Brooks

Brooks Automation Inc.
15 Elizabeth Drive
Chelmsford, MA 01824

Tel (978) 262.2400
Fax (978) 262.2500
www.brooks.com

October 26, 2015

To: Glenn Gallagher

Email: Glenn.gallagher@arb.ca.gov

Re: Comments based on the California Air Resources Board, Draft Short-Lived Climate Pollutant Reduction Strategy, September 30, 2015

Dear Mr. Gallagher,

Thank you again for the open and collaborative discussions hosted by the California Air Resources Board in July and October.

I am writing on behalf of my employer, Brooks Automation (Chelmsford, Massachusetts, USA), to provide comments as a follow up to the feedback requested in response to the Board's published draft strategy dated September 30, 2015.

## Executive Summary:

### *Markets Served Including the Solar Industry*

Brooks Automation manufactures cryogenic and very low (also referred to as ultra low) refrigeration systems operating in the temperature range of -80 C to -160 C. These products serve the industrial vacuum deposition market and the life science market. Among our industrial users are customers who use our product in the fabrication of solar panels. Our products include both cascade refrigeration and autocascade refrigeration systems, both of which use HFC and F-Gas refrigerants and which would be impacted by the draft version of the strategy.

### *Low Leak Rate and Energy Efficiency*

Key characteristics of our systems are that they have very low leak rates, and are much more energy efficient than alternative technologies. Since these products are used in critical applications, they are designed and manufactured to be very reliable. In addition, since uptime is important to the operators, leaks are typically detected quickly thus limiting refrigerant release to the atmosphere. We estimate our average in field leak rate to be 4% per year, across our entire installed base. Our systems offer relatively high energy efficiency relative to alternate cooling technologies which use low GWP fluids such as liquid nitrogen or helium refrigeration. The net benefit of using our system, even when accounting for refrigerant leaks, varies from 3.4:1 to 6.9:1 when compared to these other technologies (based on 401 g $CO_2$ / kWh). Therefore, using our product relative to the alternatives yields a significant reduction in $CO_2$ emissions that would otherwise be generated. This has an important impact on manufacturers of solar panels since using alternate technologies would require greater energy input which would increase their cost and increase the CO2 footprint of the solar panels being produced.

## *Niche Market*

As described above, our products are used in niche markets within the Industrial and Life Science markets. Although our equipment uses HFC refrigerants, as indicated earlier, our refrigerant leak rates of 4% per annum are relatively low compared to other refrigeration systems. In addition, shipments of systems into California are very limited. Total annual shipments for our autocascade systems via precharged units, and bulk refrigerant shipments to service the installed base, total 2,100 pounds or less. The annual metric tons of equivalent CO2 vary from 3,000 to 6,000 per year (3000 to 6000 MTCO2e, or 0.003 to 0.006 MMTCO2e). Brooks is the market leader in this space and we believe our sales represent well over 75% of sales to California. Sales of Brooks' cascade systems for Life Science systems are an additional amount that is less than 10% of these figures. Compared to the draft target listed in Tables 1 and 2 of the draft strategy of reducing F-gas emissions to 24 MMTCO2e and the goals of reducing very high GWP refrigerants by 1 MMTCO2e and by 15 MMTCO2e for new equipment sales, our shipments of 0.006 MMTCO2e do not have any significant impact.

## *Technical and Safety Problems with Alternatives*

Some parties have advocated banning sales of high GWP HFC's. They point to the availability of hydrocarbon and HFO refrigerants. At the present time neither of these is technically viable. The refrigerants currently used in our autocascade systems need to be able to operate in the mixture without freezing. The particular molecules selected for our blend were qualified based on their ability to achieve freezing point depression so that they can continue to circulate at temperatures below -160 C without freezing, even though some of the components have much warmer normal freezing point temperatures. Even making a seemingly simple change like substituting ethane for R-23 is a technical risk since R-23 provides freezing point depression for warmer boiling (and warmer freezing) refrigerants, and R-23 itself benefits from freezing point depression from these other refrigerants. Much of this has to do with the synergy from the HFC molecular structures of the molecules in these mixtures. Using ethane in place of R-23 will likely not provide the same freezing point depression.

In the case of the cascade refrigeration systems used for life science storage units these are relatively large systems with a few kilograms of refrigerant charge. These are also used to cool very large storage chambers of about 1,000 to 2,000 cubic feet down to -80 C. Currently these use R-508B for the low temperature stage. Due to the size of the charge, and the size of the store volume, changing to ethane is not practical to the associated risk of fire.

We do know that using a mixture of various hydrocarbons can be used at cryogenic temperatures and we offer a product with such a mixture. These are small systems with a total charge of 150 – 200 grams. Unfortunately flammability concerns have limited adoption of this product. In some cases customers have insisted on a nonflammable blend instead due to safety concerns. In addition, the issue of flammability has prevented us from commercializing larger products with these flammable mixtures. Even if ethane could work in place of R-23 in our autocascade systems, the resulting flammability would be unacceptable to many customers due to the large refrigerant charge.

HFO's are characterized by a double bond between two carbon atoms in the molecule. All of the HFO's being commercialized at present have at least three carbon atoms. This limits their boiling points to temperatures warmer than -50 C. The HFO's with only two carbon molecules, which might be useful at lower temperatures, are all characterized as being unstable and toxic. Some are explosive. Due to these limitations there are no HFO candidates to replace R-23 or R-14.

Brooks also offers warmer refrigeration systems operating at -20 C and +4 C. We plan to migrate to the low GWP refrigerants as they become qualified by compressor manufacturer's and as applicable standards are revised to permit their use.

*Request for a -50 C exemption, or alternate suitable exemption.*

The language of the current draft strategy does contain language to allow for use of HFC's when alternatives are not technically feasible. Specifically it states:

> "***High-GWP Refrigerant Prohibitions in New Stationary Systems***
>
> This measure would prohibit the use of high-GWP refrigerants in new commercial, industrial, and residential stationary refrigeration and air-conditioning equipment. Certain exceptions could be made to any maximum GWP limit if a low-GWP refrigerant is not technically feasible in a specific application."

Brooks' concern is that this may be too vague and may result in supply chain disruptions without a more clearly worded exemption. Without this clarity, individual customers may have to endure undue administrative steps to purchase the equipment they require. In the EU, the F-Gas law has a simple exemption for systems operating below -50 C. Similarly Canada has adopted a similar exemption for systems below -50 C in their draft legislation. Our products are shipped globally and in some cases one OEM customer needs to ship to multiple end destinations depending on where their end users are located. For this reason Brooks respectfully request that the California Air Resources Board consider adding a similar exemption in its final strategy. If such an exemption would compromise the state's reduction goals, then please consider an alternate specific exemption that allows our customers clear access to our products. As indicated above, there are significant technical and safety issues preventing us from adopting other chemistries. In addition, granting such an exemption, at least in the case of our systems would have no discernable impact on the state's goal to reduce green house gas emissions due to F-Gasses or very-high GWP HFC's.

# Detailed Feedback to the Draft Strategy Dated September 30, 2015:

About Brooks Automation's Refrigeration Products:

Brooks is an OEM whose products include cryogenic refrigeration products that serve the Industrial Vacuum Coating and Life Science Markets. Our Industrial Vacuum Coating products are cryogenic water vapor pumps that enable vacuum deposition processes which are critical for many manufacturing processes. Our Life Science products provide long term reliable storage of sample cells used by researchers in the fight against cancer and other diseases. The refrigeration products Brooks uses in both these market rely on HFC and FC (F-Gas) refrigerants for which there are no ready replacements which meets all of the safety and performance requirements of the market place.

Brooks' product line includes a number of different refrigeration technologies and refrigerants. The focus of this communication is on mixed gas refrigeration systems which use HFC and FC refrigerants. However, Brooks also manufactures mixed gas refrigeration systems based purely on hydrocarbon and inert refrigerants. Brooks also manufactures helium based refrigeration systems. The industrial refrigeration groups within Brooks have been in business for over 40 years and have a depth of experience in this area. I have been working for Brooks for 26 years and have been involved in the transitions from CFC's to HCFC's and from HCFC's to HFC's. I am leveraging my professional experience and the company's combined experience when I make the following statements.

The Industrial and Life Science product lines that utilize F-Gasses provide net benefits from a TEWI analysis relative to using liquid nitrogen (LN2) which was the previous source of refrigeration in both of these markets. As an example, a TEWI analysis is provided for our autocascade systems, model MaxCool 4000H, in Attachment One which shows a benefit of 5:1 compared with LN2. If these units were no longer available in California customers would be forced to go back to LN2 which has a greater impact on global warming than our current products do. In addition to the calculation of the CO2 emissions associated with LN2 production that were used for our TEWI analysis, there are also CO2 emissions associated with transportation which result in LN2 being even less attractive environmentally especially for short lived climate pollutants. In Attachment Two a separate TEWI analysis is provided comparing the benefit of the MaxCool 4000H to the largest helium refrigeration system made by the company, the M1500. In this comparison the MaxCool 4000H provides a benefit ratio of 3.3:1. Similar TEWI comparisons are made for the R-508B chiller and it has beneficial ratios of 5.8 :1 relative to LN2, and 3.8:1 relative to a helium refrigerator.

Brooks needs continued ability to sell bulk refrigerants and precharged system into California in order to support its high tech customers in California. The R-508B cascade systems are used to provide refrigeration to life science applications in which researchers store biological samples for research purposes. The industrial cryogenic products use an autocascade refrigeration system which uses R-236fa/-245fa/-125/-23/-14 and inert gases in a blend to achieve these cryogenic temperatures. These are used for water vapor cryopumping in vacuum deposition systems that provide high value coatings for a variety of consumer and industrial products. Several customers in California are using these water vapor cryopumps in the manufacture of photovoltaic cells used in solar panels. Forcing manufacturers of these solar panels to switch to LN2 or alternate technologies would result in a reduction in the environmental benefit of these solar panels since the manufacture of these solar panels would result in greater CO2 emissions. These autocascade refrigeration systems are now also being adopted for biological storage systems.

Following is my feedback, on behalf of Brooks Automation, with regards to the discussion from this forum.

1) As currently proposed, the ARB is considering mechanisms to achieve significant reductions in green house gas emissions in keeping with the Governor's goals. One of the main mechanisms considered are rules and legislation that would prohibit the use of high GWP fluorinated refrigerants in certain applications. As these rules are considered I would encourage ARB to segregate the market into sectors based on the application and formulate rules that are appropriate for each sector. As an example, these sectors can be broken out by:
    a. User (i.e. residential, mobile, commercial, industrial),
    b. Use (air conditioning, food storage, transport refrigeration, industrial thermal management, cryogenic processing, etc).
    c. Temperature Range (i.e. + 20 C to 0 C, 0 C to -50 C, -50 C to -90 C, colder than -90 C),
    d. Size of Compressor or Input Energy.

    Based on the specific application, low GWP alternatives may be very feasible or could be technically very difficult or infeasible. Rules and legislation developed should be appropriate based on the specifics of each sector. The current strategy seeks to ban high – GWP refrigerants but does not do this in regard to the various market segments. We recommend defining the target markets for the high-GWP ban rather than making it across the board.

2) Further, these various applications can be compared based on their annual usage of high-GWP refrigerants to identify which ones are the main contributors to the State's green house gas emissions and which ones contribute very little to these emissions.

    In addition to the fact that our systems are more energy efficient than other refrigeration alternatives our systems represent a very small fraction of all refrigerant use in California. Total annual shipments of our autocascade precharged units and bulk refrigerant shipments to service the installed base total 2,100 pounds or less on an annual basis. The annual metric tons of equivalent CO2 vary from 3,000 to 5,600 per year (3000 to 6000 MTCO2e, or 0.003 to 0.0056 MMTCO2e). Sales of cascade systems for life science systems are about 100 pounds per year of these figures. For discussion purposes we will use 0.006 MMTCO2e to cover all of these refrigerants. Details of the shipment history of F-Gasses to customers in California is detailed in Attachment Three. As mentioned in the summary, these numbers are so small they do not have any significant impact on the F-Gas reduction targets (15 MMTCO2e for new equipment and 1 MMTCO2e for service charges) identified in the draft strategy.

3) If the HFC and FC refrigerants used by Brooks today were phased out we would not be able to implement alternatives that meet the demands for product safety and energy usage. Although HFO's are becoming commercially available, there are no HFO's available in the boiling point range needed for ultralow and cryogenic refrigeration. The smallest molecule, and the one with a lowest boiling point in the HFO family is CF2=CF2, which is highly explosive. Similarly, the other combinations of fluorine and hydrogen with two double bonded carbons are also very dangerous and there is no consideration in the industry to commercialize these. Beyond this, the lowest boiling

point low-GWP refrigerants available or in development are in the same range of R-134a and R-22. These do not allow us to achieve a low GWP blend. In particular R-23, R-508B (R-23 + R-116) and R-14 are really unique molecules for which no other equivalent molecules exist with regards nonflammability, low toxicity, boiling point, freezing point, thermophysical properties, and zero ODS. Although ethane meets many of these requirements for the R-23 and R-508B refrigerants it is flammable and results in a flammable blend which represents an unacceptable risk for our customers. As one example, consider the life science application where researchers store critical samples for 10+ years. An evaporator leak of ethane into the storage space represents an unacceptable risk.

One of the HFC refrigerants we use is HFC-23 which has been singled out by some groups due to its high GWP. They advocate substituting ethane in its place. Although there are cases where ethane can be safely used, and poses no technical risks, that is not the case in our systems. One example cited by the ethane advocates is for a life science freezer with a 50 cubic foot storage capacity. The cited system has a small hydrocarbon charge of about 200 grams. In contrast the Life Science storage systems we produce have storage volumes of 1,000 to 2,000 cubic feet and the refrigerant system has a charge of 4.5 - 9 kilograms. Whereas the safety risk of using ethane on a small system may be acceptable, the safety risk on our much larger systems does not allow for ethane, especially since a key requirement for owners of these stores is the safe, assured preservation of the many tens of thousands of samples stored by researchers. A leak of flammable refrigerant to the inside of these stores, which have active electronics to drive the robotic retrieval systems, would represent an unacceptable risk. Therefore, the use of ethane in our cascade and autocascade refrigeration systems is not acceptable.

Similarly, our autocasde systems have relatively high refrigerant mass amounts over 1.6 kilograms and up to 9 kilograms. Changing from R-23 to ethane in our systems will result in a flammable charge which may not be acceptable in the market place due to the large refrigerant mass.

Another risk with ethane relates to the chemistry of our systems. Some of the refrigerants used in our autocascade system will freeze at the evaporator temperatures we achieve. These warm freezing refrigerants are present in small concentrations at the evaporator. To prevent freezeout we rely on HFC-23 to provide freezing point depression with these warmer freezing HFC refrigerants. Switching to ethane which has a different chemistry, as it lacks fluorine, would likely not provide this same freezing point depression. As with consideration of new HFO refrigerants, such a change requires years of development and in the end may prove unfeasible.

4) Although alternatives are now being identified for individual refrigerants (R-236fa, R-245fa, and R-125) there is still additional work needed with regard to safety and flammability before these can be designed into conventional refrigeration systems. In addition to resolving those issues, for use in standard refrigeration applications, it is not known whether these new refrigerants will be suitable for use in autocascade systems due to the additional criteria that must be met with regard to freezing point and freezing point depression in the mixture (since all refrigerants in the mixture are present, at some concentration level in all parts of the system). It is important to point out that in an autocascade system all refrigerants in the system are present at the coldest parts of the system which can be as low as -160 C. For this reason the freezing point of the individual refrigerants, and their

freezing point depression in a mixture are critical success criteria to reliable operation of the system. As of today the vendors of these HFO fluids cannot even tell me what the actual freezing points of these fluids are. Even if this information was available today, it would take years of research to quality alternative refrigerants in our systems and this would be of limited benefit since we still need to use R-23 and R-14. Even if R-23 could be eliminated in favor of ethane, there are no substitutes for R-14 which is also a critical component of our autocascade blends.

5) During the July meeting the question was asked of me: “What would customers do if the refrigerants we use today were not available?” The answer is simple. Customers would be forced to go back to using liquid nitrogen (LN2). As shown in attachment one, even when factoring in refrigerant leakage from our systems, they still provide a significant environmental advantage of 5:2 over LN2 based on our TEWI analysis (Attachment One). Without access to Brooks products LN2 is the closest match for all of the application requirements that Brooks serves today. However, if switching back to LN2 customers would experience longer process cycles since LN2 lacks a rapid hot gas defrost capability provided by our systems when used for water vapor cryopumping.

Although other cryogenic technologies exist, none can match the same physical interface cooling capacity and energy efficiency that our products provide. Helium expansion cycles are commercially used (i.e. Stirling and Gifford-McMahon), and Brooks Automation makes these as well so we are well aware of their benefits and limitations. Commercially available helium refrigeration systems have capacities that are limited to tens of watts up to 400 watts. In contrast our main cascade and autocascade refrigeration products provide capacities of 1000 – 4000 watts. Scale up of a helium system to provide the same capacity of cooling we provide, would require input energy that about 4.5 times higher than what our systems require. So although a helium system could potentially serve as an alternative means of cooling, the increased energy consumption and associated CO2 emissions would not meet the State’s reduction goals. Further, the helium systems provide localized spot cooling (producing a cold finger) rather than providing a stream of cold refrigerant. In contrast, our autocascade systems provide a stream of cold refrigerant which can flow through a cryogenic evaporator. This allows us to cool a large surface area which is critical to providing high pumping speeds of water vapor in these vacuum systems (since, in a molecular flow vacuum system, pumping speed is dictated purely by surface area, conductance and temperature). As a result, use of a helium system would require additional pumps to circulate a secondary fluid through a tube in order to provide the same effect and this would require even more input power.

Attachment Two provides a TEWI analysis comparing an autocascade refrigeration system and R-508B cascade chillers to a helium based refrigeration system. Even in this analysis both systems offer significant energy efficiency. The autocascade system provides a benefit ratio of 3.4 to 1 and the R-508B chiller offers a benefit ratio of 4.5 : 1.

The benefit calculated from the TEWI analyses in Attachments One and Two assumed a CO2 emission rate of 401 g CO2/kwh. However, the actual CO2 emission rate per varies from year to year based on the energy sources used in the state. Figure 1 shows a sensitivity analysis of the TEWI benefit ratio as a function of CO2 emission rate per kWh. In all cases the TEWI benefit ratio remains favorable with ratios of at least 3:1 even down to 100 g CO2 / kWh. Further analysis shows that CO2 emission rates of less than 10 g/kWh would be needed to observe an unfavorable ratio.

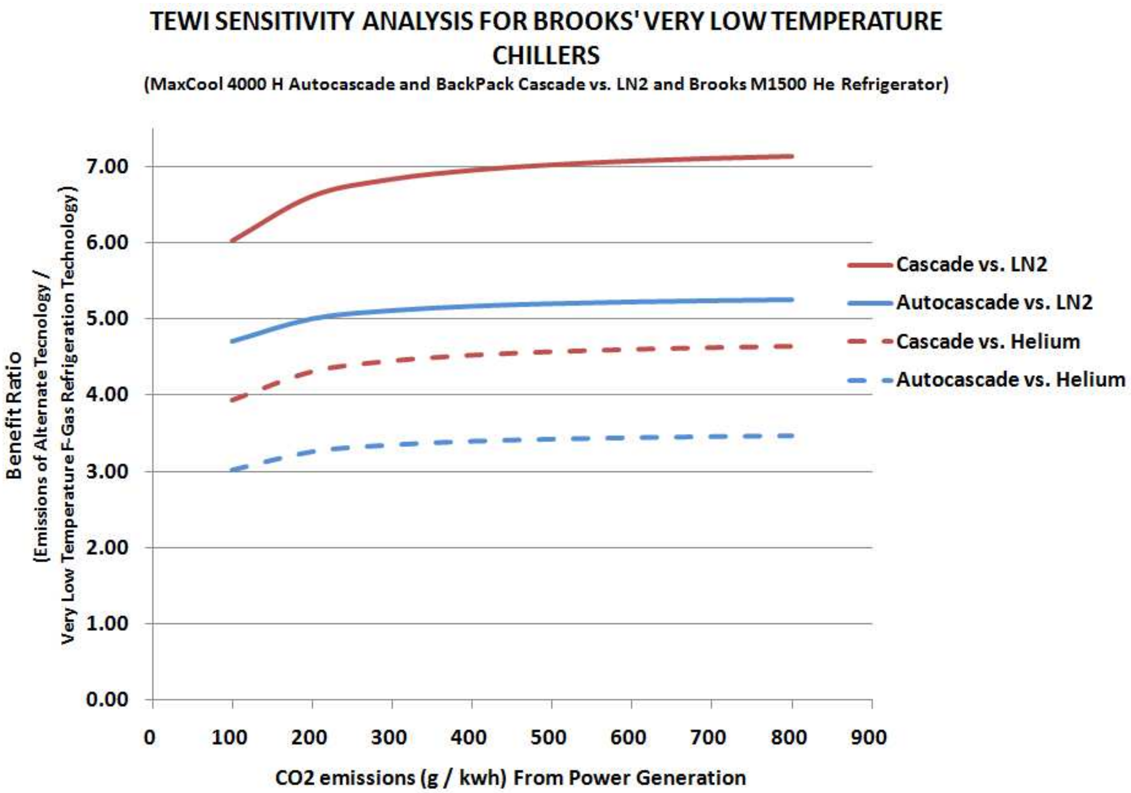

Figure 1. TEWI Sensitivity Analysis as a Function of CO2 Emission Rate per kWh.

6) When the EU was developing their aggressive laws to reduce greenhouse gas emissions they considered these application factors. Based on the legislation enacted it appears that it did not make sense to prohibit the high GWP refrigerants used in very low, ultralow temperature refrigeration and cryogenic refrigeration. I believe this was due to the fact that changing to low GWP alternatives is not technically feasible, and that alternate technologies would result in higher CO2 emissions. In addition, as both of these applications are very small in the overall use of high GWP refrigerants, prohibiting or restricting these products would have a negligible impact on the green house gas reduction goals of the legislation. The specific provision in the law, is that they do not place any use restrictions on applications providing temperatures at -50 C or below. Similarly, Environment Canada has allowed for this same use exemption in their proposed legislation.

As currently worded, the draft strategy does not clearly identify which applications qualify for an exemption from the proposed sales ban of high GWP refrigerants. Brooks is deeply concerned that without a specific exemption, customers could experience significant delays in buying and receiving bulk refrigerant service charges or precharged refrigerant. Brooks is requesting to add a specific exemption for refrigeration systems operating below -50 C. This would be consistent with the EU F-gas law and the proposed Canadian legislation. If the Board is concerned that such a temperature based exemption might be too broad and allow significant use of high-GWP F-Gasses in other market segments then we would ask the Board to consider alternate exemptions that would provide clear language that would allow our customers the continued ability to buy, operate, and service our products.

As the Air Resources Board continues its work to determine a successful path to meet the states goals for green house gas reduction, I would again ask that it consider the feasibility for each sector, and to consider the impact each sector has relative to achieving these reduction goals. Further, I would request that ARB consider adopting the same -50 C use exemption as adopted by the EU, and being considered by Canada. Based on the infeasibility to change to low GWP refrigerants, and the negligible impact this sector has on the State's green house gas emissions this seems to be a reasonable approach.

Brooks thanks the California Air Resources Board for providing an opportunity to comment and looks forward to working in a constructive manner to address HFCs and other F-Gasses. If you have any questions, please feel free to reach me at kevin.flynn@brooks.com or +1(707)206-1543.

Best regards,

Kevin Flynn, PE

Mixed Gas Refrigeration Technology Manager

Brooks Automation

**Attachment One.**
**TEWI Evaluation of various very cold refrigeration products compared to using liquid nitrogen.**

TEWI components: For this evaluation we consider Direct and Indirect contributions to the Total Equivalent Warming Impact (TEWI).

The Direct component is the global warming resulting from refrigerant emissions to the atmosphere.

The Indirect component is the global warming resulting from CO2 emissions generated as a result of power generation. The power requirements considered are those required to operate these very low temperature refrigeration products and those required to produce liquefied nitrogen (LN2).

For this analysis, data from the 8th Edition (4/24/15) of the Documnetaion of California's Greenhouse Gas Inventory is used (http://www.arb.ca.gov/cc/inventory/doc/docs1/1a1ai_importedelectricityspecified_nevada_apexgstation(nv)_electricitygeneration_mostlyfromnaturalgas_co2_2013.htm ).
The average CO2 emission per 1 kW-hour is 401 grams. For one year, this means that 3,513 kg of CO2 are generated in California per kW-year (or 7,745 lbs/kW-year).

**Case 1: Operation of a MaxCool 4000H for one year when operated at rated load**

| | | | |
|---|---|---|---|
| TEWI = | Direct | + | Indirect |
| | 3,983 lb CO2 | | 119,929 lb CO2 |

= 123,912 lb CO2/yr

**Case 2: Use of Liquid Nitrogen for one year providing same refrigeration as a MaxCool 4000H**

| | | | |
|---|---|---|---|
| TEWI = | Direct | + | Indirect |
| | 0 | | 639,725 lb CO2 |

= 639,725 lb CO2

## Benefit of using a MaxCool 4000H compared with LN2: 5.2 to 1

Note: This analysis does not include carbon emissions associated with transport of LN2 to the site of use.

**Case 3: Operation of a Cascade Chiller (R-508B for low stage) for one year when operated at rated load**

**Attachment One (continued)**

TEWI = Direct + Indirect
2,390 lb CO2 44,567 lb CO2

= 46,957 lb CO2/yr

**Case 4: Use of Liquid Nitrogen for one year providing same refrigeration as a "BackPack" R-508B chiller.**

TEWI = Direct + Indirect
0 326,284 lb CO2

= 326,284 lb CO2

## Benefit of using a R-508B BackPack Chiller compared with LN2: 6.9 to 1

## Attachment One (continued)

### Case 1: Summary of TEWI assessment for a MaxCool 4000H:

A MaxCool 4000H will produce a refrigeration effect of 4000 W at –100 C and will require an input power of 15.5 kW. During the course of a year it is estimated that the unit will lose 4% of its 18.7 pound refrigerant charge to the atmosphere, or 0.75 pounds of refrigerant which has a 100 yr GWP of 5310. For the majority of the refrigerants we use, the 100 year GWP value is higher than the 20 year GWP, and represents a conservative assessment.

**Direct Impact:**
Total = 3,983 lbs CO2e

**Total Direct Impact = 3,983 lb CO2/yr**

**Indirect Impact:**
15.5 kW X 1 yr X 7,745 lb CO2 / kW-yr = 119,929 lb CO2

**Total Indirect Impact = 119,929 lb CO2/yr**

(Note: The direct impact is only 3.3 % of the total impact).

### Case 2: Summary of TEWI Assessment for Using Liquid Nitrogen at -100 C:

In this case LN2 will be used to produce the same refrigeration effect provided by a MaxCool 4000H: 4000 W at –100 C

**Direct Impact:**

None since nitrogen is not produced in the process and is the prime atmospheric gas.

**Total Direct Impact = 0 lb CO2/yr**

**Indirect Impact:**
82.68 kW X 1 yr X 7,745 lb CO2 / kW-yr = 639,725 lb CO2

(see attachment describing estimate of required input power)

**Total Indirect Impact = 639,725 lb CO2/yr**

### Case 3: Summary of TEWI assessment for a Cascade 508B chiller (“BackPack”):

A BackPack, R-508B cascade chiller will produce a refrigeration effect of 2,100 watts at –90 C and will require an input power of 5.76 kW. During the course of a year it is estimated that the unit will lose 4% of its 5 pound refrigerant charge to the atmosphere, or 0.2 pounds of refrigerant which has a 100 yr GWP of 11,950.

**Direct Impact:**

Total = 2,390 lbs CO2e

**Total Direct Impact = 2,390 lb CO2/yr**

**Indirect Impact:**
5.76 kW X 1 yr X 7,745 lb CO2 / kW-yr = 44,567 lb CO2

**Total Indirect Impact = 44,567 lb CO2/yr**

(Note: The direct impact is only 5.3 % of the total impact).

### Case 4: Summary of TEWI Assessment for Using Liquid Nitrogen at -90 C:

In this case LN2 will be used to produce the same refrigeration effect provided by a BackPack: 2,100 W at –90 C

**Direct Impact:**

None since nitrogen is not produced in the process and is the prime atmospheric gas.

**Total Direct Impact = 0 lb CO2/yr**

**Indirect Impact:**
42.17 kW X 1 yr X 7,745 lb CO2 / kW-yr = 326,284 lb CO2

(see attachment describing estimate of required input power)

**Total Indirect Impact = 326,284 lb CO2/yr**

**Attachment One (continued)**

**Estimate of power requirements for LN2:**

To produce refrigeration at –100 C LN2 can be boiled and superheated at 1 atmosphere. The energy absorbed by LN2 as it changes from fully saturated liquid at –196 C to superheated gas at –100 C is 302.11 KJ/kg (ASHRAE 2001 Fundamentals Handbook). To produce 4000 Watts of cooling would require:

4000 W / 301.06 KJ/kg = 0.0133kg/s of LN2 delivered to the customer's application.

In the course of transporting LN2 from the point of manufacture to an onsite storage facility and then to provide internal distribution in the customers plant will result in significant thermal losses. These losses can be as high as 3 to 6 kg of LN2 being lost for each kg actually delivered to the end application. For purposes of this assessment we assume that half the LN2 will be lost from the point of production to the end application.

Rate of LN2 required = 0.0133 kg/s X 2 (for losses in delivery)
= 0.0266 kg/s

The energy that must be removed from gaseous nitrogen at 1 atmosphere and +27 C to saturated liquid at –196 C and 1 atmosphere is 432.11 kJ/kg. Hence the required heat removal is:

Refrigeration required to liquefy N2 = 0.0266 kg/s * 432.11 kJ/kg
= 11.49 kW

To determine the input energy needed to produce this refrigeration effect we need to know the COP of the process. COP is defined as:

COP (Coefficient of Performance) = Refrigeration Provided / Input Power

In the case of an ideal (Carnot) process with no losses this is:

Refrigeration Temperature / (Ambient Temperature – Refrigeration Temperature)

For this case, these values are:

COP ideal = 77 K / (300 K – 77 K)
= 0.345

In typical nitrogen liquefaction processes, efficiencies of 40% of ideal.

COP typical = 0.4 X COP ideal
= 0.138

**Attachment One (continued)**

Hence the required input work is:
Input work = Refrigeration Provided / COP typical
= 11.49 kW / 0.138
= 83.26 kW (to produce 4000 W of cooling at –100 C)

Note: This analysis does not consider additional energy required to separate nitrogen from the air which may increase the required input power substantially.

In the case of producing 2100 watts at -90 C, there is some additional cooling derived from the gaseous nitrogen due to the warmer temperature:

2.1 kW / 311.51 KJ/kg = 0.00674 kg/s of LN2 delivered to the customer’s application.

Assuming a 50% loss in transportation and delivery requires a total generation rate of 0.01348 kg/s

Refrigeration required to liquefy N2 = 0.01348 kg/s * 432.11 kJ/kg
= 5.82 kW

Hence the required input work is:
Input work = Refrigeration Provided / COP typical
= 5.82 kW / 0.138
= 42.17 kW (to produce 2,100 W of cooling at –90 C)

**Attachment Two.**

**TEWI Evaluation of various very cold refrigeration products compared to using a Gifford McMahon helium refrigeration system.**

TEWI components: For this evaluation we consider Direct and Indirect contributions to the Total Equivalent Warming Impact (TEWI).

The Direct component is the global warming resulting from refrigerant emissions to the atmosphere.

The Indirect component is the global warming resulting from CO2 emissions generated as a result of power generation. The power requirements considered are those required to operate these very low temperature refrigeration products and those required to produce liquefied nitrogen (LN2).

For this analysis, data from the 8th Edition (4/24/15) of the Documentation of California's Greenhouse Gas Inventory is used (http://www.arb.ca.gov/cc/inventory/doc/docs1/1a1ai_importedelectricityspecified_nevada_apexgstation(nv)_electricitygeneration_mostlyfromnaturalgas_co2_2013.htm ).
The average CO2 emission per 1 kW-hour is 401 grams. For one year, this means that 3513 kg of CO2 are generated in California per kW-year (or 7,745 lbs/kW-year)..

**Case 1: Operation of a MaxCool 4000H for one year when operated at rated load**

TEWI = Direct + Indirect
3,983 lb CO2 119,929 lb CO2

= 123,912 lb CO2/yr

**Case 2: Use of a helium based Gifford McMahon refrigerator, Brooks Model M1500 for one year providing same refrigeration as a MaxCool 4000H**

TEWI = Direct + Indirect
0 425,555 lb CO2

= 425,555 lb CO2

## Benefit of using a MaxCool 4000H compared with model M1500 helium refrigerator: 3.4 to 1

Note: A helium GM refrigerator does not provide a "like in kind" solution since it does not deliver cooling over a wide area. This would likely require additional energy input to pump a chilled fluid through tubing in order to provide the same distributed surface provided by the MaxCool.

**Case 3: Operation of a Cascade Chiller (R-508B for low stage) for one year when operated at rated load**

TEWI = Direct + Indirect
2,390 lb CO2 44,567 lb CO2

= 46,957 lb CO2/yr

**Case 4: Use of a helium based Gifford McMahon refrigerator, Brooks Model M1500 for one year providing same refrigeration as a "BackPack" R-508B chiller.**

TEWI = Direct + Indirect
0 212,777 lb CO2

= 212,777 lb CO2

## Benefit of using a R-508B BackPack Chiller compared with LN2: 4.5 to 1

**Attachment Two (continued).**

**Case 1: Summary of TEWI assessment for a MaxCool 4000H:**

A MaxCool 4000H will produce a refrigeration effect of 4000 W at –100 C and will require an input power of 15.5 kW. During the course of a year it is estimated that the unit will lose 4% of its 18.7 pound refrigerant charge to the atmosphere, or 0.75 pounds of refrigerant which has a 100 yr GWP of 5310. For the majority of the refrigerants we use, the 100 year GWP value is higher than the 20 year GWP, and represents a conservative assessment.

**Direct Impact:**

Total = 3,983 lbs CO2e

**Total Direct Impact = 3,983 lb CO2/yr**

**Indirect Impact:**

15.5 kW X 1 yr X 7,745 lb CO2 / kW-yr = 119,929 lb CO2

**Total Indirect Impact = 119,929 lb CO2/yr**

(Note: The direct impact is only 3.3 % of the total impact).

**Case 2: Summary of TEWI Assessment for Using a Helium Based Refrigeration System:**

Use of a helium based Gifford McMahon refrigerator, Brooks Model M1500 for one year providing same refrigeration as a MaxCool 4000H to provide the same refrigeration effect provided by a MaxCool 4000H: 4000 W at –100 C.

The M1500 provides 400 watts of cooling at -100 C and requires 5500 watts of cooling. Therefore it would require ten of these to provide the 4000 watt capacity and this would require an input power of 55,000 watts.

**Direct Impact:**

None since helium is a natural atmospheric gas.

**Total Direct Impact = 0 lb CO2/yr**

**Indirect Impact:**

55 kW X 1 yr X 7,745 lb CO2 / kW-yr = 425,555 lb CO2

**Total Indirect Impact = 425,555 lb CO2/yr**

**Case 3: Summary of TEWI assessment for a Cascade 508B chiller ("BackPack"):**

A BackPack, R-508B cascade chiller will produce a refrigeration effect of 2,100 watts at –90 C and will require an input power of 5.76 kW. During the course of a year it is estimated that the unit will lose 4% of its 5 pound refrigerant charge to the atmosphere, or 0.2 pounds of refrigerant which has a 100 yr GWP of 11,950.

**Direct Impact:**

Total = 2,390 lbs CO2e

**Total Direct Impact = 2,390 lb CO2/yr**

**Indirect Impact:**

5.76 kW X 1 yr X 7,745 lb CO2 / kW-yr = 44,567 lb CO2

**Total Indirect Impact = 44,567 lb CO2/yr**

(Note: The direct impact is only 5.3 % of the total impact).

**Case 4: Summary of TEWI Assessment for Using a Helium Based Refrigeration System:**

Use of a helium based Gifford McMahon refrigerator, Brooks Model M1500 for one year providing same refrigeration as a MaxCool 4000H to provide the same refrigeration effect provided by a MaxCool 4000H: 4000 W at –100 C.

The M1500 provides 420 watts of cooling at -90 C and requires 5500 watts of input energy. Therefore it would require five of these to provide the 2,100 watt capacity and this would require an input power of 27,500 watts.

**Direct Impact:**

None since helium is a natural atmospheric gas.

**Total Direct Impact = 0 lb CO2/yr**

**Indirect Impact:**

27.5 kW X 1 yr X 7,745 lb CO2 / kW-yr = 212,777 lb CO2

**Total Indirect Impact = 212,777 lb CO2/yr**

## Attachment Three

## Brooks Automation Shipments of F-Gas Refrigerants to California Customers for 2010 – 2015

| | **2010[1]** | **2011** | **2012** | **2013** | **2014** | **2015[2]** |
|---|---|---|---|---|---|---|
| **Total Pounds Shipped** | **1344** | **1901** | **2079** | **1627** | **1191** | **1162** |
| **GWP[3] * Pounds Shipped (GWP-lbs)** | **8,656,685** | **10,269,666** | **12,318,120** | **9,324,250** | **6,660,397** | **6,238,426** |
| **MTCO2e[4]** | **3,926** | **4,657** | **5,586** | **4,228** | **3,021** | **2,829** |
| **MMTCO2e[5]** | **0.003926** | **0.004657** | **0.005586** | **0.004229** | **0.003021** | **0.002829** |

This data represents sales of autocascade refrigeration systems shipped to addresses in California. This includes refrigerant shipped in precharged equipment and in cylinders for use in service charges. These service shipments are also referred to as bulk shipments.

This data does not include shipments of F-Gas in small cryocoolers. The total annual shipment of these products is less than 40 lbs.

This data also does not include shipment of R-508B for use in Cascade systems as these refrigerants. Typical annual usage in California over the period 2010 – 2015 is less than 100 pounds. R-508B has a 100 yr GWP of 11,950. 100 pounds of 508B is equivalent to 1,195,000, an MTCO2e of 542, and an MMTCO2e of 0.000542.

For purposes of this discussion, Brooks will use a value of 0.006 MMTCO2e to reflect all annual shipments to California in this time period.

Notes:

1) Data from 2010 was limited to Q4 only. Values shown are the result of multiplying this data by 4.
2) Data from 2015 was limited to January – August. Values shown are the result of multiplying this data by 1.5 (12/8).
3) GWP values taken from EN378-1 : 2008+ A2:2012 (100 year integration).
4) MTCO2e: Metric tons (1,000 kg), CO2 equivalent.
5) MMTCO2e: Million Metric tons (1,000,000,000 kg), CO2 equivalent.