SUPERCRITICAL CO_2 TECHNOLOGY

FOR POYURETHANE SPRAY FOAM

UNDP REPORT

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ASSESSMENT OF THE USE IN COLOMBIA OF THE SUPERCRITICAL CO_2 TECHNOLOGY

UNDP REPORT

Executive Summary

This project was developed as response to the Decision 55/43 of the Multilateral Fund Executive Committee and is part of a limited group of projects with the objective to assess new technology options that use non-ODP low GWP blowing agents.

In the context of Decision XIX/6 there is a concern on the availability in Article 5 parties of validated cost effective and environmental sound technologies to phase-out HCFC-141b. This is particularly critical for the application of polyurethane (PU) spray rigid foam where most of the end users are small enterprises with a poor control of the operation and safety discipline. Several work orders are done in-doors with limited ventilation.

The proven technical options to replace HCFC-141b as blowing agent for PU spray foam are mainly limited to high GWP HFCs, HFC-245fa or HFC-365mfc/HFC-227ea blend, which have GWP values of 1030 and 964 respectively. Recent publications show promissory results with the new unsaturated HFC/HCFC blowing agents, commonly known as HFOs, that exhibit GWP values lower than 10, but the commercial availability is uncertain for the time of the conversion. The barrier for hydrocarbon technology in this application is safety during foaming because of their flammability.

The present project was designed to evaluate in an article 5 party such as Colombia the performance of super-critical CO_2, a proven technology applied in Japan for PU spray foam since 2004. A local commercialised HCFC-141b based formation was used as standard. Espumlatex, the largest Colombian 100% owned PU system house, served as local technical host to coordinate the demonstration, foam application and testing activities. The experimental protocol included two statistical full factorial designs, one 2x2x3 for polyurethane foam (PUR) and other 2x2 for polyisocyanurate (PIR). The qualitative factors (independent variables) were the technology (super-critical CO_2 versus HCFC-141b), the foaming location (Barranquilla at sea level versus Bogota at 2600 m over sea level) and foam density. To check processability field in-door applications were done in industrial warehouses in Barranquilla and Bogota and to determine the physical properties test foam sprayed samples were prepared and analysed following ASTM and JIS methods in Achilles and Espumlatex laboratories. In addition few samples (PIR and PUR) were made for E-84 fire performance testing at QAI laboratories in the United States.

The following conclusions can be pointed out:

- Supercritical CO_2 technology is a non-flammable, 0 ODP and low GWP technology. Compared to HCFC-141b based technology it does not create any incremental industrial hygiene and safety hazard.
- Supercritical CO_2 is a proven commercialised technology for spray foam that has been used in Japan since 2004.
- In Colombia, a developing country with tropical weather and various levels of altitude over sea level, Supercritical CO_2 showed a similar processability to the standard HCFC-141b based system currently used. Polyol and isocyanate components of both technologies were stable during the six months of project duration.
- In terms of physical properties of PUR foam, compared to HCFC-141b based formulations Supercritical CO_2 showed:
  - ✓ Higher thermal conductivity but better aging. The difference in lambda value between the two technologies decreased with time.
  - ✓ Similar aging behaviour in compressive strength. Values kept stable with time (initial versus six months)
  - ✓ Similar dimensional stability performance at -20 ºC. All values for both technologies were below 0.6%.
  - ✓ Improved dimensional stability at 60 ºC and 96% RH.
  - ✓ Similar adhesion strength to galvanised steel.
- In terms of physical properties of PIR foam, compared to HCFC-141b based formulations Supercritical CO_2 showed the same performance pattern than PUR:
  - ✓ Higher thermal conductivity but better aging. The difference in lambda value between the two technologies decreased with time.
  - ✓ Similar aging behaviour in compressive strength. Values kept stable with time (initial versus six months)
  - ✓ Similar dimensional stability performance at -20 ºC. All values for both technologies were below 0.6%.
  - ✓ Similar dimensional stability at 60 ºC and 96% RH in absolute values. However, the behaviour was totally different: meanwhile Supercritical CO_2 experienced a negative change in volume the HCFC-141b formulation had a positive one.
  - ✓ Lower adhesion strength to galvanised steel.
- According to fire performance test ASTM E84-12c, run on just one sample per formulation, the PIR and PUR foams based on Supercritical CO_2 would be classified as A and B respectively (NFPA).
- The cost of the required retrofit of a typical spray machine to apply the Supercritical CO_2 is in the range from 9,800 to 13,700 US dollars for PUR foam and from 11,800 to 15,700 US dollars for PIR foam.

- Supercritical CO2 technology is based on proprietary polyol and isocyanate formulations developed by Achilles. The FOB price in Japan of the Supercritical CO_2 system by kg is 7 dollars.
- Supercritical CO2 technology is a patented technology owned by Achilles Corporation. The interested parties should come to an agreement with Achilles on technology fees.

1. INTRODUCTION

In the context of Decision XIX/6 there is a concern on the availability in Article 5 parties of validated cost effective and environmental sound technologies to phase-out HCFC-141b in the different foam applications.

This project was developed as response to the Decision 55/43 of the Multilateral Fund Executive Committee and is part of a limited group of projects with the objective to assess new technology options that use non-ODP low GWP blowing agents. UNDP has prepared six demonstrations projects covering a wide spectrum of foam applications on methyl formate, methylal, pre-blended hydrocarbons and HFO-1234ze for XPS. They are already completed or are being implemented. The present project was designed to evaluate in developing countries the performance of super-critical CO_2, a relatively new technology currently used in Japan for polyurethane (PU) spray rigid foam.

PU spray rigid foams are closed-celled, air tight, resistant to mildew and fungal attack, provide no food value to rodents and have good vapour barrier properties (Randall & Lee, 2002). They find utility as an *in situ* applied insulation in applications where irregular shapes or the need for a monolithic layer of foam exists. These applications include building envelope, pipe insulation, tank insulation, rail cars, residential roofing and floors (Gum, 1992). Spray foam is now finding increasing use in retrofitting/refurbishing roofs, walls, floors and windows of existing buildings as well as in new constructions such us commercial offices, industrial factories and warehouses, agricultural pig and chicken farms (Randall & Lee, 2002). In the 2008 Progress Report the Foams Technical Options Committee (FTOC) states: "*PU Spray Foam is being increasingly recognized as an efficient means of retrofitting a number of building types*".

For developing countries, the proven technical options to replace HCFC-141b as blowing agent for PU spray foam are mainly limited to high GWP HFCs, HFC-245fa or HFC-365mfc/HFC-227ea blend, which have GWP values of 1030 and 964 respectively (100yr ITH, IPCC 4th Assessment Report 2008). Recent publications show promissory results with the new unsaturated HFC/HCFC blowing agents, commonly known as HFOs, that exhibit GWP values lower than 10, but the commercial availability is uncertain for the time of the conversion (Bodgan, 2011; Costa, 2011). The barrier for hydrocarbon technology in this application is safety during foaming because of their flammability. This issue is particularly critical for this sector where most of the enterprises are small in size with a poor control of the operation and safety discipline. Several work orders are done in-doors with limited ventilation.

One alternative that has been sporadically applied is the use as sole blowing agent of CO_2 generated from the water-isocyanate reaction (all water blown foam). It is a non-flammable and low GWP technology that does not require significant modifications in the machinery. However, despite of some success, three major drawbacks are generally associated with this approach: poor dimensional stability, caused by the high CO_2 permeability through the polyurethane matrix; poor adhesion to the different substrates due to the significant polyurea content of the polymer and relatively high thermal conductivity.

In 2004, in an effort to overcome some of the weaknesses of water blown foam, Achilles Corporation, a Japanese company, patented a spray technology based on the direct injection of CO_2 to a PU all water blown system (Japanese Patent JP2004107376). It was reported that with a minor modification to a conventional spray machine (Gusmer FF type with a 1:1 mixing ratio by volume) and by adding 1.5% of liquid CO_2, isotropic cells were obtained which lead to dimensional stable foams at the density comparable to HCFC-141b blown foams (Ohnuma & Mori, 2003, figure 2). Figure 1 shows how the modified equipment looks like. Liquid CO_2 cooled to 0 °C with a heat exchanger is supplied to the Gusmer auxiliary pump which is remodelled so that brine might circulate internally and injected to the polyol component.

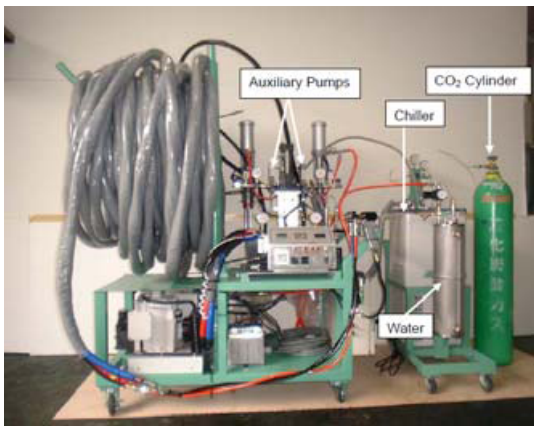


Figure 1. Modified spray machine for Supercritical CO_2

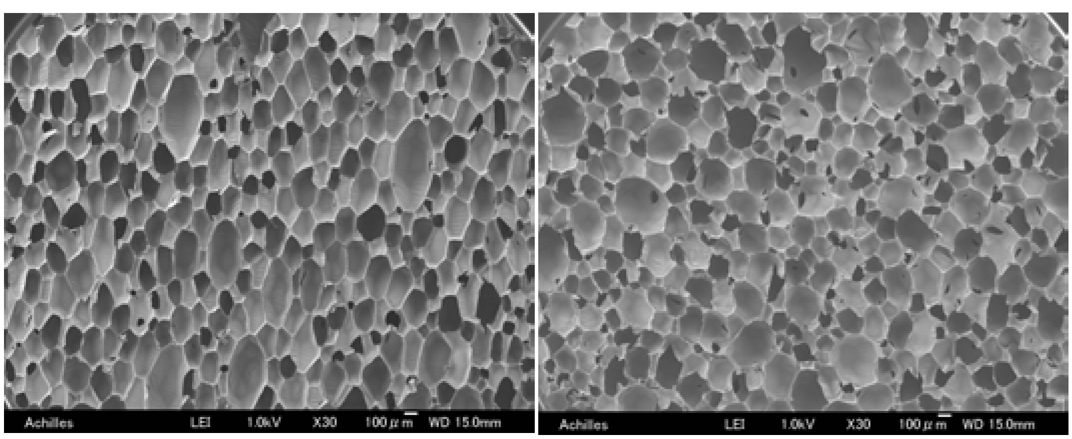


Figure 2. Spray foam with 0% liquid CO_2 versus spray foam with 1.5% liquid CO_2

The FTOC registered this development and in its 2008 progress report wrote: "*Super-critical CO_2 spray foam technologies have become established in Japan but market penetration is no more than 10%. The technology is yet to make any significant market penetration beyond Japan*".

2. PROJECT OBJECTIVES AND IMPLEMENTATION

According to the document submitted and approved in the 60th meeting of the Executive Committee of the Multilateral Fund held in Montreal in April 2010, the project objectives are:

1. Make a technical and economic assessment of the use in an Article 5 party (Colombia) of the super-critical CO_2 technology for the application of PU spray rigid foam. **Local commercial formulation based on HCFC-141b served as standard.**
2. Disseminate the technology to interested system houses in Colombia and other Latin American countries.

Espumlatex, the largest Colombian 100% owned PU system house, served as local technical host to coordinate the demonstration, foam application and testing activities.

The start-up of the project took place the week of July 25, 2012. The implementation was done in a team effort among Achilles Corp., Espumlatex, the National Ozone Unit (UTO) and UNDP. The following activities were carried out:

Activity	Date
Project Kick-off. Definition of evaluation plan and experimental protocol.	June 25 - 29, 2012
Shipment of injection equipment modified to use the Supercritical CO_2 technology. Shipment of Achilles PU materials, nationalization and in-land transportation.	July 13 - September 30
Application of Supercritical CO_2 and HCFC-141b based systems. Preparation of foam samples to test physical properties	October 1 - 7
Evaluation of foam physical properties (Espumlatex, Achilles, QAI laboratories)	October 15, 2013 - March 31, 2013
Preparation of Final Report	May, 2013
Presentation of the final results and conclusions in an international seminar	June, 2013

3. EXPERIMENTAL

3.1 Experimental Design

When a specific process or experiment is repeated under what are, as nearly as possible, the same conditions, the observed results are never identical (Box & Hunter & Hunter, 1978). This statement is particularly true in the field of PU foam. This fluctuation that occurs from one repetition to another is called *experimental error* and refers to variations that are unavoidable such as human errors of measurement, analysis and sampling. The no consideration of experimental error can lead to false conclusions about the *real* effect of a specific independent variable. In the line of these thoughts and having in mind that usually is most efficient to estimate the effects of several variables simultaneously, it was decided to apply for this project the technique of statistical design of experiments, commonly known as DOE.

Two full factorial designs were conducted, one 2x2x3 for polyurethane foam (PUR) and other 2x2 for polyisocyanurate (PIR). The qualitative factors (independent variables) and levels are described in tables 1 and 2. *Genuine* replicates were made in all points of the design to have the best estimate of the error variance across the experimental region.

Table 1. Experimental Design for PUR

Factors (independent variables)	Levels
Technology	Supercritical CO_2
	HCFC-141b, High Water
	HCFC-141b, Low Water
Location	Barranquilla: sea level, high ambient temperature (30 ºC), high relative humidity (80%)
	Bogotá: 2,600 m over sea level, low ambient temperature (20 ºC), moderate relative humidity (60%)
Foam Density	High
	Low

Table 2. Experimental Design for PIR

Factors (independent variables)	Levels
Technology	Supercritical CO_2
	HCFC-141b
Location	Barranquilla: sea level, high ambient temperature (30 ºC), high relative humidity (80%)
	Bogotá: 2,600 m over sea level, low ambient temperature (20 ºC), moderate relative humidity (60%)

3.2. Formulations

For **Supercritical CO_2 technology** three Achilles proprietary water blown formulations were used:

- PUR formulation, 30 kg/m_3 density, designed for walls in Japan. It was applied in Bogota and Barranquilla. For the experimental design it was denominated as “Supercritical CO_2, PUR, Low Density (LD)”.
- PUR formulation, 40 kg/m_3 density, designed for roofing. It was applied in Bogota and Barranquilla. For the experimental design it was denominated as “Supercritical CO_2, PUR, High Density (HD)”.
- PIR formulation, 30 kg/m_3 density, designed for walls in Japan. It was applied in Bogota and Barranquilla. Because of the high altitude over sea level for the application in Bogotá a reduced amount of water was added in the machine, directly to the polyol component. For the experimental design it was denominated as “Supercritical CO_2, PIR”.

For **141b based technology** five Espumlatex proprietary formulations, four for PUR and one for PIR, were used:

- PUR formulation, high water content, low density. It was applied in Bogota and Barranquilla. For the experimental design it was denominated as "HCFC-141b, PUR, High Water (HW), Low Density (LD)".
- PUR formulation, high water content, high density. It was applied in Bogota and Barranquilla. For the experimental design it was denominated as "HCFC-141b, PUR, High Water (HW), High Density (HD)".
- PUR formulation, low water content, low density. It was applied in Bogota and Barranquilla. For the experimental design it was denominated as "HCFC-141b, PUR, Low Water (LW), Low Density (LD)". **This is the commercial formulation sold by Espumlatex in the local market.**
- PUR formulation, low water content, high density. It was applied in Bogota and Barranquilla. For the experimental design it was denominated as "HCFC-141b, PUR, High Water (HW), High Density (HD)". **This is the commercial formulation sold by Espumlatex in the local market.**
- PIR formulation. It was applied in Bogota and Barranquilla. For the experimental design it was denominated as "HCFC-141b, PIR".

The table 3 summarizes the blowing agent characteristics of the HCFC-141b based formulations for PUR:

Table 3. Blowing agent characteristics of HCFC-141b formulations for PUR				
	LW-LD	LW-HD	HW-LD	HW-HD
CO_2 moles /kg of polymer	0.23	0.21	0.66	0.58
HCFC-141b moles /kg of polymer	0.94	0.84	0.38	0.38
Total gas moles/kg of polymer	1.17	1.05	1.04	0.96
Initial mole fraction, CO_2	0.19	0.20	0.64	0.61
Initial mole fraction HCFC-141b	0.81	0.8	0.36	0.39

3.3. Spray application conditions

Field in-door applications of both systems, Supercritical CO_2 and HCFC-141b, were done in industrial warehouses in Barranquilla and Bogota. *Both materials were easy to process and no particular issues were observed.*

For physical test samples the foam was sprayed to a thickness of 5 mm in one primer and three passes applied in crossed directions (dead time between passes: 1 minute) on 1.50 m x 0.80 m pieces of plywood. Additional samples were sprayed on 2.50 m long pieces for E-84 testing. The Table 4 shows the spray conditions.

Table 4. Spray conditions				
	Supercritical CO_2		HCFC-141b	
	Barranquilla	Bogota	Barranquilla	Bogota
Spray machine	NF-12J Proportioning unit		Graco E-10	
Spray gun	GAP Pro (round pattern)		Fusion AP	
Percentage by weight of CO_2, %	1.0 for PUR, 1.75 for PIR		Non applicable	
Ambient Temperature, ºC	31	19 - 20	31	19 - 20
Relative Humidity, %	62 - 89	62 - 69	62 - 67	52 - 62
Substrate Temperature, ºC	31	19 - 20	32	20 - 22
Iso Temperature, ºC	45	45	50	50
Polyol Temperature, ºC	45	45	49	49
Primary Heater	Off	45	Off	Off
Hose length, m	45	45	15	15
Hose Temperature, ºC	40 (PUR) 45 (PIR)	40 (PUR) 45 (PIR)	40	40
Static Pressure, psi	1,000		1,600	
Dynamic Pressure, psi	750		1,400	
Tack Free Time, /Rise Time, (s/s)	6/10 (PUR) 2/5 (PIR)	10/15 (PUR) 3/7 (PIR)	2/7 sec (PUR) 2/5 sec (PIR)	4/12 sec (PUR) 2/7 sec (PIR)

3.4. Test Methods

Table 5 lists the different test methods to determine the foam physical properties

Table 5. Test Methods		
Property	**Test**	**Testing Laboratory**
Reactivity	Visual	In-situ during application
Foam core density	ASTM D-1622	Espumlatex
Thermal Conductivity	ASTM C-518	Espumlatex
Compression strength	ASTM D-1621	Espumlatex
Adhesion strength	ASTM D-1623	Espumlatex
Water vapour permeability	JIS A-9526	Achilles
Water absorption	JIS A-9511	Achilles
Closed cell content	ASTM D-2856	Achilles
Dimensional stability	ASTM D-2126	Espumlatex
Aging		
Thermal Conductivity	ASTM C-518	Espumlatex
Compressive strength	ASTM D-1621	Espumlatex
Fire Performance	ASTM E-84, 12c	QAI Laboratories

4. RESULTS

During the six months of the duration of the project the polyol side formulations of both technologies, Supercritical CO_2 and HCFC-141b based, were stable and no component separation was observed. The table 6 and 7 show the physical properties of the PUR and PIR foams. They correspond to the experimental designs described in tables 1 and 2.

Table 6. Physical Properties of PUR foam

Property	Supercritical CO2				HCFC-141b, Low Water				HCFC-141b, High Water			
	Barranquilla		Bogota		Barranquilla		Bogota		Barranquilla		Bogota	
	HD	LD	HD	LD	HD	LD	HD	LD	HD	LD	HD	LD
Core Density, kg/m^3	46.5	35.3	38.0	28.5	43.6	37.8	36.0	31.0	45.0	48.3	41.2	34.6
	44.1	41.1	33.9	33.6	44.2	40.5	39.3	31.1	45.1	47.3	43.9	36.5
Thermal Conductivity, 24ºC, 24 hours, mw/mK	34.23	33.95	34.09	34.02	23.97	24.84	24.47	23.79	25.99	28.84	28.47	28.37
	34.11	33.94	34.07	33.99	24.23	24.24	24.11	24.34	27.32	29.01	29.78	28.56
Thermal Conductivity, 24ºC, 2 weeks at 20 ºC and 50% RH, mw/mK	34.19	34.04	34.30	34.05	24.68	25.82	25.40	24.88	29.81	29.84	29.89	29.58
	34.06	33.88	34.19	34.01	24.83	25.18	25.11	24.92	29.05	30.04	30.36	29.57
Thermal Conductivity, 24ºC, 4 weeks at 20 ºC and 50% RH, mw/mK	34.22	34.28	34.19	34.19	25.35	26.05	25.80	25.37	30.19	30.16	30.15	29.33
	34.07	34.04	34.03	34.03	25.42	25.61	25.76	25.56	29.68	30.35	30.70	30.36
Compressive Strength, parallel to rise, kPa	179.98	191.00	158.20	134.78	313.37	254.48	248.76	206.24	350.60	302.43	265.25	174.29
	206.32	211.05	160.27	153.08	330.79	268.94	275.35	189.37	343.67	306.85	249.03	202.20
Compressive Strength, parallel to rise, 6 months, kPa	213.41	189.79	151.61	123.83	326.28	251.45	248.95	204.36	325.64	289.19	289.50	195.61
	233.68	245.68	154.51	136.54	339.74	299.32	269.66	171.86	339.34	305.15	264.46	235.16
Dimensional Stability, -20 ºC, 24 hours, Vol. %	0.026	-0.414	-0.126	-0.304	0.021	-0.003	-0.141	-0.269	0.032	-0.056	-0.010	-0.071
	-0.150	0.094	-0.115	-0.121	0.082	0.045	-0.242	0.055	-0.139	-0.067	-0.023	-0.677
One week, %	-0.145	-0.568	-0.023	-0.389	-0.045	-0.003	-0.221	-0.378	0.092	-0.189	0.065	0.108
	-0.531	-0.198	0.014	-0.329	-0.224	-0.069	-0.040	-0.243	-0.004	-0.173	0.075	-0.146
Two weeks, %	-0.139	-0.262	-0.132	-0.563	0.045	-0.138	-0.332	-0.024	0.105	0.074	-0.113	-0.126
	-0.433	0.069	-0.039	-0.056	0.165	0.032	-0.242	-0.433	0.022	0.036	0.010	-0.267
Dimensional Stability, 60 ºC, 95% RH, 24 hours, Vol. %	3.114	1.056	10.449	3.231	1.903	2.933	2.939	2.882	0.284	1.679	0.979	1.813
	1.731	2.030	8.103	3.132	1.542	2.514	2.501	2.817	0.445	1.795	2.112	1.796
One week, %	0.572	0.584	6.066	1.009	2.456	3.534	3.153	3.201	0.510	1.660	0.791	1.867
	-0.809	0.783	4.803	0.745	1.987	3.302	2.922	3.178	0.482	2.100	1.594	1.496
Two weeks, %	0.069	0.430	5.271	0.412	2.521	3.789	3.347	3.382	0.743	1.821	0.814	1.727
	-1.314	0.545	4.261	0.515	2.156	3.585	3.094	3.302	0.878	2.037	1.720	1.328
Dimensional Stability, 70 ºC, Ambient RH, 24 hours, Vol. %	-2.670	0.315	3.724	0.189	-0.114	0.780	-0.664	0.453	-0.962	-0.822	-1.551	-1.101
	-0.768	-0.080	1.116	0.595	-0.103	-0.233	0.407	0.139	-0.883	-0.399	-0.544	-1.147
One week, %	-3.084	-0.240	2.972	-0.438	-0.043	0.886	-0.672	0.961	-0.709	-0.510	-1.400	-0.842
	-1.387	-0.831	0.639	-0.058	0.044	-0.090	0.485	0.036	-0.684	-0.638	-0.274	-0.931
Two weeks, %	-3.893	-0.473	2.883	-0.451	0.098	1.073	-0.432	1.293	-0.627	-0.808	-1.002	-0.381
	-1.726	-0.399	0.630	-0.244	0.212	-0.043	0.641	0.662	-0.591	-0.023	0.058	-0.470
Closed Cell Content, %	64.30	64.00	83.50	71.10	75.80	81.50	92.30	91.60	78.40	81.80	89.10	90.10
	72.30	73.90	80.10	82.00	69.90	78.10	91.80	90.50	74.10	86.60	90.40	90.30
Water absorption, g/100 cm^2	0.80	1.12	1.17	1.53	0.77	1.01	0.58	0.42	0.76	0.84	0.56	0.81
	0.75	0.93	1.02	1.31	0.84	0.88	0.56	0.50	0.73	0.92	0.57	0.63
Water Vapour Permeability, ng/Pa.s.m	3.44	6.06	4.57	5.89	3.88	4.61	3.72	4.14	4.43	4.46	4.41	4.97
	3.92	3.82	5.62	4.00	3.59	4.01	3.65	3.57	4.33	4.62	4.14	4.74
Adhesion Strength to metal (galvanized steel), N/cm^2	14.33	20.56	7.83	14.99	11.14	4.31	11.36	8.46	12.34	20.59	6.63	15.47
	13.96	15.33	7.94	15.24	4.70	1.66	31.35	8.02	15.91	6.66	27.99	15.59

HD: High Density. LD: Low Density

Table 7. Physical Properties of PIR foam				
Property	Supercritical CO2		HCFC-141b	
	Barranquilla	Bogota	Barranquilla	Bogota
Core Density, kg/m3	40.8	37.0	43.0	32.3
	35.7	37.8	44.4	32.4
Thermal Conductivity, 24ºC, 24 hours, mw/mK	34.42	34.02	28.39	20.70
	34.27	34.11	27.92	20.82
Thermal Conductivity, 24ºC, two weeks at 20 ºC and 50% RH, mw/mK	34.66	34.33	30.05	22.48
	33.76	34.27	28.23	22.22
Compressive Strength, parallel to rise, kPa	141.18	126.32	225.37	132.89
	119.38	144.49	235.59	134.43
Compressive Strength, parallel to rise, 6 months, kPa	119.15	139.77	221.62	140.29
	129.40	130.58	209.99	142.68
Dimensional Stability, -20 ºC, 24 hours, Vol. %	0.258	0.598	0.117	-0.041
	0.148	0.013	0.156	-0.229
One week, %	0.018	-0.228	-0.023	-0.120
	-0.194	-0.044	0.072	-0.178
Two weeks, %	0.299	-0.449	-0.018	0.030
	0.572	-0.023	0.067	-0.006
Dimensional Stability, 60 ºC, 95% RH, 24 hours, Vol. %	-1.695	-2.121	4.355	3.347
	-1.920	-2.768	5.904	2.565
One week, %	-3.197	-3.798	3.721	4.865
	-3.851	-4.904	4.986	4.211
Two weeks, %	-3.731	-4.180	3.107	5.944
	-4.371	-5.502	4.406	5.537
Dimensional Stability, 70 ºC, Ambient RH, 24 hours, Vol. %	-0.877	-0.292	-0.484	-0.371
	-1.515	0.033	-0.387	-0.316
One week, %	-2.929	-1.618	0.212	-0.086
	-4.108	-1.042	-0.767	-0.226
Two weeks, %	-3.768	-2.168	-0.053	-0.030
	-3.793	-1.554	-1.073	-0.067
Closed Cell Content, %	19.60	39.60	88.50	86.50
	42.20	53.10	89.30	84.50
Water absorption, g/100 cm2	1.67	1.70	1.94	3.13
	1.59	1.54	1.89	3.26
Water Vapour Permeability, ng/Pa.s.m	8.63	5.88	8.58	6.34
	8.38	6.27	8.62	6.59
Adhesion Strength to metal (galvanized steel), N/cm2	7.58	6.57	16.97	11.23
	8.71	9.34	16.30	6.89

The table 8 shows the results of the fire performance test, ASTM E-84, run on four foam samples: Supercritical CO_2, PUR and PIR, and HCFC-141b, PUR -low water content- and PIR.

Table 8. Fire Performance Test, ASTM E84-12c				
Technology		Flame Spread	Smoke Developed	NFPA Class
Supercritical CO2	PUR	70	331	B
	PIR	20	286	A
HCFC-141b	PUR, low water	390	100*	C
	PIR	25	200	A

* Due to heat production and lack of air flow through the chamber, the test was terminated at 1 minute, 42 seconds. Had the test continued for the normal 10 minute period, the flame spread value would have remained unchanged. The smoke number is the smoke value at time of termination.

5. ANALYSIS OF RESULTS

To assess the statistical significance of the effect of the different factors on the foam properties an analysis of variance (ANOVA) was developed for each property. In this section the ANOVA of few selected foam properties, critical for the thermal insulation performance, such as initial thermal conductivity (lambda value) and aging of lambda value, will be shown for PUR and PIR. The analysis of core density, dimensional stability, compressive strength, aging of compressive strength and adhesion to galvanised steel are described in the annex 1.

5.1. PUR foam

Analysis of initial thermal conductivity for PUR

The tables 9 and 10 show a summary of the results of the initial thermal conductivity (Lambda value) and the corresponding ANOVA.

	Table 9. Lambda Value, 24 ºC, 24 hours, mW/mK						
	Supercritical CO_2		HCFC-141b, low water		HCFC-141b, high water		AVERAGE
	HD	LD	HD	LD	HD	LD	
Barranquilla	34.17*	33.95	24.10	24.54	26.66	28.93	28.72
Bogotá	34.08	34.01	24.29	24.07	29.13	28.47	29.01
AVERAGE	34.05		24.25		28.29		

	AVERAGE
HD	28.74
LD	28.99

* All the values are the average of two genuine replicates (table 6).

Table 10. ANOVA of Lambda value, 24 ºC, 24 hours						
Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	*P**	
Technology	2	388.174	194.087	1052.437	0.000	Significant
Density	1	0.388	0.388	2.1039	0.173	
Location	1	0.479	0.479	2.5974	0.133	
Tec*Dens	2	0.977	0.489	2.6489	0.112	
Dens*Loc	1	1.978	1.978	10.7257	0.007	Significant
Tec*Loc	2	1.582	0.791	4.2892	0.039	Significant
Pure Error	12	2.213	0.184			

* Probability of Type I error (rejecting the null hypothesis when it is in fact true). If $P < 0.05$ it is considered that the effect of the factor is significant.

From table 9 it is concluded there is a statistical significant difference in the initial lambda value among the three systems: Supercritical CO_2 developed a thermal conductivity 20.3% higher than high water-HCFC-141b and 40.4% higher than low water-HCFC-141b. As expected the low water-HCFC-141b provided a better (lower) value than high water-HCFC-141b because of the greater initial mole fraction of HCFC-141b in the gas cell. No significant differences in Lambda between the two locations and the high and low density formulations were observed.

Lambda value, aged 4 weeks at 20 ºC and 50% RH, 24 ºC

The tables 11 and 12 describe the results of Lambda value, aged four weeks at 20 ºC and 50% RH, and the corresponding ANOVA.

	Table 11. Lambda Value, 24 ºC, 4 weeks, mW/mK						
	Supercritical CO_2		HCFC-141b, low water		HCFC-141b, high water		AVERAGE
	HD	LD	HD	LD	HD	LD	
Barranquilla	34.14	34.16	25.38	25.83	29.93	30.25	29.95
Bogotá	34.11	34.11	25.78	25.47	30.43	29.85	29.96
AVERAGE	34.13		25.61		30.11		

	AVERAGE
HD	29.96
LD	29.94

Table 12. ANOVA of Lambda value, 24 ºC, 4 weeks						
Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	*P*	
Technology	2	290.529	145.265	1725.91	0.000	Significant
Density	1	0.002	0.002	0.02	0.885	
Location	1	0.000	0.000	0.00	0.962	
Tec*Dens	2	0.041	0.021	0.24	0.787	
Dens*Loc	1	0.469	0.469	5.57	0.036	Significant
Tec*Loc	2	0.007	0.004	0.04	0.958	
Pure Error	12	1.010	0.084			

Results are similar to those of the initial lambda value (24 hours) but the difference among the three PU systems became shorter: Supercritical CO_2 provided a thermal conductivity 33.2% higher than high water-HCFC-141b and 13.3% higher than low water-HCFC-141b.

Aging of Lambda, 4 weeks versus 24 hours

The variation percentage of the lambda value, four weeks versus 24 hours, was calculated and analysed in a similar way than the other properties.
The tables 13 and 14 show a summary of the results and the corresponding ANOVA.

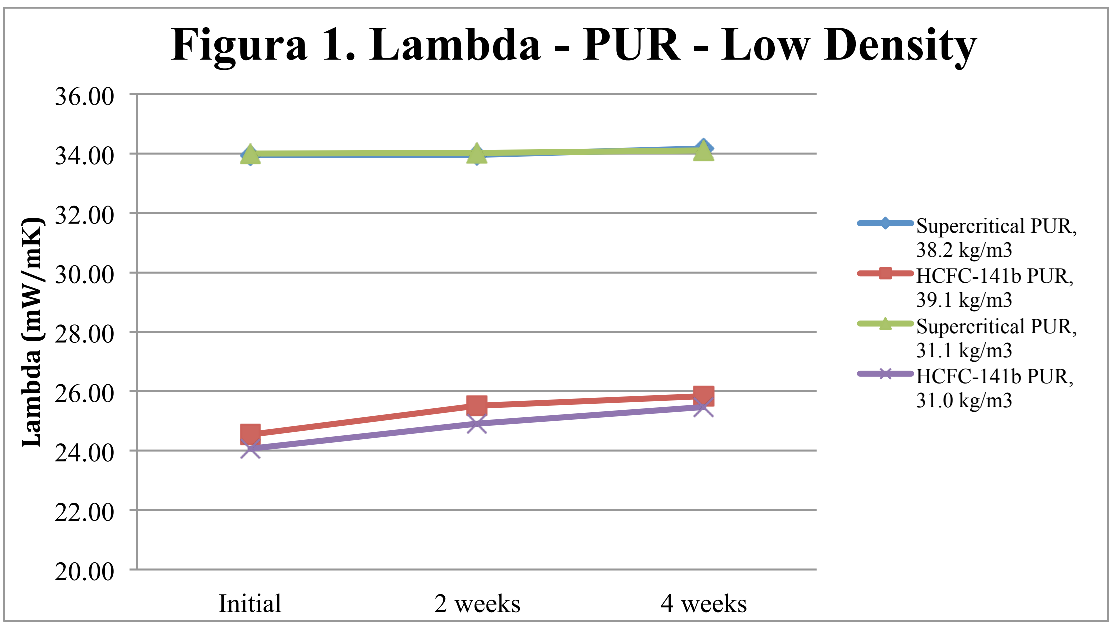
	Table 13. Variation Percentage in Lambda Value, 4 weeks versus 24 hours, %						
	Supercritical CO_2		HCFC-141b, low water		HCFC-141b, high water		AVERAGE
	HD	LD	HD	LD	HD	LD	
Barranquilla	-0.08	0.64	5.33	5.26	12.39	4.59	4.69
Bogotá	0.09	0.32	6.13	5.83	4.50	4.84	3.62
AVERAGE	0.24		5.64		6.58		

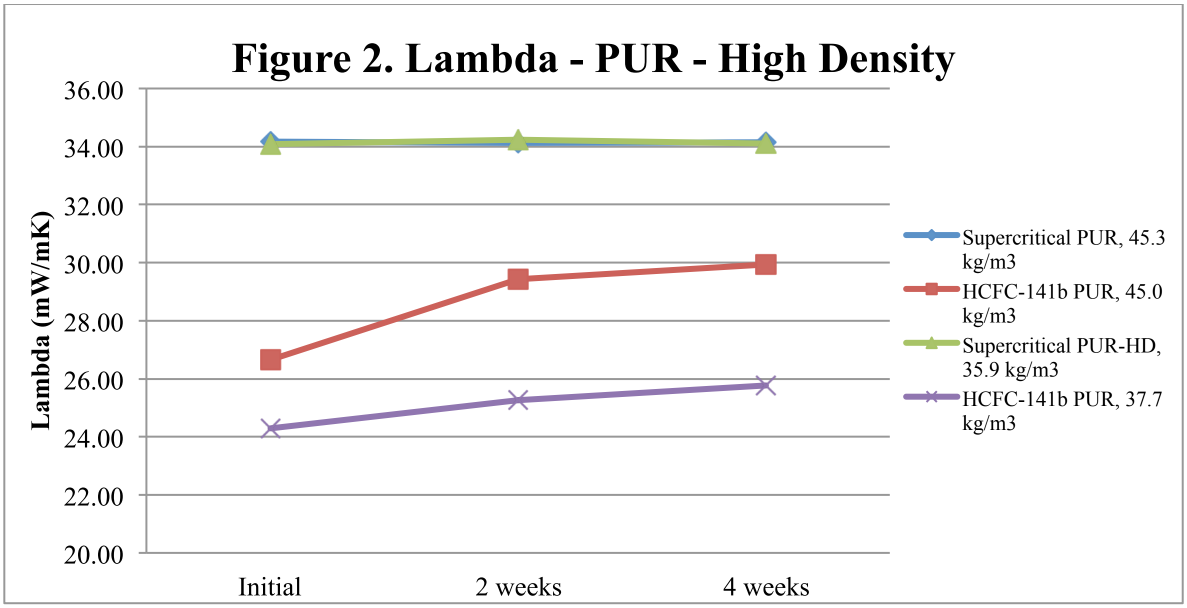
	AVERAGE
HD	4.73
LD	3.58

Table 14. ANOVA of variation percentage in lambda value						
Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	*P*	
Technology	2	187.161	93.581	28.17	0.000	Significant
Density	1	7.880	7.880	2.37	0.149	
Location	1	6.865	6.865	2.07	0.176	
Tec*Dens	2	20.403	10.202	3.07	0.084	
Dens*Loc	1	9.154	9.154	2.76	0.123	
Tec*Loc	2	23.233	11.617	3.50	0.064	
Pure Error	12	39.870	3.323			

The Supercritical CO_2 technology exhibited a statistically significant better performance than the 141b based systems: its variation percentage was in average 0.24% compared to 5.64% of low water-HCFC-141b and 6.58% of high water-HCFC-141b.

These results are graphically shown in figures 1 and 2.





5.2. PIR foam

Initial thermal conductivity for PIR

The tables 15 and 16 show the results of initial thermal conductivity (lambda) and the corresponding ANOVA.

	Table 15. Lambda Value, 24 ºC, 24 hours, mW/mK		
	Supercritical CO_2	HCFC-141b	AVERAGE
Barranquilla	34.35*	28.16	31.25
Bogotá	34.07	20.76	27.41
AVERAGE	34.21	24.46	

* All the values are the average of two genuine replicates (table 7).

Table 16. ANOVA of lambda value, 24 ºC, 24 hours						
Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	*P*	
Technology	1	190.060	190.060	5590.0	0.000	Significant
Location	1	29.440	29.440	865.8	0.000	Significant
Tec*Loc	1	25.323	25.323	744.8	0.000	Significant
Pure Error	4	0.136	0.034			

From table 16 there is a statistical significant different in the initial lambda value between the two systems: on average Supercritical CO_2 developed a thermal conductivity 39.9% higher than HCFC-141b although the difference greatly varied with the location (significant interaction between technology and location).

Thermal Conductivity (lambda), aged 4 weeks at 20 ºC and 50% RH, 24 ºC

The tables 17 and 18 describe the results of the thermal conductivity (lambda), aged four weeks at 20 ºC and 50% RH, and the corresponding ANOVA.

	Table 17. Lambda Value, 24 ºC, 4 weeks, mW/mK		
	Supercritical CO_2	HCFC-141b	AVERAGE
Barranquilla	34.06	29.51	31.78
Bogotá	33.59	23.41	28.50
AVERAGE	33.82	26.46	

Table 18. ANOVA of lambda value, 24 ºC, 4 weeks						
Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	*P*	
Technology	1	108.511	108.511	580.27	0.000	Significant
Location	1	21.550	21.550	115.24	0.000	Significant
Tec*Loc	1	15.839	15.839	84.70	0.001	Significant
Pure Error	4	0.748	0.187			

Results were similar to those of the initial lambda value (24 hours) but the difference between the two PU systems became shorter: Supercritical CO_2 provided a thermal conductivity 27.8% higher than HCFC-141b. It is important to note the significant interaction between the technology and location, especially in the case of HCFC-141b that provided when sprayed in Barranquilla a lambda 26% higher than the formulation applied in Bogotá. Supercritical CO_2 gave similar values for both locations.

Aging of Lambda value, 4 weeks versus 24 hours

The variation percentage of the lambda value, 4 weeks versus 24 hours, was calculated and analysed in a similar way than the other properties. The tables 19 and 20 show a summary of the results and the corresponding ANOVA.

	Table 19. Variation Percentage in Lambda Value, 4 weeks versus 24 hours		
	Supercritical CO_2	HCFC-141b	AVERAGE
Barranquilla	-0.85%	4.56%	1.85%
Bogotá	-1.42%	11.31%	4.94%
AVERAGE	-1.14%	7.93%	

Table 20. ANOVA of variation percentage in lambda value						
Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	*P*	
Technology	1	0.0164463	0.0164463	176.32	0.000	Significant
Location	1	0.0019077	0.0019077	20.45	0.011	Significant
Tec*Loc	1	0.0026864	0.0026864	28.80	0.006	Significant
Pure Error	4	0.0003731	0.0000933			

The Supercritical CO_2 technology exhibited a statistically significant better performance than the 141b based system: the lambda values measured in 4 weeks were in average 1.14% lower that the initials (24 hours) meanwhile the thermal conductivity of HCFC-14b based formulation increased by 7.93%. This result is graphically observed in figure 3.

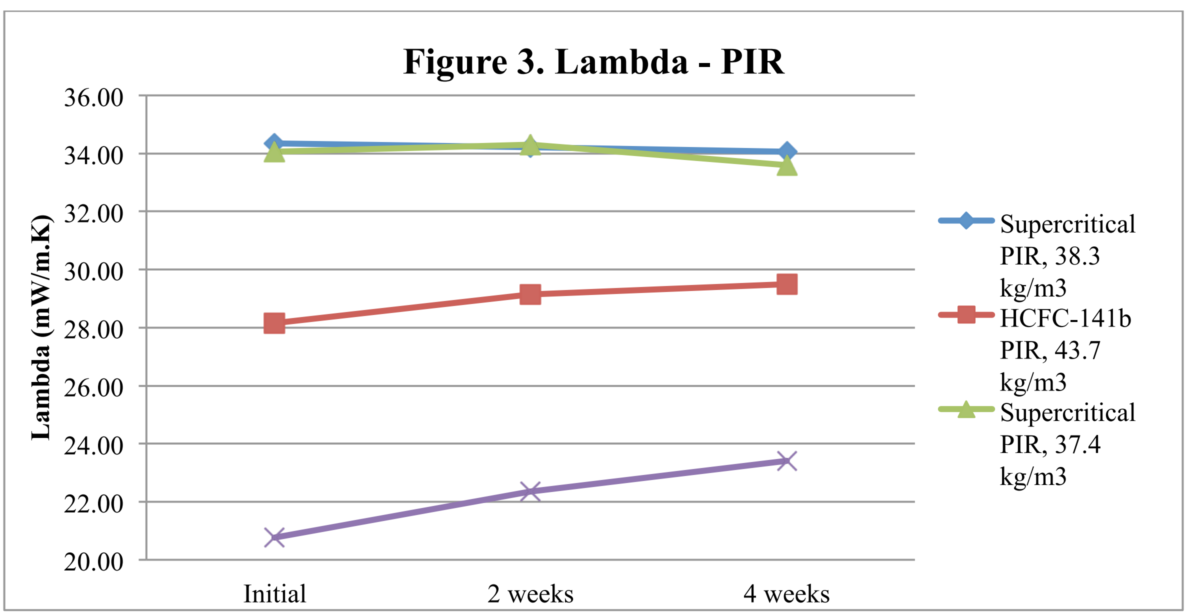


Figure 3. Lambda - PIR

6. SAFETY & INDUSTRIAL HYGIENE

The Supercritical CO_2 technology is based on PU all water blown systems. Compared to conventional HCFC-141b based formulations they do not exhibit any incremental issue on safety and industrial hygiene. Nevertheless, when not properly handled the PU chemicals can severely affect the human health. Handling procedures and precautions stipulated by suppliers should be followed. The Material Safety Data Sheets (MSDS) of the Achilles products for Supercritical CO_2 are provided in the Appendix.

7. INCREMENTAL COSTS OF THE SUPERCRITICAL CO_2 TECHNOLOGY

7.1. Incremental Capital Costs

Several conventional spray machines can be retrofitted to work with Supercritical CO_2 technology. The critical features that they should have are:
Proportioning Pump: working pressure of 2,000 psi, piston stroke equal or higher than 3 inches. Heated hose: longer than 45 meters (40 ºC for PUR, 45 ºC for PIR).

The table 39 lists the models of typical spray machines that are suitable for retrofit and the associated cost.

Table 21. Suitable spray machines suitable to retrofit and associated retrofitting cost

Model	PUR (US dollars)	PIR (US dollars)
Gusmer models: FF 1600(converted hydraulically-driven), HF-1600	9,800	11,800
Gusmer models: H-2000, H20/35	13,700	15,700
Graco models: A-20, A25	9,800	11,800
Graco models: H-25	13,700	15,700

The Supercritical CO2 technology is a patented technology owned by Achilles Corporation. The interested parties should come to an agreement with Achilles on technology fees.

7.2. Incremental Operating Costs

The Supercritical CO2 technology is based on proprietary polyol and isocyanate formulations developed by Achilles. The FOB price in Japan for the PUR and PIR systems is 7.00 US dollars per kg. The CIF price of a HCFC-141b based spray system for PUR in Colombia is in the range from 3.80 to 4.20 US dollars.

8. CONCLUSIONS

- Supercritical CO_2 technology is a non-flammable, 0 ODP and low GWP technology. Compared to HCFC-141b based technology it does not create any incremental industrial hygiene and safety hazard.
- Supercritical CO_2 is a proven commercialised technology for spray foam that has been used in Japan since 2004.
- In Colombia, a developing country with tropical weather and various levels of altitude over sea level, Supercritical CO_2 showed a similar processability to the standard HCFC-141b spray system currently used. Polyol and isocyanate components of both technologies were stable during the six months of project duration.
- In terms of physical properties of PUR foam, compared to HCFC-141b based formulations Supercritical CO_2 showed:
  - ✓ Higher thermal conductivity but better aging. The difference in lambda value between the two technologies decreased with time.
  - ✓ Similar aging behaviour in compressive strength. Values kept stable with time (initial versus six months)
  - ✓ Similar dimensional stability performance at -20 ºC. All values for both technologies were below 0.6%.
  - ✓ Improved dimensional stability at 60 ºC and 96% RH.
  - ✓ Similar adhesion strength to galvanised steel.
- In terms of physical properties of PIR foam, compared to HCFC-141b based formulations Supercritical CO_2 showed the same performance pattern than PUR:
  - ✓ Higher thermal conductivity but better aging. The difference in lambda value between the two technologies decreased with time.
  - ✓ Similar aging behaviour in compressive strength. Values kept stable with time (initial versus six months)
  - ✓ Similar dimensional stability performance at -20 ºC. All values for both technologies were below 0.6%.
  - ✓ Similar dimensional stability at 60 ºC and 96% RH in absolute values. However, the behaviour was totally different: meanwhile Supercritical CO_2 experienced a negative change in volume the HCFC-141b formulation had a positive one.
  - ✓ Lower adhesion strength to galvanised steel.
- According to fire performance test ASTM E84-12c, run on just one sample per formulation, the PIR and PUR foams based on Supercritical CO_2 would be classified as A and B respectively (NFPA).
- The cost of the required retrofit of a typical spray machine to apply the Supercritical CO_2 is in the range from 9,800 to 13,700 US dollars for PUR foam and from 11,800 to 15,700 US dollars for PIR foam.

- Supercritical CO2 technology is based on proprietary polyol and isocyanate formulations developed by Achilles. The FOB price in Japan of the Supercritical CO_2 system by kg is 7 dollars.
- Supercritical CO2 technology is a patented technology owned by Achilles Corporation. The interested parties should come to an agreement with Achilles on technology fees.

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ANNEX 1. ANALYSIS OF VARIANCE OF THE FOAM PROPERTIES

In the section 5 of the report the ANOVA corresponding to the foam thermal conductivity and its aging was presented. In this annex the ANOVA of the rest of the foam properties are shown for PUR and PIR.

1. PUR

Foam Core Density

The tables A-1 and A-2 show a summary of the results of the foam core density (values taken from table 6) and the corresponding ANOVA. As expected there are statistically significant differences in density between the high and low density formulations (HD > LD), explained by the different recipes, and between the two locations (Barranquilla > Bogota), explained by the different altitudes over sea level. It is also observed that Supercritical CO_2 and low water-HCFC-141b exhibit similar core densities, but lower than high water-HCFC-141b.

Table A-1. Foam core density, kg/m³

	Supercritical CO_2		HCFC-141b, low water		HCFC-141b, high water		AVERAGE
	HD	LD	HD	LD	HD	LD	
Barranquilla	45.3*	38.2	43.9	39.2	45.1	47.8	43.23
Bogotá	36.0	31.1	37.7	31.1	42.6	35.6	35.63
AVERAGE	37.63		37.94		42.74		

	AVERAGE
HD	41.73
LD	37.13

* All the values are the average of two genuine replicates

Table A-2. ANOVA of foam core density, PUR

Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	*P**	
Technology	2	131.401	65.701	13.99	0.001	Significant
Density	1	126.96	126.960	27.04	0.000	Significant
Location	1	346.56	346.560	73.81	0.000	Significant
Tec*Dens	2	18.483	9.242	1.97	0.182	
Dens*Loc	1	14.727	14.727	3.14	0.102	
Tec*Loc	2	1.308	0.654	0.14	0.871	
Pure Error	12	56.34	4.695			

The tables A-3 and A-4 show a similar summary and ANOVA than the tables A-1 and A-2 but only comparing Supercritical CO_2 and low water-HCFC-141b in an effort to check if there is a significant difference in density between these two formulations.

	Table A-3. Foam core density, kg/m^3				
	Supercritical CO_2		HCFC-141b, low water		AVERAGE
	HD	LD	HD	LD	
Barranquilla	45.3	38.2	43.9	39.2	41.64
Bogotá	36.0	31.1	37.7	31.1	33.93
AVERAGE	37.63		37.94		

	AVERAGE
HD	40.70
LD	34.86

Table A-4. ANOVA of foam core density, PUR						
Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	P	
Technology	1	0.391	0.4	0.06	0.810	
Density	1	136.306	136.3	21.64	0.002	Significant
Location	1	237.931	237.9	37.78	0.000	Significant
Tec*Dens	1	0.106	0.1	0.02	0.900	
Dens*Loc	1	0.131	0.1	0.02	0.946	
Tec*Loc	1	1.156	1.2	0.18	0.680	
Pure Error	8	50.385	6.3			

From table A-4 it is concluded that there is no evidence that there is a density difference between the two PU systems: Supercritical CO_2 and low water - HCFC-141b. Having in mind that some foam properties depend on the density, particularly compressive strength and dimensional stability, *this result is important for a fair comparison.*

Aging of Compressive Strength, 6 months versus 24 hours

Similar to the case of lambda (table 13), from the table 6 the variation percentage of compressive strength, 6 months versus 24 hours, was calculated and analysed (Tables A-5 and A-6). From the ANOVA there is no evidence of any difference in aging among the three PU systems.

	Table A-5. Variation Percentage in Compressive Strength, 6 months versus 24 hours						
	Supercritical CO_2		HCFC-141b, low water		HCFC-141b, high water		AVERAGE
	HD	LD	HD	LD	HD	LD	
Barranquilla	13.69	6.73	3.30	4.47	-4.47	-2.57	3.52
Bogotá	-4.03	-10.48	-1.02	-5.56	7.10	12.46	-0.25
AVERAGE	1.48		0.30		3.13		

	AVERAGE
HD	2.43
LD	0.84

Table A-6. ANOVA of variation percentage in compressive strength						
Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	*P*	
Technology	2	0.324	0.162	0.72	0.506	
Density	1	0.151	0.151	0.67	0.428	
Location	1	0.857	0.857	3.82	0.074	
Tec*Dens	2	1.068	0.534	2.38	0.135	
Dens*Loc	1	0.005	0.005	0.02	0.883	
Tec*Loc	2	9.810	4.905	21.86	0.000	Significant
Pure Error	12	2.692	0.224			

Dimensional Stability

As observed in the table 6, the values of dimensional stability at low temperature (-20 ºC) were all below 0.6%. For this reason it was decided to analyse the dimensional stability at 60 ºC and 95% RH (tables A-7 and A-8).

	Table A-7. Dimensional Stability at 60 ºC and 95% RH, two weeks, Vol. %						
	Supercritical CO_2		HCFC-141b, low water		HCFC-141b, high water		AVERAGE
	HD	LD	HD	LD	HD	LD	
Barranquilla	-0.622	0.488	2.338	3.687	0.811	1.929	1.438
Bogotá	4.766	0.463	3.220	3.342	1.267	1.527	2.431
AVERAGE	1.274		3.147		1.383		

	AVERAGE
HD	1.963
LD	1.906

Table A-8. ANOVA of Dimensional Stability at 60 ºC and 95% RH, two weeks						
Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	*P*	
Technology	2	17.6668	8.833	50.38	0.000	Significant
Density	1	0.0204	0.020	0.12	0.739	
Location	1	5.8979	5.898	33.64	0.000	Significant
Tec*Dens	2	7.1311	3.566	20.34	0.000	Significant
Dens*Loc	1	9.3507	9.351	53.33	0.000	Significant
Tec*Loc	2	8.5984	4.299	24.52	0.000	Significant
Pure Error	12	2.1039	0.175			

There is a statistically significant difference in dimensional stability among the three PU systems: Supercritical CO_2 provided the best performance (average 1.274 % in volume change) followed by high water-HCFC-141b (3.147 %) and low water-HCFC-141b (1.383 %). The fact that the location when the foam was raised gave a significant difference could be explained by the variation in atmospheric pressure that is in equilibrium with the cell pressure during the foaming process (Bogota: 560 mm Hg; Barranquilla: 760 mm Hg).

Adhesion to metal (galvanized steel)

The tables A-9 and A-10 show a summary of the results and the ANOVA for the adhesion strength to galvanized steel. From the statistical analysis it is concluded that none of the factors has a significant effect on adhesion. There is no evidence that there exits a difference among the performance of the three PU systems in relation to adhesion.

	Table A-9. Adhesion strength to metal, N/cm^2						
	Supercritical CO_2		HCFC-141b, low water		HCFC-141b, high water		AVERAGE
	HD	LD	HD	LD	HD	LD	
Barranquilla	14.144	17.946	7.922	2.983	14.124	13.627	11.791
Bogotá	7.887	15.117	21.355	8.241	17.310	15.530	14.240
AVERAGE	13.773		10.125		15.148		

	AVERAGE
HD	13.790
LD	12.241

Table A-10. ANOVA of Adhesion Strength to metal						
Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	*P*	
Technology	2	107.79	53.90	1.14	0.353	
Density	1	14.41	14.41	0.30	0.592	
Location	1	35.98	35.98	0.76	0.401	
Tec*Dens	2	212.00	106.00	2.23	0.150	
Dens*Loc	1	6.06	6.06	0.13	0.727	
Tec*Loc	2	192.93	96.47	2.03	0.174	
Pure Error	12	569.58	47.47			

2. PIR

Foam Core Density

The tables A-11 and A-12 show a summary of the results of the foam core density (values taken from table 7) and the corresponding ANOVA.

	Table A-11. Foam core density, kg/m^3		
	Supercritical CO_2	HCFC-141b	AVERAGE
Barranquilla	38.25	43.69	40.97
Bogotá	37.40	32.33	34.87
AVERAGE	37.83	38.01	

Table A-12. ANOVA of foam core density						
Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	P	
Technology	1	0.067	0.06700	0.018	0.899	
Location	1	74.517	74.51700	20.302	0.011	Significant
Tec*Loc	1	55.166	55.16600	15.030	0.018	Significant
Error	4	14.682	3.67050			

From the table A-12 there is no statistical evidence of a difference in density between the foam samples of the two PU systems, Supercritical CO_2 and HCFC-141b. The average values are quite close, 37.83 versus 38.01 kg/m^3.

Dimensional Stability

Similar to what happened with PUR foam, the values of dimensional stability (Vol. %) at low temperature (-20 ºC) were all below 0.6%. For this reason it was decided to analyse the most critical case: dimensional stability at 60 ºC and 95% RH (tables A-13 and A-14).

	Table A-13. Dimensional Stability at 60 ºC and 95% RH, two weeks, Vol. %		
	Supercritical CO_2	HCFC-141b	AVERAGE
Barranquilla	-4.051%	3.756%	-0.147%
Bogotá	-4.841%	5.740%	0.450%
AVERAGE	-4.446%	4.748%	

Table A-14. ANOVA of Dimensional Stability at 60 ºC and 95% RH, two weeks						
Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	P	
Technology	1	0.0169067	0.0169067	337.12	0.000	Significant
Location	1	0.0000713	0.0000713	1.42	0.299	
Tec*Loc	1	0.0003848	0.0003848	7.67	0.050	Significant
Pure Error	4	0.0002006	0.0000502			

From the table A-14 there is a statistically significant difference in dimensional stability between the two PU systems. The behaviour was totally different: meanwhile Supercritical CO_2 experienced a negative change in volume the HCFC-141b formulation had a positive one. Similar to PUR the foams raised in Bogota experienced a greater volume change in absolute values that those developed in Barranquilla.

Adhesion to metal (galvanized steel)

The tables A-15 and A-16 show a summary of the results and the ANOVA for the adhesion strength to galvanized steel.

	Table A-15. Adhesion strength to metal, N/cm^2		
	Supercritical CO_2	HCFC-141b	AVERAGE
Barranquilla	8.146	16.637	12.392
Bogotá	7.958	9.061	8.509
AVERAGE	8.052	12.849	

Table A-16. ANOVA of Adhesion Strength to metal						
Factor	Degrees of Freedom	Sum of Squares	Mean Square	F	P	
Technology	1	46.032	46.032	13.07	0.022	Significant
Location	1	30.143	30.143	8.56	0.043	Significant
Tec*Loc	1	27.293	27.293	7.75	0.050	Significant
Pure Error	4	14.084	3.521			

The table A-16 shows that there is a significant difference in adhesion to galvanised steel between the two PU systems: in average the HCFC-141b based formulation gave an adhesion strength 59.6% higher than Supercritical CO_2.

ANNEX 2. Material Safety Data Sheets of Supercritical CO_2 components

See PDF attachment.