADA
V3W 7R7 (604) 590-7500

TEST REPORT

Page 1 of 1
File: 12531-36

TEST: **ANSI/IAS NGV2-1998**
Clause 18.3 AMBIENT TEMPERATURE CYCLING TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 5, 8

Part Data: 3,600 psi service pressure

TEST PROCEDURE:

The test was performed in accordance with Clause 18.3 of the ANSI/IAS NGV2-1998 standard.

Two finished containers were provided for the ambient temperature pressure cycling test. Each container was pressure cycled at ambient temperature from not more than 300 psi (less than or equal to 10% of the maximum filling pressure) to not less than 4,500 psi (greater than or equal to 1.25 times the service pressure) with water for 11,250 cycles. The rate of pressure cycling was 4 to 5 cycles per minute. During each pressure cycle, the pressure was held at the maximum pressure and minimum pressure for 1 second to allow the pressure to stabilize and ensure an accurate reading.

TEST RESULTS:

Containers 5 and 8 withstood 45,000 cycles without leakage.

Tested by: Approved by:

L. R. GAMBONE

N. Neufeld L.R. Gambone, P.Eng.

Date: November 6, 2000

ANSI/IAS NGV2-1998 Clause 18.5 Hydrostatic Burst Test

Powertech
Gas Systems Engineering

12388 - 88th Avenue
Surrey, B.C. CANADA
V3W 7R7 (604) 590-7500

TEST REPORT

Page 1 of 1
File: 12531-36

TEST: **ANSI/IAS NGV2-1998**
Clause 18.5 HYDROSTATIC BURST TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 4, 5

Part Data: 3,600 psi service pressure

TEST PROCEDURE:

The test was performed in accordance with Clause 18.5 of the ANSI/IAS NGV2-1998 standard.

Two finished containers were provided for the hydrostatic burst test. Container 4 was previously subjected to Clause 18.7 (Drop Test) of the ANSI/IAS NGV2-1998 standard, whereas container 5 was previously subjected to Clause 18.3 (Ambient Temperature Cycling Test) of the ANSI/IAS NGV2-1998 standard.

Each container was pressurized with water at a rate of 100 psi per second.

TEST RESULTS:

The burst pressure of each container exceeded the minimum required burst pressure.

Container 4 burst at a pressure of 11,330 psi. Container 5 was pressurized to 9,380 psi before a leak occurred at the aft end fitting.

Tested by:
N. Neufeld

Approved by:
L.R. Gambone, P.Eng.

L. R. GAMBONE

Date: November 6, 2000

Powertech
Gas Systems Engineering

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V3W 7R7 (604) 590-7500

TEST REPORT

Page 1 of 3
File: 12351-36

TEST: **ANSI/IAS NGV2-1998**
Clause 18.8 BONFIRE TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 7

Part Data: 3,600 psi service pressure, GFI Control Systems P1750-30W PRD

TEST PROCEDURE:

The test was performed in accordance with Clause 18.8 of the ANSI/IAS NGV2-1998 standard. The test setup is shown in the attached Figure 1.

One finished container was provided for the bonfire test. The container was pressurized to 3,600 psi (70°F) with compressed natural gas and centered horizontally over a 65 in. long propane burner unit such that the bottom of the container was 4 in. above the fire source. Metallic shielding was used to protect the PRD from direct flame impingement. Three thermocouples were suspended in the flame approximately 1 in. below the bottom of the container. A fourth thermocouple was attached to the PRD itself. A schematic of the test setup is shown in Figure 2. The thermocouple temperatures and container pressure were recorded.

TEST RESULTS:

Three thermocouple temperatures exceeded 800°F (430°C) within 31 seconds of burner ignition. The pressure relief device activated after 1 minute 2 seconds. The container vented down (<100 psi) 2 minutes 22 seconds after the pressure relief device activated. The bonfire test pressure and temperature data is appended (Page 3).

Tested by:

N. Neufeld

Approved by:

L. R. GAMBONE

L.R. Gambone, P.Eng.

Date: October 13, 2000

Powertech Gas Systems Engineering	**TEST REPORT**	Page 2 of 3 File: 12351-36
12388 - 88th Avenue Surrey, B.C. CANADA V3W 7R7 (604) 590-7500	**TEST:**	**ANSI/IAS NGV2-1998 Clause 18.8 BONFIRE TEST**

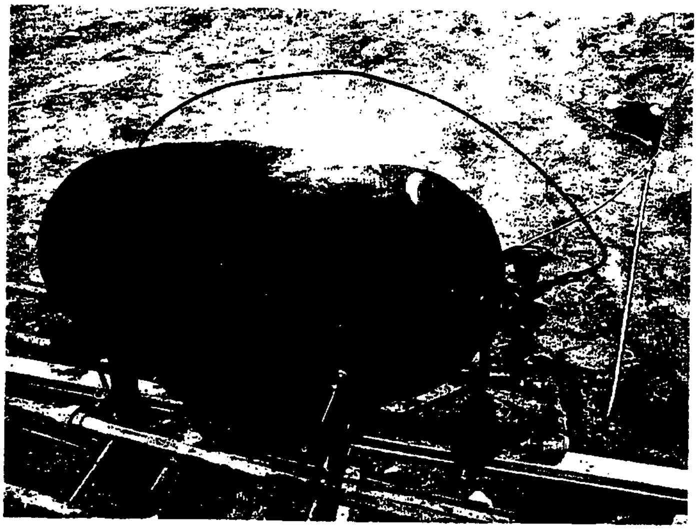


Figure 1: Bonfire test setup.

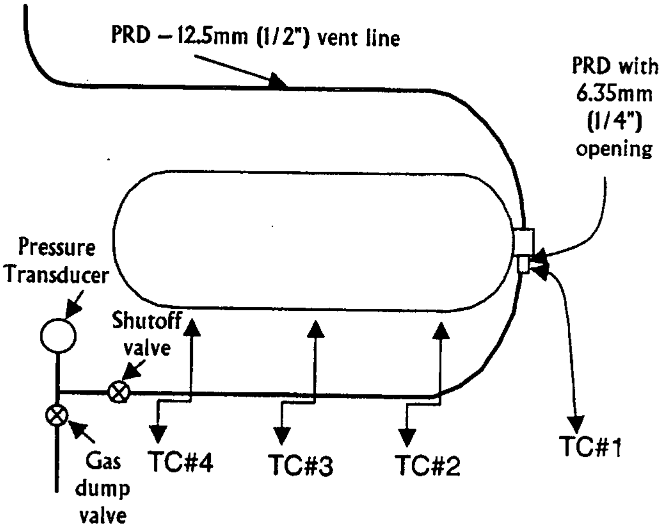
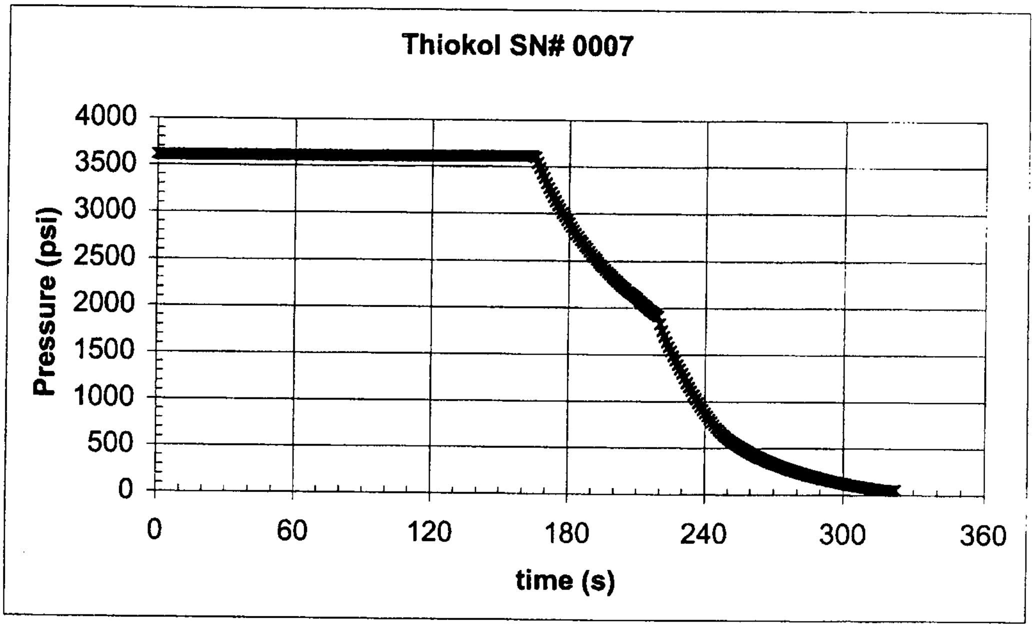
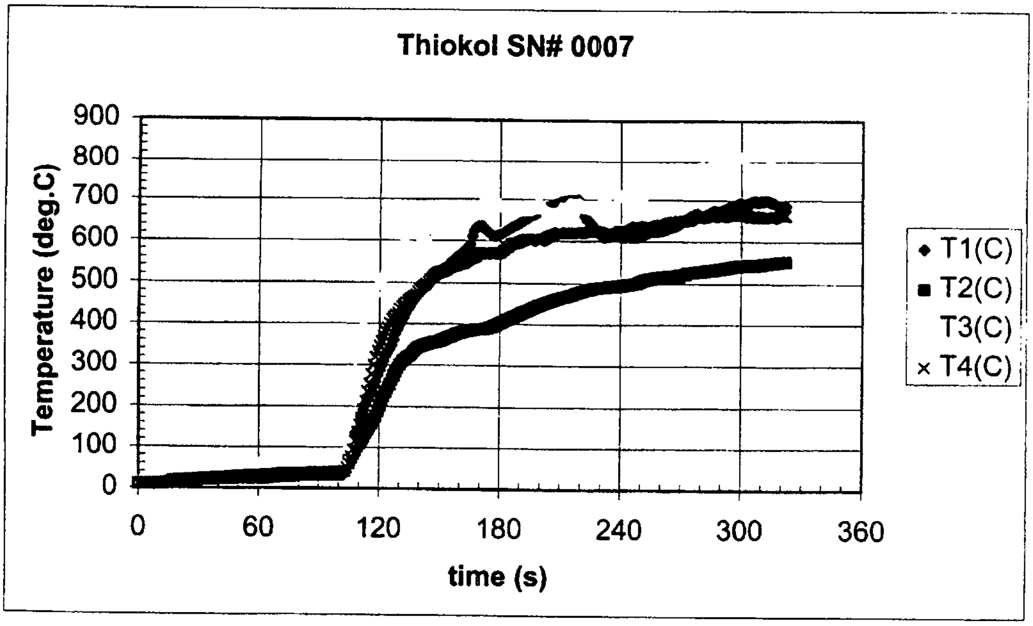


Figure 2: Bonfire test schematic showing location of thermocouples.

Powertech Gas Systems Engineering 12388 - 88th Avenue Surrey, B.C. CANADA V3W 7R7 (604) 590-7500	**TEST REPORT**	Page 3 of 3 File: 12351-36
	TEST:	**ANSI/IAS NGV2-1998** **Clause 18.8 BONFIRE TEST**





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TEST REPORT

Page 1 of 3
File: 12351-36
Revision 1

TEST: **FMVSS 304 (October 20, 2000)**
Section 8.3 BONFIRE TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 13

Part Data: 3,600 psi service pressure, GFI Control Systems P1750-30W PRD

TEST PROCEDURE:

The test was performed in accordance with Section 8.3 of the FMVSS 304 standard (October 20, 2000). The test setup is shown in the attached Figure 1.

One finished container was provided for the bonfire test. The container was pressurized to 900 psi (70°F) with compressed natural gas and centered horizontally over a 65 in. long propane burner unit such that the bottom of the container was 4 in. above the fire source. Metallic shielding was used to protect the PRD from direct flame impingement. Three thermocouples were suspended in the flame approximately 1 in. below the bottom of the container. A fourth thermocouple was attached to the PRD itself. A schematic of the test setup is shown in Figure 2. The thermocouple temperatures and container pressure were recorded.

TEST RESULTS:

Two thermocouple temperatures exceeded 800°F (430°C) within 7 seconds of burner ignition. The pressure relief device activated after 45 seconds. The container vented down (<100 psi) 44 seconds after the pressure relief device activated. The bonfire test pressure and temperature data is appended (Page 3).

Tested by:
Sean Allan
S/Allan, E.I.T.

Approved by:
L.R. Gambone, P.Eng.

L. R. GAMBONE

Date: March 23, 2001

TEST: FMVSS 304 (October 20, 2000)
Section 8.3 BONFIRE TEST

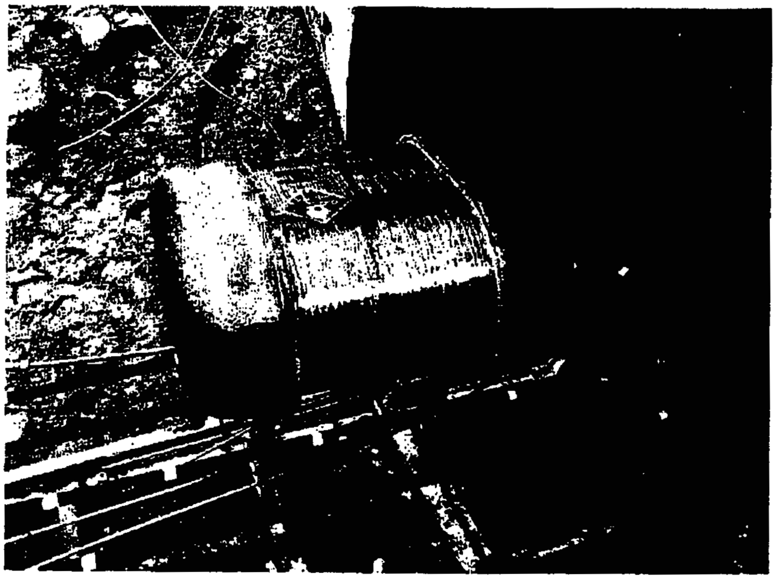


Figure 1: Bonfire test setup.

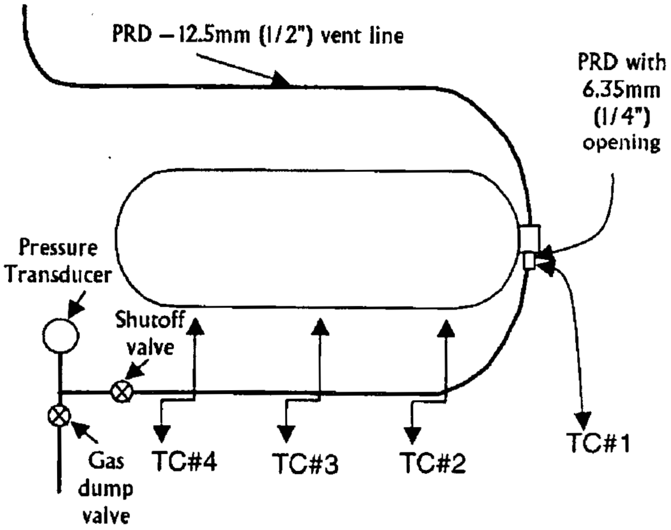
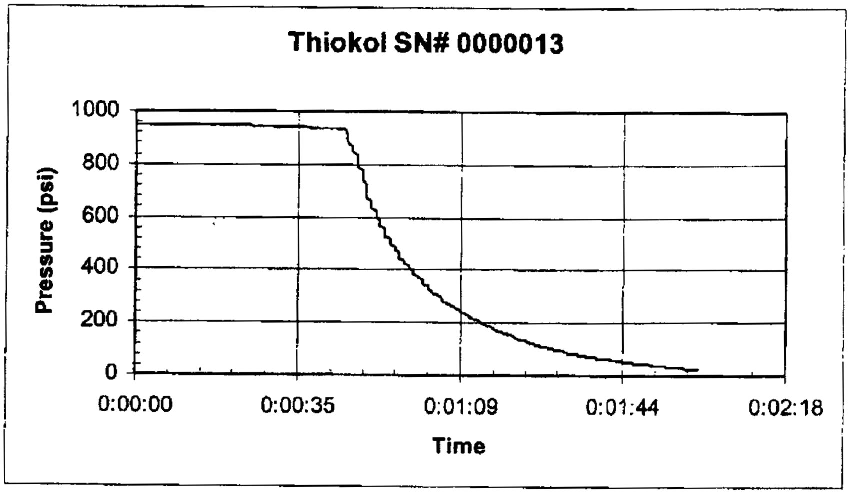
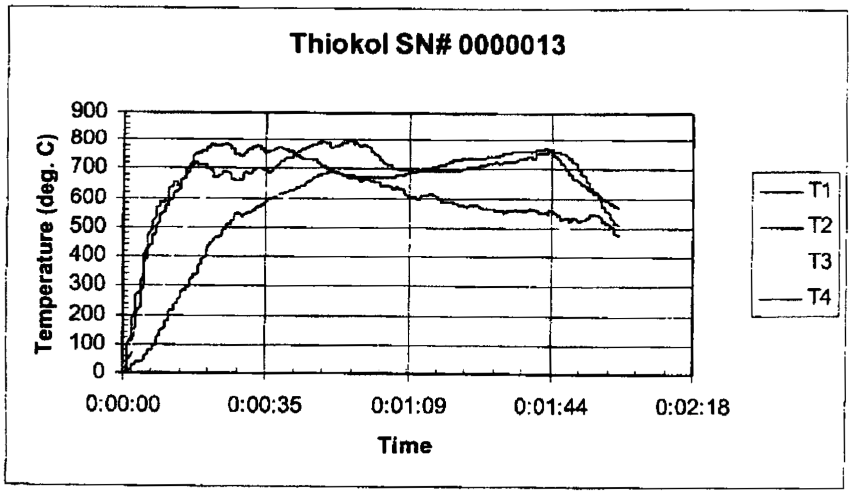


Figure 2: Bonfire test schematic showing location of thermocouples.

Powertech Gas Systems Engineering 12388 - 88th Avenue Surrey, B.C. CANADA V3W 7R7 (604) 590-7500	**TEST REPORT**	Page 3 of 3 File: 12351-36
	TEST:	**FMVSS 304 (October 20, 2000)** **Section 8.3 BONFIRE TEST**





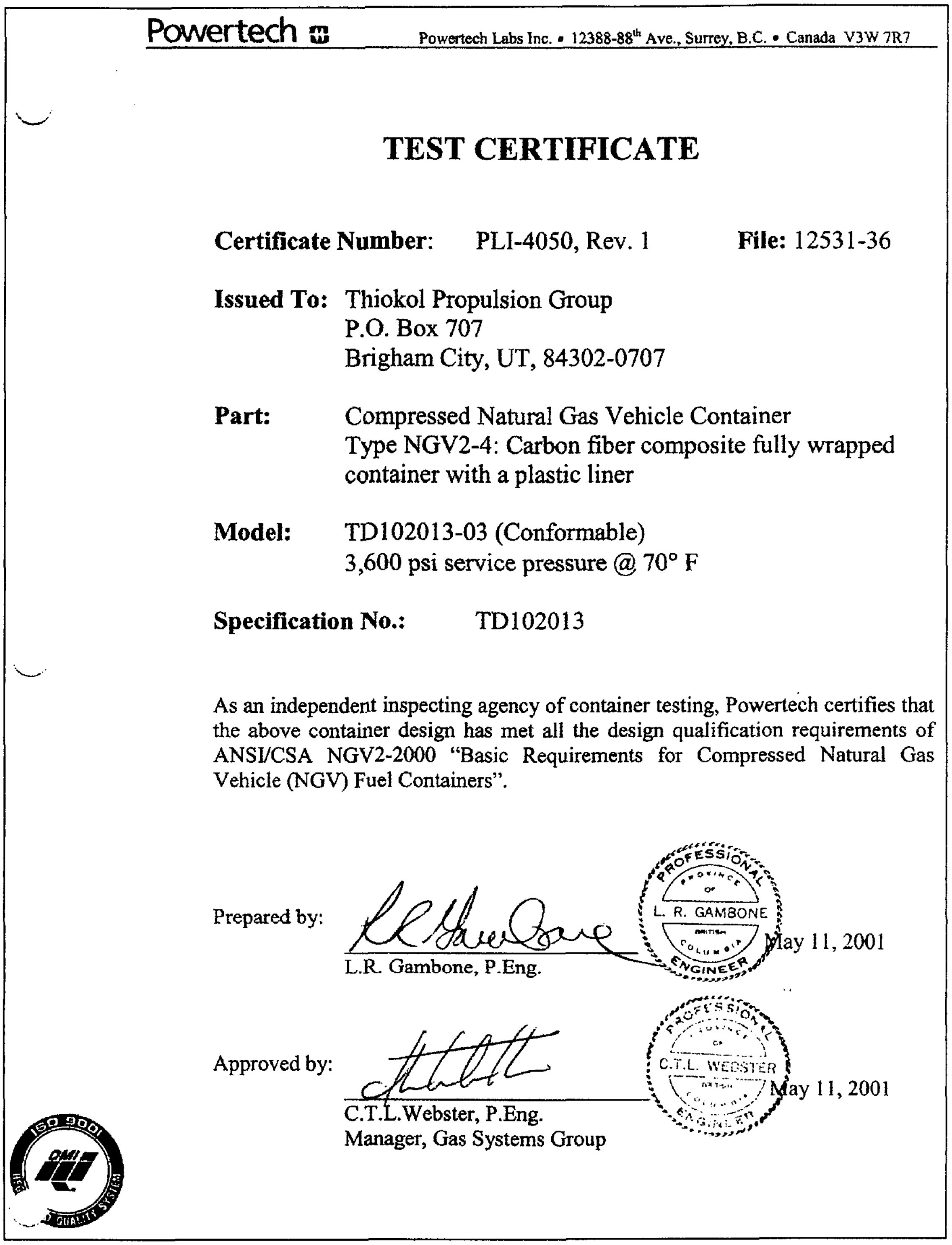
Appendix 2: NGV2-2000 Test Documentation Summary

Powertech Labs of Surrey, British Columbia, Canada conducted the qualification testing of the conformable tank design per the NGV2-1998 and 2000 standard. A summary of the qualification tests and requirements are given in **Error! Reference source not found.**.

Table A2-1: Tank Testing and Requirements Summary

Test	Basic Requirement
Ambient Cycling	Pressure cycle tank with water between 10% and 125% of the service pressure 45,000 times at ambient temperature. No leaks allowed for first 15,000 cycles.
Environmental	Pressure cycle and hold with corrosive fluid exposure and impact damage
Extreme Temperature Cycling	Pressure cycle tank at high and low temperature
Hydrostatic Burst	Tank ruptures with an internal pressure greater than 2.25 times service pressure
Composite Flaw Tolerance	Complete the ambient pressure cycle test with known flaws machined into the tank
Drop Test	Complete the ambient pressure cycle test after tank has been dropped six times from 6 feet
Bonfire test	Tank vents through pressure relief device without rupture or fragmentation.
Accelerated Stress Rupture	75% of the design burst pressure after being held at 125% service pressure at 150°F for 1,000 hours
Penetration	Tank does not fragment when pressurized to service pressure and punctured
Permeation	Leak rate to be less than 0.25 scc/hr/liter
Natural Gas Cycling	No liner deterioration after 1,000 pressure cycles using service gas

The conformable tank design has passed all the qualification tests. Complete test reports from Powertech Labs for are provided in the following pages. Figure A2- 2 shows the test certificate received from Powertech certifying the tank has met all the design requirements of the NGV2-2000 standard.



Powertech
Powertech Labs Inc. • 12388-88th Ave., Surrey, B.C. • Canada V3W 7R7

TEST CERTIFICATE

Certificate Number: PLI-4050, Rev. 1 **File:** 12531-36

Issued To: Thiokol Propulsion Group
P.O. Box 707
Brigham City, UT, 84302-0707

Part: Compressed Natural Gas Vehicle Container
Type NGV2-4: Carbon fiber composite fully wrapped container with a plastic liner

Model: TD102013-03 (Conformable)
3,600 psi service pressure @ 70° F

Specification No.: TD102013

As an independent inspecting agency of container testing, Powertech certifies that the above container design has met all the design qualification requirements of ANSI/CSA NGV2-2000 "Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers".

Prepared by: L.R. Gambone, P.Eng. May 11, 2001

L. R. GAMBONE

Approved by: C.T.L.Webster, P.Eng.
Manager, Gas Systems Group
May 11, 2001

C.T.L. WEBSTER

Figure A2- 2: Powertech Labs Test Certificate

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Gas Systems Engineering

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Surrey, B.C. CANADA
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TEST REPORT

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File: 11838-34

TEST: **ANSI/IAS NGV2-1998**
Clause 18.3 AMBIENT TEMPERATURE CYCLING TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102006-03 (conformable design) Serial #: 19, 20

Part Data: 3,600 psi service pressure

TEST PROCEDURE:

The test was performed in accordance with Clause 18.3 of the ANSI/IAS NGV2-1998 standard. The test setup is shown in Figure 1.

Two finished containers were provided for the ambient temperature pressure cycling test. Each container was pressure cycled at ambient temperature from not more than 300 psi (less than or equal to 10% of the maximum filling pressure) to not less than 4,500 psi (greater than or equal to 1.25 times the service pressure) with water for 11,250 cycles. The rate of pressure cycling was 4 to 5 cycles per minute. During each pressure cycle, the pressure was held at the maximum pressure and minimum pressure for 1 second to allow the pressure to stabilize and ensure an accurate reading.

TEST RESULTS:

Container 19 withstood 60,126 cycles without leakage, whereas container 20 leaked after 37,082 cycles in the transition region on the aft end of the container.

Tested by: PER
N. Neufeld

Approved by:
L. R. GAMBONE
L.R. Gambone, P.Eng.

Date: July 14, 1999

Revision 1

TEST: **ANSI/IAS NGV2-1998**
Clause 18.3 AMBIENT TEMPERATURE CYCLING TEST

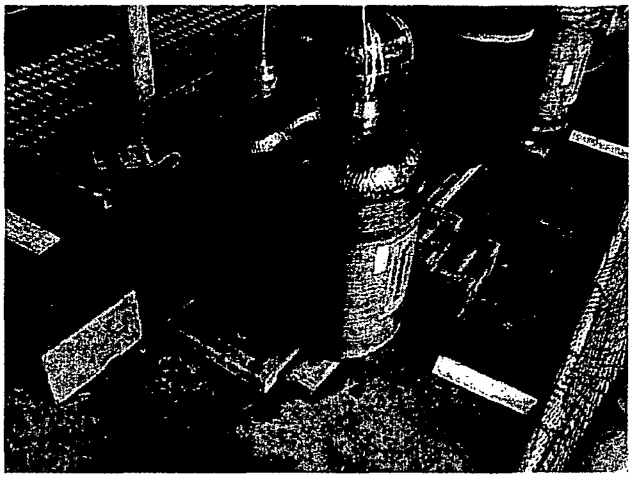

Figure 1: Ambient temperature pressure cycling test setup.

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V3W 7R7 (604) 590-7500

TEST REPORT

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File: 12531-36

TEST: **ANSI/IAS NGV2-1998**
Clause 18.3 AMBIENT TEMPERATURE CYCLING TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 5, 8

Part Data: 3,600 psi service pressure

TEST PROCEDURE:

The test was performed in accordance with Clause 18.3 of the ANSI/IAS NGV2-1998 standard.

Two finished containers were provided for the ambient temperature pressure cycling test. Each container was pressure cycled at ambient temperature from not more than 300 psi (less than or equal to 10% of the maximum filling pressure) to not less than 4,500 psi (greater than or equal to 1.25 times the service pressure) with water for 11,250 cycles. The rate of pressure cycling was 4 to 5 cycles per minute. During each pressure cycle, the pressure was held at the maximum pressure and minimum pressure for 1 second to allow the pressure to stabilize and ensure an accurate reading.

TEST RESULTS:

Containers 5 and 8 withstood 45,000 cycles without leakage.

Tested by:
N. Neufeld

Approved by:
L.R. Gambone, P.Eng.

L. R. GAMBONE

Date: November 6, 2000

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TEST REPORT

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File: 12531-36

TEST: **DRAFT ANSI/IAS NGV2-2000**
Clause 18.4 ENVIRONMENTAL TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 3

Part Data: 3,600 psi service pressure

TEST PROCEDURE:

The test was performed in accordance with Clause 18.4 of the draft ANSI/IAS NGV2-2000 standard.

One finished container was provided for the environmental test. The upper section of the container was divided into 5 distinct areas (nominally 4 in. in diameter) and marked for pendulum impact preconditioning and fluid exposure. Each of the 5 areas were impacted by a pendulum body at the center of the area (the container was unpressurized during this preconditioning).

The pendulum impact body was made of steel and had the shape of a pyramid with equilateral triangle faces and a square base, the summit and the edges being rounded to a radius of 0.12 in. (see Figure 1). The center of percussion of the pendulum coincided with the center of gravity of the pyramid; its distance from the axis of rotation of the pendulum was 40 in. The total mass of the pendulum referred to its center of percussion was 33 lbs. The energy of the pendulum at the moment of impact was 22.1 ft-lb.

Each marked area was exposed to one of the following 5 solutions during the test:
a) Sulfuric acid – 19% solution by volume in water
b) Sodium hydroxide – 25% solution by weight in water
c) Methanol/gasoline – 5/95% concentration of M5 fuel meeting the requirements of ASTM standard D4814
d) Ammonium nitrate – 28% by weight in water
e) Windshield washer fluid (50% by volume solution of methyl alcohol and water).

The container was hydrostatically pressure cycled from not more than 300 psi (less than or equal to 10% of the service pressure) to not less than 4,500 psi (greater than or equal to 125% of the service pressure) with water for 3,000 cycles. After pressure cycling, the container was pressurized to 4,500 psi and held at that pressure for 48 hours while being exposed to the 5 environmental solutions.

TEST RESULTS:

There was no apparent deterioration to container 3 caused by exposure to the test solutions or the pressure cycling and pressure hold phase.

Tested by:

N. Neufeld

Approved by:

R. GAMBONE

L.R. Gambone, P.Eng.

Date: November 6, 2000

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Surrey, B.C. CANADA
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TEST REPORT

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File: 12531-36

TEST: **DRAFT ANSI/IAS NGV2-2000**
Clause 18.5 EXTREME TEMPERATURE CYCLING TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 3

Part Data: 3,600 psi service pressure

TEST PROCEDURE:

The test was performed in accordance with Clause 18.5 of the draft ANSI/IAS NGV2-2000 standard.

A container that had been previously subjected to Clause 18.4 (Environmental Test) of the draft ANSI/IAS NGV2-2000 standard was provided for the extreme temperature cycling test. The container was hydrostatically pressure cycled from not more than 300 psi (less than or equal to 10% of service pressure) to not less than 4,500 psi (greater than or equal to 125% of service pressure) for 4,000 cycles at 180°F (82°C). The container was subsequently hydrostatically pressure cycled from not more than 300 psi (less than or equal to 10% of service pressure) to not less than 2,880 psi (greater than or equal to 80% of service pressure) for 4,000 cycles at -40°F (-40°C).

TEST RESULTS:

Container 3 withstood the extreme temperature cycling test without evidence of leakage or rupture.

Tested by:

N. Neufeld

Approved by:

L. R. GAMBONE

L.R. Gambone, P.Eng.

Date: November 15, 2000

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TEST REPORT

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File: 12531-36

TEST: **ANSI/IAS NGV2-1998**
Clause 18.5 HYDROSTATIC BURST TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 4, 5

Part Data: 3,600 psi service pressure

TEST PROCEDURE:

The test was performed in accordance with Clause 18.5 of the ANSI/IAS NGV2-1998 standard.

Two finished containers were provided for the hydrostatic burst test. Container 4 was previously subjected to Clause 18.7 (Drop Test) of the ANSI/IAS NGV2-1998 standard, whereas container 5 was previously subjected to Clause 18.3 (Ambient Temperature Cycling Test) of the ANSI/IAS NGV2-1998 standard.

Each container was pressurized with water at a rate of 100 psi per second.

TEST RESULTS:

The burst pressure of each container exceeded the minimum required burst pressure.

Container 4 burst at a pressure of 11,330 psi. Container 5 was pressurized to 9,380 psi before a leak occurred at the aft end fitting.

Tested by:
N. Neufeld

Approved by:
L.R. Gambone, P.Eng.

PROFESSIONAL PROVINCE OF BRITISH COLUMBIA ENGINEER
L. R. GAMBONE

Date: November 6, 2000

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Gas Systems Engineering

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TEST REPORT

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File: 11838-34

TEST: **ANSI/IAS NGV2-1998**
Clause 18.6 COMPOSITE FLAW TOLERANCE TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibers)

Part Model: TD 102006-03 (conformable design) Serial #: 15

Part Data: 3,600 psi service pressure

TEST PROCEDURE:

The test was performed in accordance with Clause 18.6 of the ANSI/IAS NGV2-1998 standard.

One finished container was provided for the composite flaw tolerance test. Two flaw pairs were cut in the longitudinal direction into the composite sidewall of one cell and into the composite hoop layer connecting the two cells (see Figure 1). Each flaw pair consisted of a flaw 1 in. long and 0.050 in. deep and a second flaw 8 in. long and 0.030 in. deep.

The container was pressure cycled at ambient temperature from not more than 300 psi (less than or equal to 10% of the maximum fill pressure) to not less than 4,500 psi (greater than or equal to 1.25 times the service pressure) with water for 11,250 cycles. The rate of pressure cycling was 4 to 5 cycles per minute. During each pressure cycle, the pressure was held at the maximum pressure and minimum pressure for 1 second to allow the pressure to stabilize and ensure an accurate reading.

TEST RESULTS:

A leak occurred at the transition region of one cell after 53,975 cycles. There was some evidence of composite delamination in the vicinity of the flaw cuts (see Figure 2).

Tested by:
N. Neufeld

Approved by:
C.T.L. WEBSTER
C. T. Webster, P.Eng.

Date: July 27, 1999

Revision 1

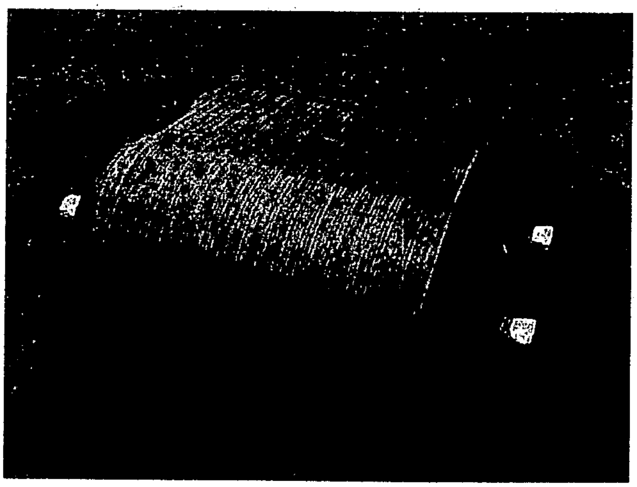

Figure 1: Locations of flaw pairs in container 15.

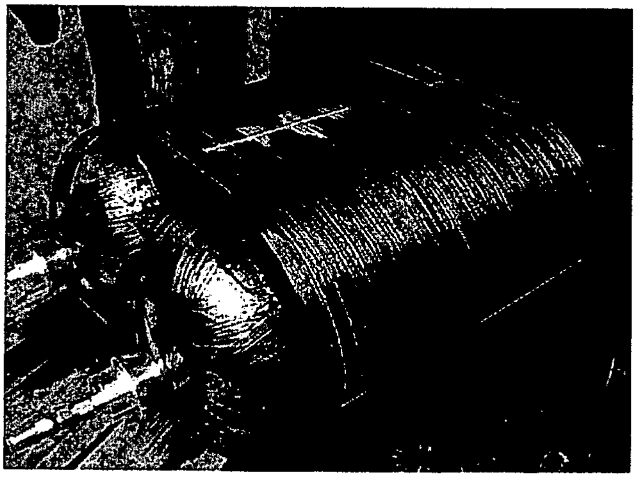

Figure 2: Composite delamination visible in the vicinity of the flaw cuts.

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TEST REPORT

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TEST: **ANSI/IAS NGV2-1998**
Clause 18.7 DROP TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 4

Part Data: 3,600 psi service pressure

TEST PROCEDURE:

The test was performed in accordance with Clause 18.7 of the ANSI/IAS NGV2-1998 standard.

One finished container was drop tested at ambient temperature without internal pressurization. The surface onto which the container was dropped was a smooth, horizontal concrete pad. The same container was dropped under the following conditions:

a) The container was dropped twice in a horizontal position (cells aligned horizontally and vertically) with the lowest point of the container 72 in. above the surface onto which it was dropped (illustrated in Figures 1 – 2).
b) The container was dropped vertically on each end such that the height of the lower end was 72 in. above the surface onto which it was dropped (illustrated in Figures 3 – 4).
c) The container was dropped at a 45° angle twice onto a dome (cells aligned horizontally and vertically) from a height such that the center of gravity of the container was at 72 in. (illustrated in Figures 5 – 6).

Following the drop test, the container was subjected to ambient pressure cycling in accordance with Clause 18.3 of the ANSI/IAS NGV2-1998 standard, i.e. the container was cycled from not more than 300 psi to not less than 4,500 psi with water for 11,250 cycles.

TEST RESULTS:

Container 4 withstood 11,250 cycles without leakage.

Tested by:

N. Neufeld

Approved by:

L.R. Gambone, P.Eng.

PROFESSIONAL ENGINEER
PROVINCE OF BRITISH COLUMBIA
L. R. GAMBONE

Date: November 6, 2000

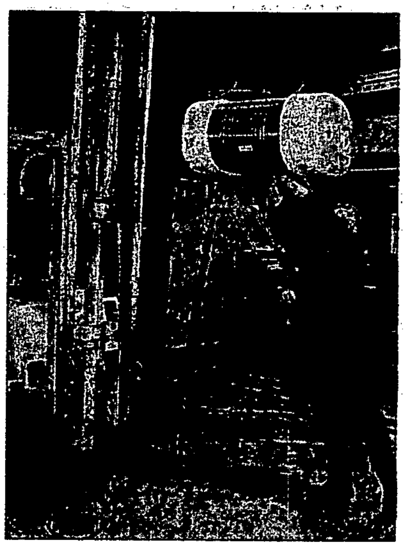

Figure 1: Illustration of horizontal drop test with cells aligned horizontally.

Figure 2: Illustration of horizontal drop test with cells aligned vertically.

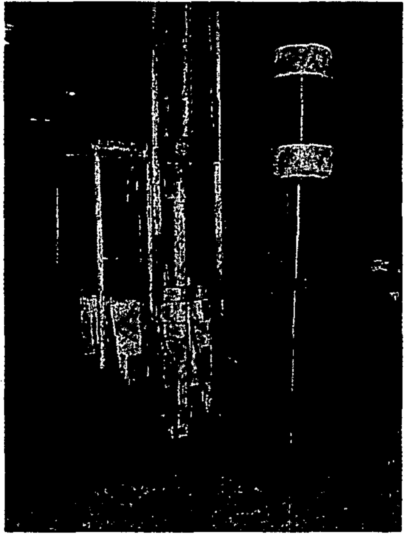

Figure 3: Illustration of vertical drop test.

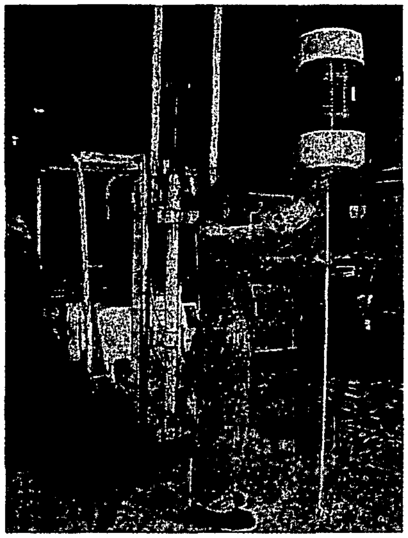

Figure 4: Illustration of vertical drop test (end opposite to Figure 3).

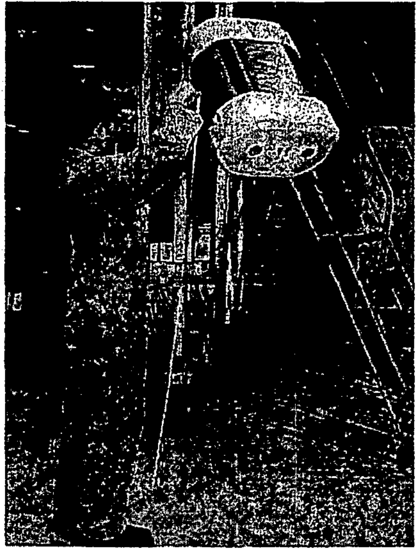

Figure 5: Illustration of 45 degree angle drop test with cells aligned horizontally.

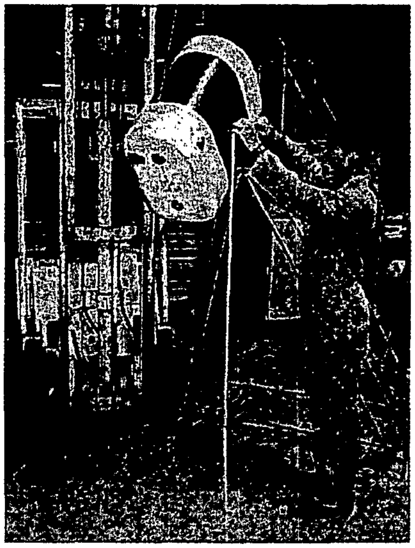

Figure 6: Illustration of 45 degree angle drop test with cells aligned vertically.

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TEST REPORT

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File: 12351-36

TEST: **ANSI/IAS NGV2-1998**
Clause 18.8 BONFIRE TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 7

Part Data: 3,600 psi service pressure, GFI Control Systems P1750-30W PRD

TEST PROCEDURE:

The test was performed in accordance with Clause 18.8 of the ANSI/IAS NGV2-1998 standard. The test setup is shown in the attached Figure 1.

One finished container was provided for the bonfire test. The container was pressurized to 3,600 psi (70°F) with compressed natural gas and centered horizontally over a 65 in. long propane burner unit such that the bottom of the container was 4 in. above the fire source. Metallic shielding was used to protect the PRD from direct flame impingement. Three thermocouples were suspended in the flame approximately 1 in. below the bottom of the container. A fourth thermocouple was attached to the PRD itself. A schematic of the test setup is shown in Figure 2. The thermocouple temperatures and container pressure were recorded.

TEST RESULTS:

Three thermocouple temperatures exceeded 800°F (430°C) within 31 seconds of burner ignition. The pressure relief device activated after 1 minute 2 seconds. The container vented down (<100 psi) 2 minutes 22 seconds after the pressure relief device activated. The bonfire test pressure and temperature data is appended (Page 3).

Tested by:

N. Neufeld

Approved by:

L.R. Gambone, P.Eng.

PROFESSIONAL
PROVINCE OF
L. R. GAMBONE
BRITISH COLUMBIA
ENGINEER

Date: October 13, 2000

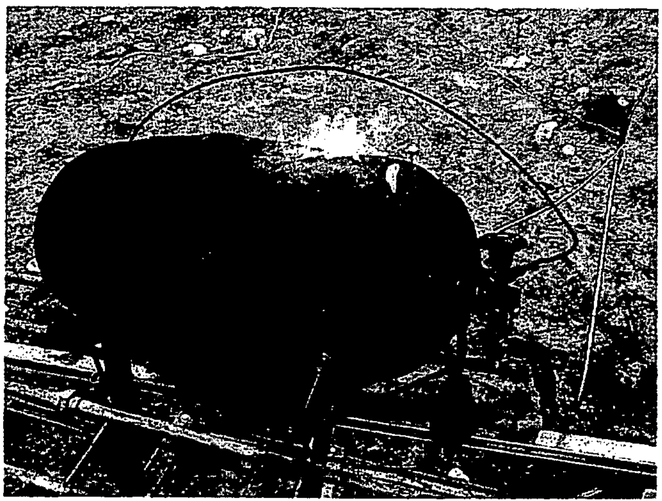


Figure 1: Bonfire test setup.

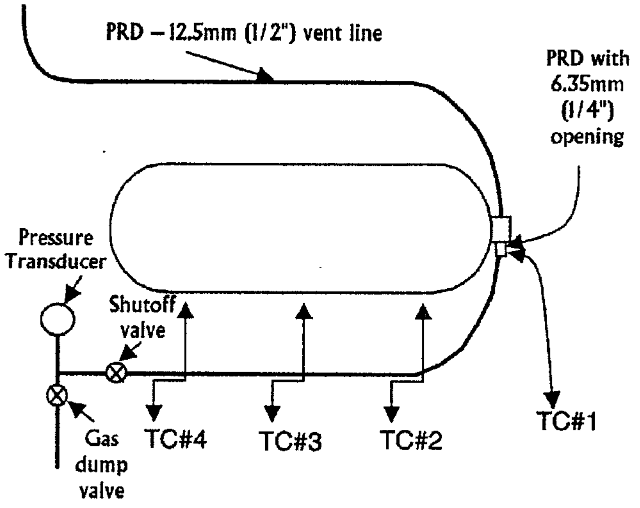
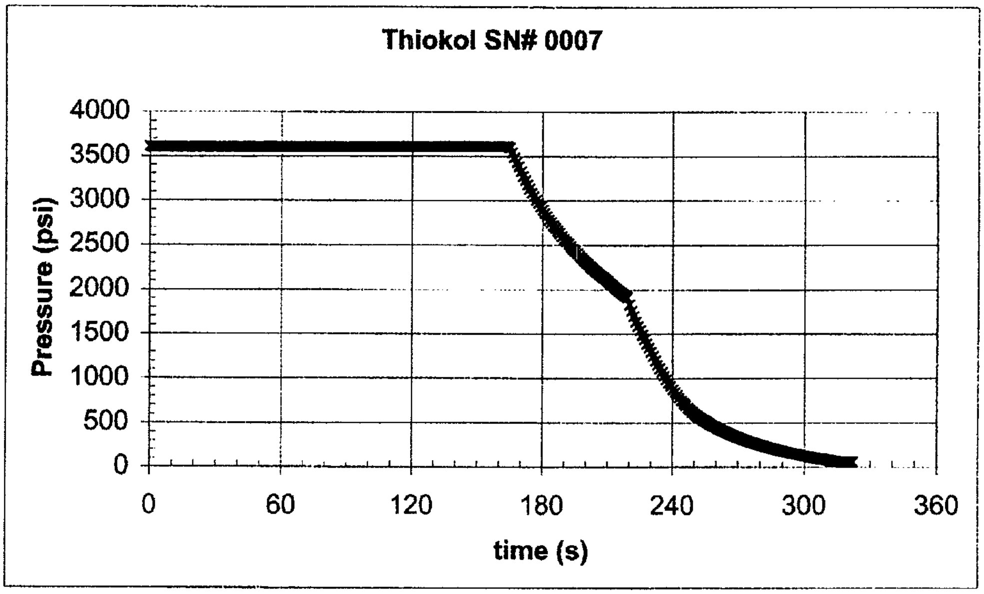
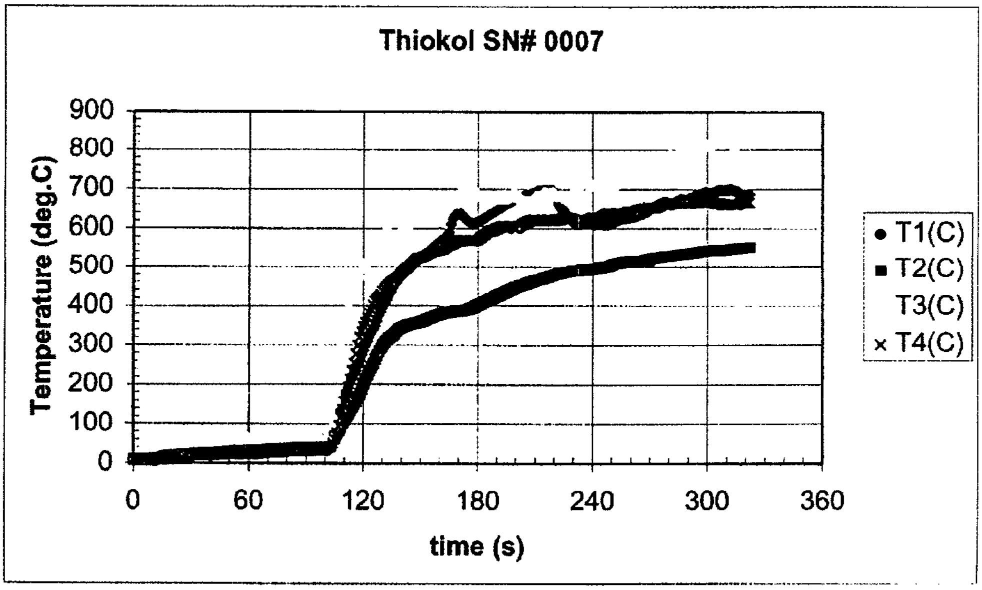


Figure 2: Bonfire test schematic showing location of thermocouples.

TEST: **ANSI/IAS NGV2-1998**
Clause 18.8 BONFIRE TEST





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TEST REPORT

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File: 12351-36
Revision 1

TEST: **FMVSS 304 (October 20, 2000)**
Section 8.3 BONFIRE TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 13

Part Data: 3,600 psi service pressure, GFI Control Systems P1750-30W PRD

TEST PROCEDURE:

The test was performed in accordance with Section 8.3 of the FMVSS 304 standard (October 20, 2000). The test setup is shown in the attached Figure 1.

One finished container was provided for the bonfire test. The container was pressurized to 900 psi (70°F) with compressed natural gas and centered horizontally over a 65 in. long propane burner unit such that the bottom of the container was 4 in. above the fire source. Metallic shielding was used to protect the PRD from direct flame impingement. Three thermocouples were suspended in the flame approximately 1 in. below the bottom of the container. A fourth thermocouple was attached to the PRD itself. A schematic of the test setup is shown in Figure 2. The thermocouple temperatures and container pressure were recorded.

TEST RESULTS:

Two thermocouple temperatures exceeded 800°F (430°C) within 7 seconds of burner ignition. The pressure relief device activated after 45 seconds. The container vented down (<100 psi) 44 seconds after the pressure relief device activated. The bonfire test pressure and temperature data is appended (Page 3).

Tested by:
S/Allan, E.I.T.

Approved by:
L.R. Gambone, P.Eng.

L. R. GAMBONE

Date: March 23, 2001

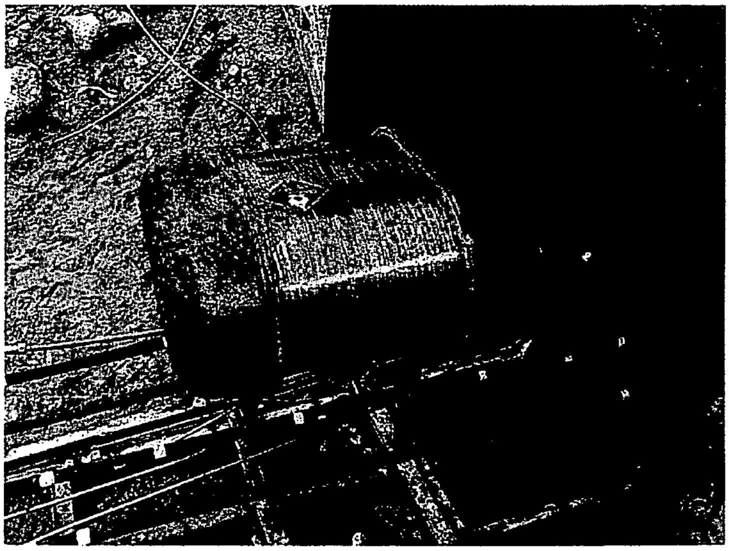


Figure 1: Bonfire test setup.

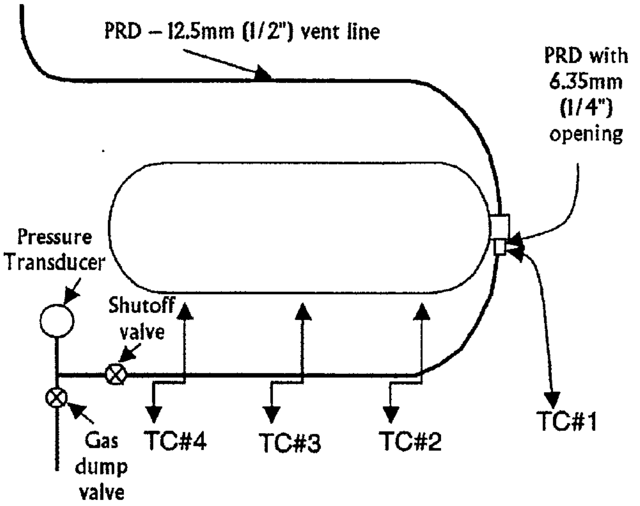
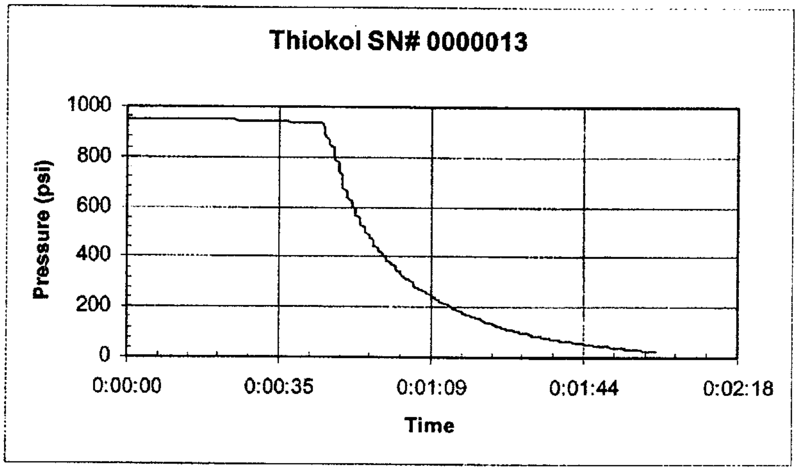
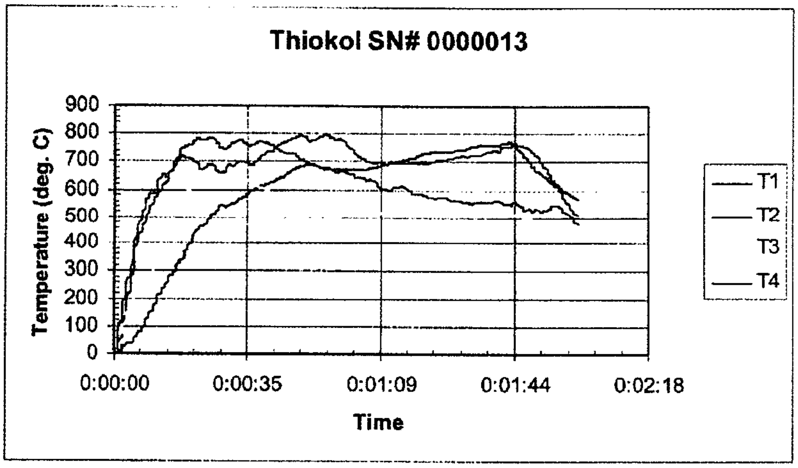


Figure 2: Bonfire test schematic showing location of thermocouples.

TEST: FMVSS 304 (October 20, 2000)
Section 8.3 BONFIRE TEST





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TEST REPORT

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File: 12531-36

TEST: **ANSI/IAS NGV2-1998**
Clause 18.9 ACCELERATED STRESS RUPTURE TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 1

Part Data: 3,600 psi service pressure

TEST PROCEDURE:

The test was performed in accordance with Clause 18.9 of the ANSI/IAS NGV2-1998 standard.

One finished container was provided for the accelerated stress rupture test. The container was hydrostatically pressurized to 4,500 psi (1.25 times the service pressure) while at a temperature of 149°F (65°C) for 1,000 hours.

The container was burst tested in accordance with Clause 18.5 of the ANSI/IAS NGV2-1998 standard.

TEST RESULTS:

Container 1 burst at a pressure of 11,590 psi which exceeded 75% of the minimum design burst pressure.

Tested by:
N. Neufeld

Approved by:
L.R. Gambone, P.Eng.

L. R. GAMBONE

Date: November 6, 2000

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TEST: **ANSI/IAS NGV2-1998**
Clause 18.10 PENETRATION TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 2

Part Data: 3,600 psi service pressure

TEST PROCEDURE:

The test was performed in accordance with Clause 18.10 of the ANSI/IAS NGV2-1998 standard.

One finished container was provided for the penetration test (see Figure 1). The container was pressurized to 3,600 psi with compressed natural gas and was penetrated by an armor piercing bullet with a diameter of 0.30 in. The bullet impacted the sidewall at an approximate angle of 45 degrees.

TEST RESULTS:

The bullet completely passed through one sidewall of the container (see Figure 2). There was no evidence of fragmentation failure. The approximate size of the bullet entrance opening was 0.30 in. in diameter.

Tested by:

N. Neufeld

Approved by:

L. R. GAMBONE

L.R. Gambone, P.Eng.

Date: October 13, 2000

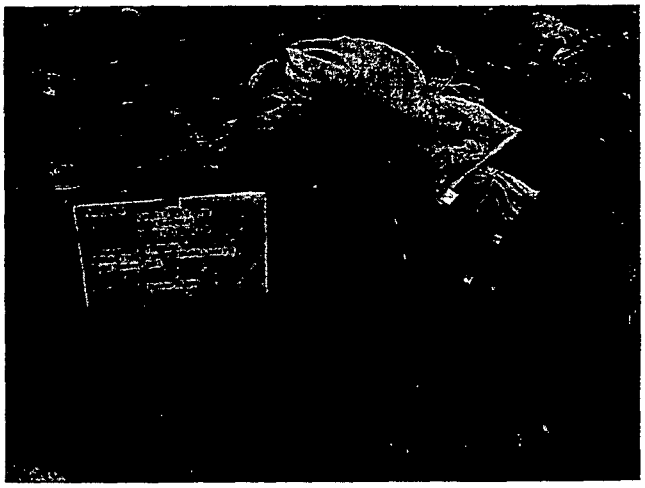

Figure 1: View of Thiokol container 2 prior to penetration test.

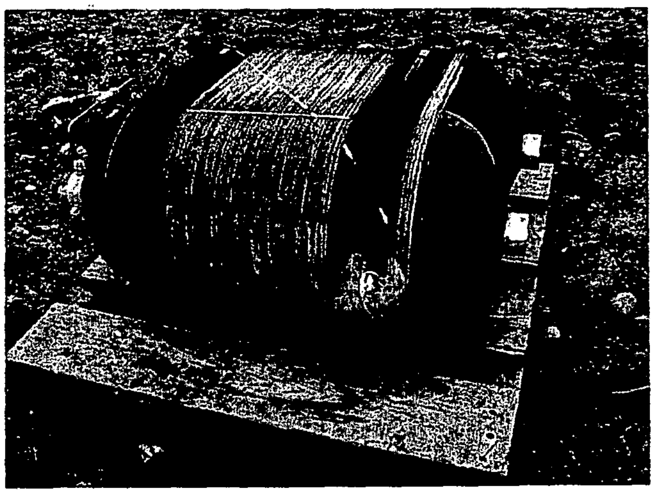

Figure 2: View of bullet penetration location.

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V3W 7R7 (604) 590-7500

TEST REPORT

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File: 12531-36

TEST: **ANSI/IAS NGV2-1998**
Clause 18.11 PERMEATION TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 2

Part Data: 3,600 psi service pressure

TEST PROCEDURE:

The test was performed in accordance with Clause 18.11 of the ANSI/IAS NGV2-1998 standard.

The valve ends of the container were connected by Swage-Lok fitting to 0.24 in. tubing and filled to 3,600 psi with compressed natural gas. The container was disconnected from the calibrated pressure gauge and sealed within a steel chamber measuring 23 in. diameter by 59 in. long. The external volume of the container was calculated as 4,551 cu. in. The dead volume in the chamber was calculated as 19,962 cu. in.

Samples of air were removed periodically from the chamber through a rubber bung fitting using a gas-tight syringe, and the samples analyzed using a Hewlett Packard Model 5830 gas chromatograph equipped with a flame ionization detector.

TEST RESULTS:

Elapsed Time (hrs)	CH_4 Conc. (ppm)	Permeation Rate (scc/hr)
1.0	0	0
213	109	0.002
405	1,250	0.015
503	3,440	0.033

Tested by:

N. Neufeld

Approved by:

L.R. Gambone, P.Eng.

L. R. GAMBONE

Date: November 6, 2000

Powertech
Gas Systems Engineering

12388 - 88th Avenue
Surrey, B.C. CANADA
V3W 7R7 (604) 590-7500

TEST REPORT

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TEST: **ANSI/IAS NGV2-1998**
Clause 18.12 NATURAL GAS CYCLING TEST

Manufacturer: Thiokol Propulsion Group, P.O. Box 707, Brigham City, UT, 84302-0707

Part Type: Type NGV2-4 (plastic liner fully-wrapped with carbon and glass fibres)

Part Model: TD 102013 (conformable design) Serial #: 6

Part Data: 3,600 psi service pressure

TEST PROCEDURE:

The test was performed in accordance with Clause 18.12 of the ANSI/IAS NGV2-1998 standard.

One finished container was provided for the natural gas cycling test. The container was pressurized with compressed natural gas from 300 psi to 3,600 psi (70°F) at a rate of 3-4 cycles per hour.

Following the natural gas cycling test, the container was subjected to the leak test in accordance with Clause 11.3 of the ANSI/IAS NGV2-1998 standard. The container was subsequently sectioned and the liner and liner/end boss interface were inspected for signs of deterioration.

TEST RESULTS:

The container completed the 1,000 cycle test without signs of external deterioration.

There was no evidence of container leakage either during or after the natural gas cycling test.

The liner and liner/end boss interface showed no signs of damage at the completion of the test (see Figures 1 – 3).

Tested by:
for
N. Neufeld, A.Sc.T.

Approved by:
L. R. GAMBONE
L.R. Gambone, P.Eng.

Date: February 19, 2001

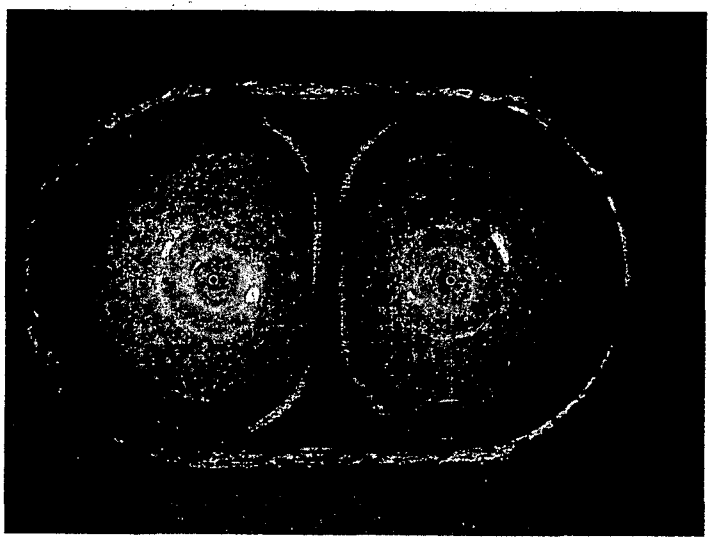

Figure 1: View of internal liner condition at the liner/end boss interface at the fill end.

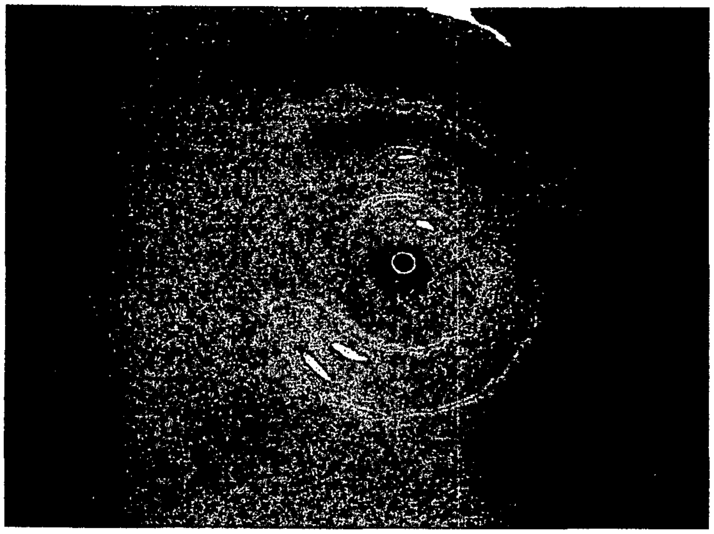

Figure 2: Close-up view of one of the liner/end boss interfaces at the fill end.

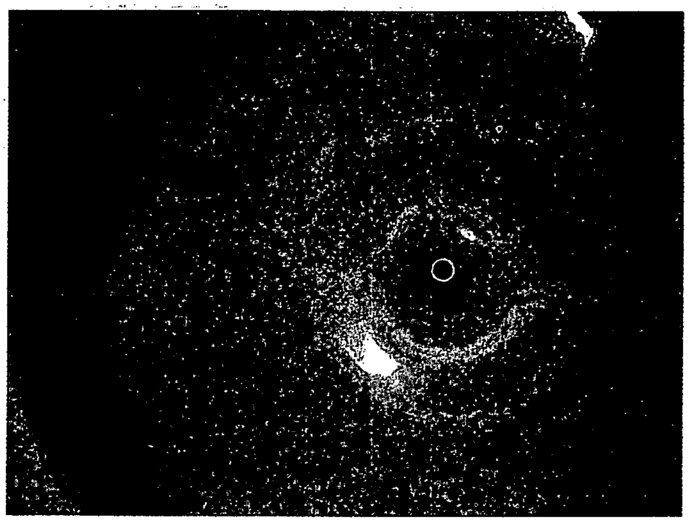

Figure 3: Close-up view of one of the liner/end boss interfaces at the fill end.