Final Report

DEMONSTRATION PROJECT FOR THE PHASE-OUT OF HCFCS BY USING HFO AS FOAM BLOWING AGENT IN THE SPRAY FOAM APPLICATIONS IN HIGH AMBIENT TEMPERATURES SAU/REF/76/DEM/27

2020

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1. Objective

Demonstrate benefits from the use of the HFO-1233zd(E) and HFO-1336mzz(Z), which have very low GWP in replacement of HCFC-141b with water, in terms of lower GWP and CO2 release and insulation properties in the PU spray foam insulation sector;
Demonstrate the easy applicability of the technology and, consequently, the replicability of the results;
Demonstrate that lower cost structure as compared to other alternatives can be obtained by means of lower foam density and lower thermal conductivity;
Objectively analyze, if the incremental operating cost could be reduced overall in similar future projects by means of using optimized water / physical foam blowing agent applied in the foaming process;
Objectively analyze, if the incremental capital cost at the System Houses can be utilized by means of lesser focus on the flammable gas detection and ventilation. In particular, the extensive exhaust ventilation in the countries with hot climate may result in unexpected costs in the air-conditioning production area during the hot summer periods.

Table 1-1 – HFO Foaming agent

Common Name	**HCFC-141b**	**Formacel® 1100**	**Solstice Liquid BA™**	**Forane® 1233zd**
		1336mzz(Z)	1233zd(E)	1233zd(E)
Chemical Formula	CH_3CFCl_3	Cis-CF_3-CH=CH-CF_3	Trans-ClCH=CH-CF_3	Trans-ClCH=CH-CF_3
Molecular Weight	117	164	130.5	130.5
Boling Point (°C)	31.9	33	19	19
Gas thermal conductivity (W/mk)	8.8	10.7	9.52	9
Foam Properties	Good	Very good	Very good	Very good
Flammable Limits in air (Vol %)	5.6-17.7 (Effectively none-flammable)	None	None	None
GWP (100 years ITH)	725	2	1	1
TLV (ppm)	500	500	800	Not disclosed

Price (US$/kg)	2.0 – 4.0	?	USD 9 - 13	?
Manufacturer		Chemours (Formerly DuPont and Dow)	Honeywell	Arkema

2. Companies selected (background/application)

HCFC-141b is used by Sham Najd International in in-situ formed sprayed rigid polyurethane (PUR) and polyisocyanurate foam (PIR) for insulating and water proofing walls, ceilings, roofs, suspended ceilings and floors at the construction sites and industrial sites in the Kingdom of Saudi Arabia. Thus, Sham Najd was solely selected to phase-out HCFC-141b within this demonstration project by converting to HFO foaming agent technology due to its willingness and availability to act simultaneously as a demonstration project. The chosen technology is a non-ozone depleting and low GWP foaming agent. This HFO technology, which is a definitive alternative under the Montreal Protocol and additionally has a positive impact on climate, is in compliance with Decision XIX/6.

Replacing HCFC-141b in spray foam in the Kingdom of Saudi Arabia (KSA) presents an opportunity and technical challenge, making it worthy of a demonstration project. The preliminary 2014 HCFC consumption estimates show that 600 MT of HCFC-141b or 66 ODP tonnes were consumed in 2014 for spray foam in the Kingdom of Saudi-Arabia (these figures include import of pre-blended polyurethane systems). Also, in 2014, the Ministry of Municipal and Rural Affairs of KSA has made thermal insulation compulsory for all new buildings in the 24 districts of the country covering 80% of the populations. The addition of thermal insulation in new building is expected to reduce 40% of energy use in air conditioning. Today, air conditioners account for 70% of electricity consumption in the region and with 1.5 Million new homes needed to keep up with the population growth, energy demand is anticipated to double by 2030 if energy conservation measures are not put in place.

3. Technologies Considered and selected

3.1. Alternative technologies considered

In accordance with the 2014 report of the rigid and flexible foams technical options committee, there are numbers of alternatives that are available to replace the use of HCFC 141b in rigid polyurethane foam. Several foaming technologies, including the following, are used as alternate technology:

- Cyclopentane
- HFC-245fa
- HFC-365mfc/227ea

- HFC-134a
- Methyl formate
- CO2 (Water)
- u-HFC
- Liquid unsaturated HFC/HCFC (HFOs) as emerging technology (subject for this demonstration project)

3.2. Commercially Available Options

Option	Pros	Cons	Comments
Cyclopentane & n-Pentane	Low GWP	Highly flammable	High incremental capital cost, may be uneconomic for SMEs
	Low operating costs		
	Good foam properties		
HFC-245fa, HFC-365mfc/227ea, HFC-134a	Non-flammable	High GWP	Low incremental Capital Cost
	Good foam properties	High Operating Cost	Improved insulation (cf. HC)
CO2 (water)	Low GWP	Moderate foam properties -high thermal conductivity-	Low incremental Capital Cost
	Non-flammable		
Methyl Formate/Methylal	Low GWP	Moderate foam properties -high thermal conductivity-	Moderate incremental capital cost (corrosion protection recommended)
	Flammable although blends with polyols may not be flammable		

3.3. Emerging Options

Option	Pros	Cons	Comments
Liquid Unsaturated HFC/HCFC (HFOs)	Low GWP	High operating costs	First expected commercialization in 2013
	Non-flammable	Moderate operating costs	Trials in progress
			Low incremental capital cost

The Indicative assessment of criteria for commercially available options as well as emerging alternatives in PU foam is provided in the table below:

3.4. Assessment of criteria for commercially available options

	c-pentane	i-pentane n-pentane	HFC-245fa	HFC365mfc/ 227ea	CO_2 (water)	Methyl Formate
Proof of performance	+	++	++	++	++	+
Flammability	---	---	++	+(+)	+++	--
Other Health & Safety	0	0	+	+	-	0
Global Warming	+++	+++	--	---	++	++
Other Environmental	-	-	0	0	++	-
Cost Effectiveness (C)	--	---	++	++	++	0
Cost Effectiveness (O)	++	+++	--	--	+	+
Process Versatility	++	++	+	++	+	+

Assessment of criteria for Emerging Technology options

	HFO-1234ze(E)	HFO-1336mzzm(Z)	HFO-1233zd(E)
	Gaseous	liquid	Liquid
Proof of performance	0	+	+
Flammability	++	+++	+++
Other Health & Safety	+	+	+
Global Warming	+++	+++	+++
Other Environmental	+	+	+
Cost Effectiveness (C)	++	++	++
Cost Effectiveness (O)	--	--	--
Process Versatility	+	+	+

3.5. IOC comparison between major alternatives during demonstration project formulation

IOC	HCFC-141b			HFO-1233zd			Methyl Formate			Water-blown / Formic Acid		
	Formula	%	Cost/kg	Formula	%	Cost/kg	Formula	%	Cost/kg	Formula	%	Cost/kg
Polyol	100	44,29%	2,70	100	46,08%	2,70	100	37,88%	2,70	100	37,95%	2,70
B.A	15,8	7,00%	2,70	7	3,23%	11,00	9	3,41%	2,70	3,5	1,33%	2,70
MDI	110	48,72%	2,70	110	50,69%	2,70	155	58,71%	2,70	160	60,72%	2,50
Total	**225,8**	**100,00%**	**2,70**	**217**	**100,00%**	**2,97**	**264**	**100,00%**	**2,70**	**263,5**	**100,00%**	**2,58**
Thermal conductivity mW/mK			**21**			**21**			**23**			**31**
Foam density			42			42			42			42
Equivalent cost USD			**2,70**			**2,97**			**2,96**			**3,81**
Total PU consumption 2015	400000	27,99	1080000	400000		1187097	400000		1182857	400000		1522577
IOC / year USD						**107097**			**102857**			**442577**

3.6. Selection of alternative technology for the Demonstration project

The technology chosen has been HFOs due to the following:

Spray foam is used to insulate, provide air sealing and improve structural strength in buildings. The insulation potential of spray foam is dependent upon the insulating gas in the cells of the polyurethane foam. In addition to the insulation performance, polyurethane foams used for the insulation purpose require inherently superior dimensional stability and resistance to fire.

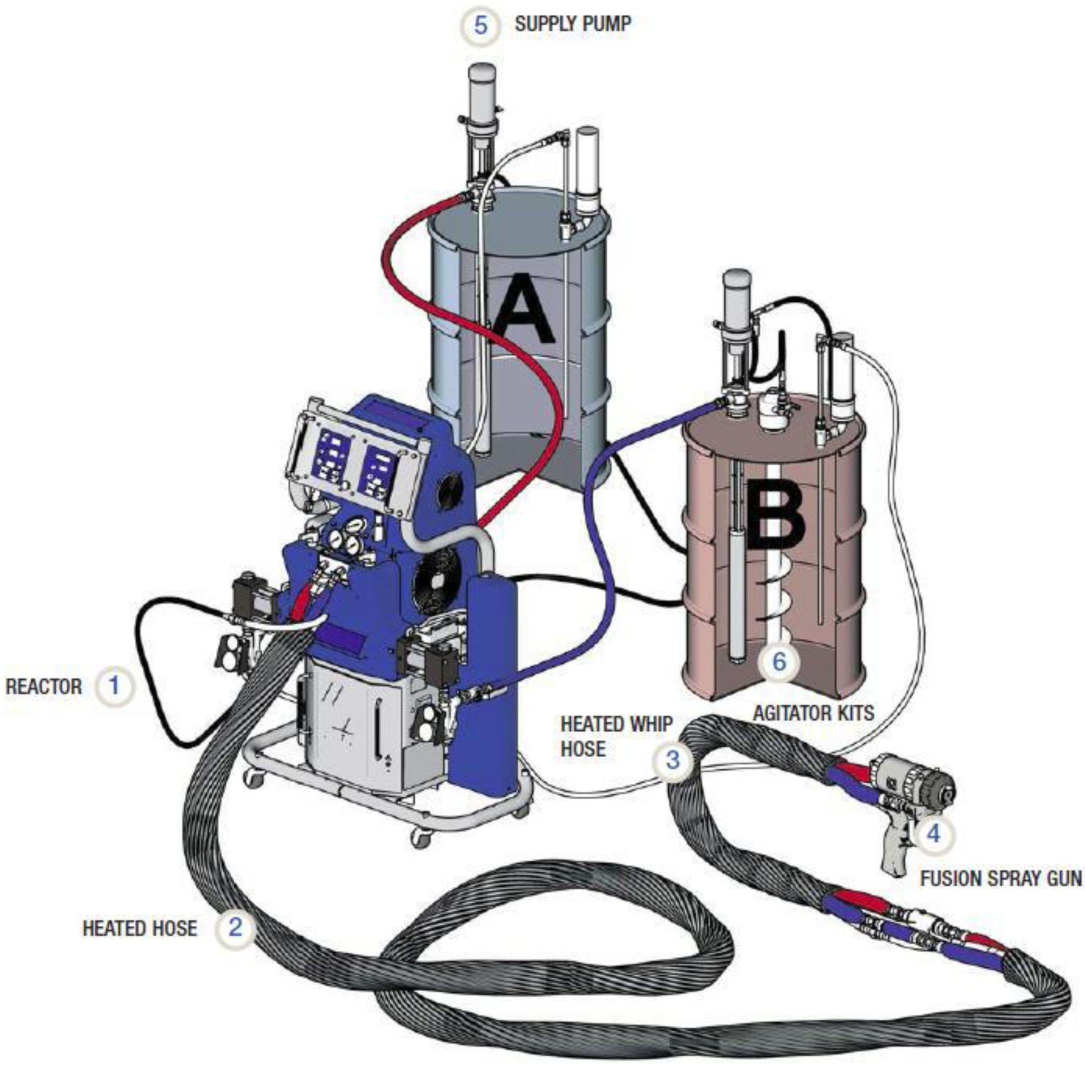
The current zero ODP options for replacement of HCFC-141b in foam applications include hydrofluorocarbons (HFCs) and hydrocarbons. Both HFCs and hydrocarbons are characterized by increased thermal conductivities compared to the HCFC, resulting in inferior insulation performance.

Few alternatives exist for replacing 141b in spray foam. Hydrocarbons are not a viable alternative for spray foam, and HFC-245fa and HFC-365, while viable, have high global warming potential (GWP). Also, the low boiling point of HFC-245fa and the flammability of hydrocarbons and HFC-365mfc present significant challenges to refrigerants processing and handling that are critically important in spray foam applications. On the other hand, foam blowing agents HFO-1233zd(E) and HFO-1336mzz(Z) have very low GWP, both less than 5, and HFO-1233zd (E) is claimed to be even less than 1. These molecules are also non-flammable and stable liquids at ambient temperatures. The HFO-1233zd(E) is already commercialized and HFO-1336mzz(Z) was expected to be commercially available from the year 2016. However, during the project implementation it was found out impossible to obtain it in such quantities which would have facilitated full-scale demonstration project. Thus, only blowing agent HFO-1233zd(E) has been tested in this demonstration project.

4. Modification of production

The foaming agent technology did not require new foaming equipment. All testing was performed with Sham Najd existing equipment (Graco E-XP1 Applicator).

Graco E-XP1 Applicator



5. Technical evaluation

Testing of the spray foam system SHPU 45 FSSL-50 from Covestro, UAE. The testing took place at Sham Najd's Labor camp & Warehouse area on 13 through 15 March 2017.

The spray foam testing operation was conducted by means of Sham Najd's existing Graco Reactor E-XP1 spray foaming machine and using the Fusion Air Purge Plural-Component Spray Gun.

The testing started on 13 March 2017 by means of spraying the standard non-fire rated spray foam system PS 105 H 40 Winter from KSA local system house SUCCO. The test results are provided in the table 1 and 2.

Testing was continued on 14 March 2017 with Covestro's HFO-1233zd blown SHPU 45 FSSL-50 fire retarded foam system. The test results are provided in table 1 and 2. All tests were conducted as follows:

Table 5-1. Test Results from the first samples in March 2017

Density	Approx. 43-47	ASTM D1622
Compressive strength	> 0.1 MPa	ASTM D 1621
Fire rating (DIN4102-1)	B2	DIN 4102
Fire rating Butler Chimney	Above 50%	ASTM 3014
Thermal Conductivity	≤0.024 W/m°K (10°C) ≤0.029 W/m°K (35°C)	ASTM C518
Dimensional Stability -20°C/+70°C, 48 hrs	Max 1%	ASTM D2126

Table 5-2. Thermal conductivity at 10°C

System	Density kg/m3	Compressive strength MPa	Dim. Stability % Max allowable 1%	Thermal conductivity W/mK @ 10°C	Aged thermal conductivity 21 days @70°C W/mK	Butler Chimney test ASTM 3014
SHPU45FSSL-50 (HFO-1233zd)	40.8	0,298	0.85	0.0210	0.0267	81.9%
PS 105 H 40 (HCFC-141b)	57.8	0,406	0.81	0.0248	0.0296	52.0%

Table 5-3. Thermal conductivity at 35°C measured two weeks after production

System	Density kg/m3	Compressive strength MPa	Dim. Stability % Max allowable 1%	Thermal conductivity W/mK @ 10°C	Aged thermal conductivity 21 days @70°C W/mK	Butler Chimney test ASTM 3014
SHPU45FSSL-50 (HFO-1233zd)	44.5	0,350	0.85	0.0246	0.0273	81.9%
PS 105 H 40 (HCFC-141b)	57.8	0,406	0.81	0.0275	0.0298	52.0%

Table 5- 4. Physical properties measured after 18 months from applying the foam on the roof. The samples were stored next to the test roof for easier testing purpose

Property		Unit	Average	Typical	Assessment of 18 months foam
Foam Density	EN 1602	kg/m^3	48,7	47	Typical value for roof insulation
Thermal Conductivity λ_{10} (+10°C)	EN 13165	mW/mk	26,1	26	Increased from 21 to 26.1, but understandable due to 18 months ageing at the construction site
Aged Thermal Conductivity (21days +70°C) λ_{10} (+10°C)	EN 13165	mW/mK	26,8	27	Shows that foam has kept insulation well
Thermal Conductivity λ_{35}(+35°C)	EN 13165	mW/mk	28,2	28	Increased from 24.6 to 28.2, but understandable due to 18 months ageing at the construction site
Aged Thermal Conductivity (21days +70°C) λ_{10} (+35°C)	EN 13165	mW/MK	28,9	29	Shows that foam has kept insulation well
Compression Behavior	EN 826	kPa	352	300	Similar to original 298 kPa -> 352 kPa (improved), which is typical that physical foam properties improve during the first months, upon all foam has after polymerized. The compression strength of PUR/PIR products remains constant with time if there is no air diffusing into the cells (ageing). If air diffusion is characteristic of the product then the compression strength will increase with time. The level of this increase will increase with the level of closed cells present, i.e. this increase will be the highest with level CCC4 (>90%) and least with level CCC1 (<20%).
Tensile Strength	EN 1602	kPa	183	150-200	This is typical for sprayfoam
Dimensional stability (3 days +70°C)	EN 1605	%	+0,66	±1	Excellent
Dimensional stability (10 days +70°C)	EN 1605	%	+0,69	±1	Excellent
Reaction to Fire Butler Chimney Test	ASTM 3014	%	91,1	80-90	Very good, practically IMPROVED FROM 81.9% to 91.1%
Reaction to Fire B2 Test	DIN 4102	cm	10,5	10-11	Has kept the fire rating well (15 cm max)
Water Vapor Resistance	ISO 12572	(m^2 s Pa/kg)	$10,5*10^9$	$8\text{-}12*10^9$	This is a typical value, and means that about 10 g water vapor goes through the 2 cm thick foam within 24 hrs, when there is 50 RH% humidity difference at 20 deg centigrade
Closed Cell Content	ISO 4590	%	93,3	90	Similar to HCFC-141b based foams
Closed Cell Content Corrected	ISO 4590	%	97,4	95	Similar to HCFC-141b based foams

Table 5-5. Following characteristics were studied due to high ambient temperature

Characteristic	Observations
The maximum concentration of HFO in the polyol to be used without pressurization of polyol vessel	12%
Impact to surfactants and catalysts	It was noticed that special package was to be introduced. Honeywell, the foaming agent supplier, was able to provide necessary package.
Pre-mixed polyol storage at the System House or Enduser's own storage	Five months during November 2016 to March 2017 did not cause any reactivity changes
Surface of the polyurethane as a product	The surface had somewhat more of pinholes compared to baseline foam formulation. However, it is meeting the customer expectations
Dimensional stability of sprayed foam	The tested foam system's dimensional stability in regard to baseline was somewhat reduced, however acceptable and meeting the spray foam standards. In regard to the most important direction against rise, the stability was good
Evaluate the correct timing for laying the protective coating for surface	The protective layer was sprayed on the foam just like on the baseline case (1.5 cm per pass)
Evaluate the performance of existing standard coating spray materials' applicability for the new product	Performance is the same

6. Commercial Evaluation

Commercial evaluation has been prepared basing on actual foaming results. If considering the thermal conductivity remains the same with HCFC-141b and HFO-1233zd the phase-out cost of HCFC-141b with present foaming agent prices the phase-out of HCFC-141b will cost USD 3.18/kg HCFC-141b. The actual laboratory tests displayed better results for HFO-1233zd based foam and in such case the phase-out cost of HCFC-141b were USD 0.52/kg.

Table 6-1 – Commercial Evaluation / IOC

Commercial Evaluation / IOC	HCFC-141b			HFO-1233zd			Water-blown / Formic Acid		
	Formula	%	Cost/kg	Formula	%	Cost/kg	Formula	%	Cost/kg
Polyol	100	38,46 %	2,46	100	38,17 %	2,70	100	37,95 %	2,80
B.A	20	7,69 %	4,00	12	4,58 %	9,50	3,50	1,33 %	2,46
MDI	140	53,85 %	3,50	150	57,25 %	3,50	160	60,72 %	3,50
Total	260	100,00 %	3,14	262	100,00 %	3,47	263,50	100,00 %	3,22
Aged Thermal conductivity mW/mK	29.8			28.2			31		
Required foam density			45			45			52
Equivalent cost USD			3.14			3.47			3.87
IOC (USD/kg HCFC 141b)						4,30			1,07
IOC (USD/kg HCFC 141b) considering change in thermal conductivity and foam density						0.33			9,53

7. Environmental impact

The project impact on the environment was studied for both chemicals i.e. HCFC-141b and HFOs. The CO_2 emission before conversion (using HCFC-141b as blowing agent with Global Warming Potential of 725) is expected as 20,282.68 metric ton per year whereas after conversion to HFO with GWP 1, it is estimated 17.32 metric ton per year. The net impact on the environment is positive. The CO_2 emission is expected to be reduced by 20,282.68 MT after implementing the new technology at Sham Najd. In whole KSA respectively the impact will be 434,643.00 CO2 MT/ year. The ODP phase-out at Sham Najd is 3.08 ODP tonnes and respectively in KSA 66 ODP tonnes. The net effect calculation is provided in the table below:

Table 7-1 – Environmental impact

Name of Industry Sham Najd	Substance	GWP	Phase out amount MT/ year	Total equivalent warming impact CO2 eq. MT/ year	ODP HCFC-141b	Total ODP
Before Conversion						
Total CO_2 emission in M tonnes	HCFC-141b	725	28	20,300.00	0.11	3.08
After Conversion						
Total CO_2 emission in M tonnes	HFO-1233zd	1	17,32	17.32	0	0
Net Impact				20,282.68		3.08
Before conversion Kingdom of Saudi Arabia						
Total CO_2 emission in M tonnes	HCFC-141b	725	600	435,000.00	0.11	66
After Conversion		1	357	357	0	0
Total CO_2 emission in M tonnes				434,643.00		66

8. Additional information

Table 8-1 – List of chemicals

Product	Supplier	Price USD / Kg
HFO-1233zd - Solistice LBA	Honeywell	9.50-15.00
Dabco 2040	Evonik	27.95
Dabco 203	Evonik	13.75
Tegostab B84711	Evonik	8.70
MDI	Sadara (Dow Chemicals' joint venture in KSA)	6.75 SAR USD 1.80

Since the spray foam systems are now available locally in KSA, there will be further local spray foam system use by Sham Najd and other spray foam applicators like Al-Babtain and customers of SUCCO and Saptex.

The SUCCO's actual field testing was conducted during early 2018 with Al-Babtain spray foam applicator for roofing of Honeywell's store area roofing. This testing was not actually connected to this Demo project but demonstrating the local Foam System Houses availability to provide foam systems, which facilitate phase-out of HCFC-141b.

Workshop with all results was held in June 2019. This workshop provided detailed information from the results in Jeddah, Riaydh and Damman.

Table 8-2 – Demo project results were presented at Foam Sector workshops during 22-25 June 2019 at Jeddah, Riyadh and Damman / Al Khobar

Place of venue	Presentations	Subjects	Audience
Jeddah Riaydh Damman	Saptex System House	Alternative foaming agent for spray and pour-in-place applications	Spray applicators 15 Construction consultants 4 National Ozone Unit UNEP
	Succo System House	Foaming results and challenges experienced in the foam formulations and expectations with PU spray foam	
	Sham Najd - Spray Applicator	Comments on the Demo Project	
	Jundi – System House	Experience in the use of natural and flammable foam blowing agent	

	UNIDO International Consultant	1st: Foaming with HFO foaming agents- Solstice LBA and Opteon 1100 2nd: Foaming results with hydrocarbons and other blowing agents 3rd: Foam cost calculations	
	Momentive	Foam formulations	
	Honeywell	4th Generation Blowing Agents	

9. Conclusion

The phase-out of HCFC-141b in Sham Najd will reduce the total CO_2 emission and ODP emissions by a significant margin. The conversion will facilitate the phase-out cost-effectively. The same approach can be applied to the whole KSA and the surrounding region respectively.

Spray foam for roofing in the KSA where the insulation demand is growing will require superior insulating and water-proofing properties and ability to be monolithically apply to all shapes and types of surfaces.

According to the field testing and resulting laboratory testing, the spray foam formulation with HFO-1233zd foaming agent appears to have a high potential to replace HCFCs and HFCs as it has very similar technical and physical attributes and has a very low GWP and zero ODP factor.

Following conclusive characteristics can be noted:

1. The end spray product is matching HCFC-141b blown spray foam in many aspects, such as adhesion, thermal conductivity, dimensional stability, paint-ability, overall foam density and compression strength;
2. Lesser amount of HFO-1233zd can be mixed due to the boiling point of polyol mix will also be lower than boiling point of HCFC-141b blown foam;
3. Storage of mixed polyol needs to be kept at max 28 degrees of centigrade - > needs upgrade of polyol mix storage room air-conditioning;
4. On construction sites, the drum storing of polyol by the spray foam applicators require shelters;
5. HFO-1233zd needs to be kept in pressure vessels;
6. HFO-1233zd needs to be mixed in the temperature-controlled mixing vessel (reactor), temperature less than 18 °C, or to use in-line pre-mixer unit;
7. HFO-based foam system needs special additives in order to avoid deterioration of ageing performance of the polyol mix, see the chemicals to be purchased.

8. Cost of foam system is presently higher than HCFC-141b blown foam. However, it is expected to be balanced within few years.

Advantages:

1. Better foam performance in the cold weather period season (lower boiling point);
2. HFO-1233zd provides future foam formulation without concern of use limitations;
3. Very low Global Warming Potential (GWP) of 1;
4. Non-ozone depleting;
5. Nonflammable (ASTM E-681), VOC exempt (per U.S. EPA) and
6. Facilitate required improved energy efficiency for the future constructions and buildings and can be used for improving old buildings to meet present insulation requirements.

Budget

Total budget approved 96,250 USD

Expenditures: **94,000 USD** (2019), which contains of:

Consultancy services and travels -	28,000 USD
Equipment/Chemicals –	48,000 USD
Workshop and laboratory test -	18,000 USD

Other notes

Response to MFS comments on Interim Report of HFO demonstration project in PU foam Saudi Arabia

1. At the 80th meeting, the Executive Committee agreed to extend the project completion date to 31 December 2018, on the understanding that no further extension of project implementation would be requested, and to request UNIDO to submit the final report no later than the 83rd meeting (decision 80/26(i)). The Secretariat notes from the present report that substantial progress has been achieved in the implementation of the demonstration, but that some activities (i.e., scale field testing and dissemination workshop) have not taken place yet. We would appreciate the following clarifications on the remaining activities to finalize the project:

(a) Please provide the characteristics of the scale field testing planned (specific tests planned, how many tests in how many enterprises, formulations to be used, duration of these tests and additional information expected);

Response: It is tentatively, and as per the project document intention to conduct the field testing only by the company Sham Najd. Intention is to obtain foam systems from KSA SHs SUCCO and Saptex. In the project document it was foreseen only Saptex, but during implementation of this project and System House projects, SUCCO appears to have the most experience in the foam formulation development. The laboratory formulations are already in place, and those are to be field tested.

(b) Please confirm estimated date of completion of all pending activities;

Response: It is foreseen that testing would be completed and results available by October 2019.

(c) Given that these reports are going to be used by other Article 5 countries as reference when implementing projects, we would appreciate that the final detailed report of the demonstration is presented to the 84th meeting, including the result of the remaining tests, any conclusions or additional information emerging from the workshop, and additional details requested the comments below.

Response: The final report is projected to be available by October 2019.

Formulations

2. Please clarify the origin of the formulation used to test HFO-1233zd(E). Was it developed by Covestro for the demonstration project, or is it a commercially formulation available to any systems house?

Response: All foam formulations details are always System Houses' own developments and secrets and based on their polyols in use. However, the additive suppliers (for instance Evonik and Momentive) and the foaming agent suppliers (Honeywell and Chemours) have R&D support available, and they actively provide their experience to the formulators at System Houses. In the case of the Spray Demo project first phase the formulation was fully developed by Covestro, and not available to any other source.

3. Kindly inform if all the tests were done with a formulation containing pure HFO-1233zd(E) or if there were also tests with formulations reduced with water. If that was the case, please also provide the results and how the foam with reduced formulations compare with pure HFO-1233zd and HCFC-141b-foam?

Response: The HFO-1233zd formulations are always substantially reduced with water. The HFO-1233zd content as foaming agent is from 8 to 12 % in polyol formulation high ambient temperature countries. Due to HFO-1233zd's low boiling point, it is not really possible to formulate cost-effectively polyol mixture, which could keep blowing agent fully soluble. The testing has shown that blowing agent start boiling strongly, and the hot climate conditions preclude this kind of high content HFO-1233zd formulations.

The below tables are providing information from the laboratory test. It is to be noted that the HCFC-141b foam was not most suitable for the comparison. However, it was only available.

System	Density kg/m3	Compressive strength MPa	Dim. Stability % Max allowable 1%	Thermal conductivity W/mK @ 10°C	Aged thermal conductivity 21 days @70°C W/mK	Butler Chimney test ASTM 3014
SHPU45FSSL-50 (HFO-1233zd)	40.8	0,298	0.85	0.0210	0.0267	81.9%
PS 105 H 40 (HCFC-141b)	57.8	0,406	0.81	0.0248	0.0296	52.0%

System	Density kg/m3	Compressive strength MPa	Dim. Stability % Max allowable 1%	Thermal conductivity W/mK @ 35°C	Aged thermal conductivity 21 days @70°C W/mK	Butler Chimney test ASTM 3014
SHPU45FSSL-50 (HFO-1233zd)	44.5	0,350	0.85	0.0246	0.0273	81.9%
PS 105 H 40 (HCFC-141b)	57.8	0,406	0.81	0.0275	0.0298	52.0%

Tests undertaken and results

4. Thank you very much for Table 1 listing the tests undertaken. Kindly inform why other typical tests such as adhesion strength (ASTM D-1623), water absorption or closed cell content (ASTM D-2856) were not included. Could they be included in the next measurements?

Response: These above-mentioned tests were to be conducted, but misunderstanding with the UAE Test laboratory, they were not able to conduct all tests. These tests will be conducted for the next test.

5. Table 2 can be considered a clear summary of the results. However, it does not contain all the information that other Article 5 countries will need as reference. We would appreciate if for the final report you could include for each of the tests listed, a brief description on how the test was done (how many times, at what temperature,

relative humidity and other conditions) and how you interpret the results found. Please feel free to include Annexes for additional tables, where necessary.

Response: The following testing will be included:

- European in-situ formed sprayed PU foam standard EN 14315;
- Thermal resistance and thermal conductivity
- Measurement of lambda values (thermal conductivity W/mK)
- Ageing of lambda value
- Reaction to fire of the products
- The reaction to fire classification of the products shall be determined in accordance with EN-13501-1 and using data obtained from tests carried out according to procedures EN ISO 11925-2 and EN 13823
- Dimensional stability under specified temperature and humidity conditions
- Dimensional stability under specified temperature and humidity conditions shall be determined in accordance with EN 1604
- Reaction profile and free-rise density
- Durability characteristics
- Durability of reaction to fire against ageing/degradation
- Durability of thermal resistance against ageing/degradation
- Durability of compression strength against ageing/degradation
- Closed cell content
- Short-term water absorption by partial immersion
- Compressive stress or compressive strength

All tests above will be conducted according to EN 14315 (Thermal insulating products for buildings — In-situ formed sprayed rigid polyurethane (PUR) and polyisocyanurate (PIR) foam products)

6. Kindly inform if the characteristics of the foam were measured again several weeks after, in order to obtain information on aging. It has been observed in several of the demonstration projects that some of the characteristics of the alternative foam may vary over time in a different way than HCFC-141b-foam. If this was measured, please include it in the final report. If this was not done, please explain the reasons and kindly consider undertaken additional measurements.

Response: We understand this need, and it is foreseen.

7. It is understood from the demonstration that no modifications were required to the foam dispenser for the application of HFO-1233zd(E) in spray foam applications. Is there any instance in which a modification to the spray foam equipment would be needed or it can be inferred that in general no changes are needed?

Response: The evaluation was done with relatively new Graco Spray foam unit, which has very good control on the pressure, mixing and heating of hoses. Thus, it can be used as such.

8. The conclusion section indicates that mixed polyols needs to be stored at maximum 28 degrees Celsius. The reasons are not explained in the report.

Response: Boiling point of the HFO-1233zd is so low that it will cause evaporation / boiling of the chemical. It is not azeotropic mixture with polyol.

9. The conclusions also indicate that HFO-1233zd should be mixed in the reactor at a temperature lower than 18 degrees Celsius. The reasons are not explained in the report.

Response: Boiling point of HFO-1233zd is 19.5 °C, and in order to avoid loss of the blowing agent during mixing process, it needs to be mixed preferable at 15°C

10. What have been identified as the main challenges to introduce HFO-1233zd(E) in spray foam application in Saudi Arabia?

Response: Ambient temperature, shelf-life of the polyol mixture, high price and motivation to the SH's due to the availability of HCFC-141b formulations and bulk.

11. Kindly include in the final report an independent technical review.

Response: Will be budgeted and included as requested.

Cost

12. What is the cost of the additional surfactants and catalysts required for the application of HFO-1233zd(E)? Please also provide an explanation on why they are required.

Response: The Evonik catalyst – emulsifier - silicone surfactant package, having the commercial product names;

- Dabco 203
- Dabco 2040 and
- Tegostab B8471

This optimized catalyst package through extensive and multi-year testing is recommended by Evonik and HFO-1223zd supplier Honeywell for spray foam formulators, when using HFO-1233zd as foam blowing agent, and this catalyst package provide self-life for polyol blend for more than 8 months. Thus, UNIDO Demonstration project needs to follow these recommendations.

Name of chemical	kg	USD/ kg	One drum	Description	Other information
Dabco 2040	200	27,50	5 500,00	Dabco 2040 catalyst is a low odor amine used to enhance cure and adhesion to substrate in HFO-blown spray foams.	
Dabco 203	200	13,20	2 640,00	Dabco 204 catalyst can help customers achieve between 6 to 8 months of polyol blend stability when used with HFO-1233zd(E). Dabco 203 catalyst performs similarly to Polycat 204 catalyst, but brings the added advantage of having a low water content, providing additional flexibility to formulators.	Typical uses levels of Dabco 203 catalyst / Dabco 204 catalyst are 2-4% by weight on the polyol side. The product can be used in conjunction with other catalysts to optimize system stability, overall reactivity as well as back-end cure speed. Recommended co-catalysts for HFO based systems include: Dabco® 2039 catalyst, Dabco® 2040 catalyst.
Tegostab B8471	200	8,25	1 650,00	TEGOSTAB® B 8471 acts as a silicone surfactant. Offers foam stabilization. Used in polyurethane rigid foam for construction applications.	Improves stability in formulation.

Momentive package is including following.

- Silicone L5107
- DMEA
- DMCHA
- Catalyst A-1 (Momentive)
- Potassium Octoate from Momentive

13. Is the formulation in Table 5 the one used in the demonstration project (Covestro HFC-1233zd blown SHPU 45 FSSL-50)?

Response: Yes.

14. Is the price of pure HFO-1233zd(E) in Saudi Arabia US $9.50/kg as indicated in Table 5?

Response: Seems to be that price in smaller quantities is USD 15,000 / MT. So, price has not been reduced as expected. In the case of Demo material from Covestro, UNIDO purchased foam as a system, and foam individual chemicall prices were not revealed.

15. Kindly explain how the IOC value of US $0.52/kg was obtained?

Response: From the calculation below, foam cost USD /kg difference is USD 0,04/kg. However, when thermal conductivity is considered, the HFO-1233zd foam USD 0.52/kg lower in cost.

Commercial Evaluation / IOC	HCFC-141b			HFO-1233zd			Water-blown / Formic Acid		
	Formula	%	Cost/kg	Formula	%	Cost/kg	Formula	%	Cost/kg
Polyol	100	38,46 %	2,46	100	38,17 %	2,70	100	37,95 %	2,80
B.A	20	7,69 %	4,00	12	4,58 %	9,50	3,50	1,33 %	2,46
MDI	140	53,85 %	3,50	150	57,25 %	3,50	160	60,72 %	3,50
Total	260	100,00 %	3,14	262	100,00 %	3,47	263,50	100,00 %	3,22
Aged Thermal conductivity mW/mK	29,8			27,3			31		
Required foam density			45			45			52
Equivalent cost USD			3,14			3,18			3,87
IOC (USD/kg HCFC 141b)						4,30			1,07
IOC (USD/kg HCFC 141b) considering change in thermal conductivity and foam density						0,52			9,53

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Construction Product Testing Laboratory

August 21th 2019

UNIDO UDITED NATIONS INDUSTRIAL DEVELOPMENT ORGANISATION

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TEST REPORT

Physical Properties of Sprayed PIR Foam							**Typical**
Property		**Unit**	**1.**	**2.**	**3.**	**Average**	**value**
Foam Density	EN 1602	kg/m^3	48,9	48,4	48,9	48,7	47
Thermal Conductivity λ10 (+10°C)	EN 13165	mW/mk	26,1	26,0	26,1	26,1	26
Aged Thermal Conductivity (21days +70°C) λ10 (+10°C)	EN 13165	mW/mK	26,7	26,4	27,3	26,8	27
Thermal Conductivity λ35(+35°C)	EN 13165	mW/mk	27,3	28,6	28,7	28,2	28
Compression Behaviour	EN 826	kPa	351	345	359	352	300
Tensile Strength	EN 1602	kPa	172	229	149	183	150-200
Dimensional stability (3 days +70°C)	EN 1605	%	+0,60	+0,63	+0,74	+0,66	±1
Dimensional stability (10 days +70°C)	EN 1605	%	+0,68	+0,63	+0,76	+0,69	±1
Reaction to Fire Butler Chimney Test	ASTM 3014	%	88,7 93,8	88,5 93,9	93,8 88,1	91,1	80-90
Reaction to Fire B2 Test	DIN 4102	cm	10 11	11 10	11 10	10,5	10-11
Water Vapour Resistance	ISO 12572	(m^2 s Pa/kg)	10,7*10^9	9,8*10^9	11,0*10^9	10,5*10^9	8-12*10^9
Closed Cell Content	ISO 4590	%	93,6	92,8	93,4	93,3	90
Closed Cell Content Corrected	ISO 4590	%	97,6	97,1	97,5	97,4	95

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