BEETIT Program Overview

B.1. BACKGROUND

Buildings consume 40% of the primary energy in the United States[1]. Buildings use 72% of the nation's electricity and 55% of natural gas[1]. Energy use by buildings account for[2] ~ 40% of CO_2 emissions in US. The energy use in the residential and commercial building sector is roughly split in half. From 2006 to 2030, the US population is expected to increase by 21% while the number of households is expected to increase by 25%. Commercial space is expected to increase by 35% over the same period[2]. Building floor space is increasing at a much faster rate in developing countries such as China and India compared to the US. It is expected that floor space will increase at an annual rate of 8.5% in India from 2010 to 2030, and at an annual rate of 3.5% in China[3], which will lead to significant increase in demand for energy in the building sector worldwide. Therefore, energy efficiency measures in the buildings sector provide a tremendous opportunity to reduce the energy demand and reduction in greenhouse gas (GHG) emissions.

Space cooling accounts for approximately 12.7% of primary energy consumption in buildings[2] and accounts for 13% of CO_2 emissions from buildings in US. This amounts to ~5% of primary energy consumption and ~ 5% of CO_2 emissions in US. Refrigerants used in vapor compressions systems for space cooling are another source of green house gas (GHG) emissions. More than 90% of cooling is provided by vapor compression based systems in the US[2,4]. The global warming potential[2,4] (GWP) of refrigerants such as hydrochloroflurocarbons (HCFC) and hydrofluorocarbons (HFC) are typically more than 1000 times that of CO_2. Although the current contribution of GHG due to HCFC, HFC and chlorofluorocarbons (CFC) in US[2] is ~1%, however, a recent report[5] suggests that the global GHG emissions from these chemicals in 2050 could be equivalent to 9–19% (CO_2-equivalent basis) of projected global CO_2 emissions in business-as-usual scenarios. This percentage increases to 28–45% compared with projected CO_2 emissions in a 450-ppm CO_2 stabilization scenario. Due to significant increase in the demand for air conditioners and refrigerators in developing countries, GHG emissions due to refrigerants from developing countries can be as much as 800% greater than in developed countries by 2050.

Vapor compression based space cooling systems come in various types depending on the tons (1 Ton = 3.5 KW of cooling load) of cooling needed. Packaged units which include unitary roof top or split system account for roughly 50% of the current systems and 50% of energy consumed in commercial building cooling[2,4]. In packaged units, air is in direct contact with expansion coils and the condenser is typically dry cooled (air cooled). In a chiller system, water is cooled in the evaporator of the refrigeration system and the chilled water is used for cooling the air. Water based chillers account for ~30% of the units and the condenser is either dry cooled or wet cooled (water cooled). The coefficient of performance (COP = cooling load (KW)/electrical power (KW)) of dry cooled systems[6] is typically less than 4. Depending on the age of the buildings[7], COP of the cooling equipment can be significantly less than 4. COP of wet cooled chillers[8] can be as high as 7. However, wet cooling is achieved by evaporation of water, which leads to significant water consumption. Since water scarcity is the other major challenge facing the planet, consumption in such huge amounts is not desirable.

Based on the discussions above, there is an urgent need to accelerate research and development of cooling technologies for buildings, which can enhance overall energy efficiency and reduce GHG emissions, while reducing the cost incurred

[1] Buildings Energy Data Book, 2007
[2] Buildings Energy Data Book, 2009
[3] Zhou N, et al. (2008) Energy use in China: Sectoral Trends and Future Outlook. Lawrence Berkeley National Laboratory paper LBNL-61904 (Lawrence Berkeley National Laboratory, Berkley, California)
[4] Energy Consumption Characteristics of Commercial Building HVAC Systems, Volume 1: Chillers, Refrigerant Compressors and Heating Systems, Arthur D. Little Report For Office of Building Technology State and Community Programs, Department of Energy
[5] Velders et al, Proc. National Academy of Sciences ,**106**, 10949 (2009)
[6] DOE report, How to Buy an Energy-Efficient Air-Cooled Electric Chiller
[7] Database for Energy Efficiency, DEER report 2005, http://www.deeresources.com/
[8] DOE report, How to Buy an Energy-Efficient Water-Cooled Electric Chiller

by the consumers. ARPA-E seeks innovative proposals for energy efficient cooling devices/air conditioners (AC) for commercial buildings to cater to these needs.

B.2. OBJECTIVES

The focus of this FOA is to develop energy efficient cooling technologies/air conditioners (AC) for buildings to reduce GHG from: (a) primary energy consumption due to space cooling; and (b) refrigerants used in vapor compression systems. ARPA-E seeks innovative research and development approaches to increase energy efficiency and reduce GHG emissions due to cooling of buildings by

- Development of cooling systems that use refrigerants with global warming potential[†] ≤ 1.
- Development of energy efficient air conditioning (AC) system for warm and humid climates to increase the coefficient of performance (COP) of ventilation load cooling by $\geq 50\%$.
- Increased efficiency of vapor compression AC system for hot climate for re-circulating air loads by increasing the COP by $\geq 50\%$.

One or a combination of these technologies can be utilized in buildings, where many factors influence the cooling load:

- Type of building such as office space versus hospital (~100 % air is fresh i.e. very high ventilation load)
- Climate type, i.e. warm and humid versus hot and dry

The unique challenge for the US market is be to come up technologies that can be retrofitted into current cooling systems. For developing economies on the other hand, there is a large market for new cooling technologies. The development of these technologies will lead to reduction in GHG emissions and significantly increase US technological lead in the world.

B.3. AREAS OF INTEREST

Area of Interest 1: Compact cooling systems that are based on refrigerants with global warming potential ≤ 1

As mentioned earlier, if the state-of-the-art cooling paradigm is continued, HFC and HCFCs used in vapor compression systems can contribute significantly to global warming. Therefore there is a critical need to develop novel cooling technologies that are not based on vapor compression of refrigerants with GHG potential. There have been significant breakthroughs in the past decade on alternate cooling technologies such as magnetic [9], thermoelectric [10], and thermoacoustic[11] cooling. Some of these technologies also have the potential to be more compact in size in comparison to vapor compression systems. This could potentially open up the opportunity to use them in other applications such as window-mounted air conditioners and automobiles. Furthermore, during low occupancy periods in buildings, the use of central chillers is inefficient for the whole building, since the energy required for cooling is wasted on zones that do not require cooling. Ideally, for low occupancy conditions, the central chiller should be switched off and only localized cooling should be provided either by storage units or by compact coolers installed in the ducts with some way to dissipate the rejected heat. Hence, decentralizing a centralized cooling system would require the development of compact coolers with potentially storage units in way that they can be integrated in existing ducting systems of a building.

Area of Interest 1a: In spite of significant advances in materials and new cooling concepts mentioned above, most of these ideas have not been translated into viable technologies due to multiple reasons. For example, the maximum cooling demonstrated for magnetic refrigeration[10] has been less than 1 KW. To show the viability of alternate cooling technologies, ARPA-E seeks innovative proposals which can show 1 Ton of cooling using approaches including, but not limited to, magnetic, thermoelectric, electrocaloric, thermionic, and closed gas cycles. Only those ideas will be

[†] The global warming potential of CO_2 is considered 1. Global warming potential for other gases can be found at: http://unfccc.int/ghg_data/items/3825.php

[9] K.A. Gschneidner and V.K. Pecharsky, International J. of Refrigeration, **31**, 2008, 945-961

[10] L.E. Bell, Science, **321**, 2008, 1457 - 1461

[11] S. L. Garrett, American J. Physics, **72**, 2004, 11 - 17

entertained which have the complete cooling system i.e. the refrigeration unit and heat exchangers on the cold and the hot side. The typical cost of conventional cooling equipment is $1000/ton of cooling[12]. Therefore, the cost of these new technologies should be targeted to be in the same range. The technology target specification for this area of interest is given in Table 1. Proposed technology development plans must have well justified, realistic potential to meet or exceed the stated "Primary Technology Target Specification" by the end of the period of performance of the proposed project in order to be considered for award. Proposed technologies will secondarily be evaluated against their well justified, realistic potential to approach the "Secondary Technology Target Specification" by the end of the period of performance of the proposed project. Proposed technologies will still be considered for award if they fall short of one or more of the Secondary Technical Targets below, but will be evaluated and compared to one another according to their ability to address these targets.

Table 1a: Primary technology target specifications for compact cooling systems, which are not based on refrigerants that have GHG potential.

Global warming potential	≤ 1.0
COP	4
Technology demonstration	1 Ton = 3.5 KW
Air entering the cold side	75°F, 60% Relative humidity
Air leaving the cold side	55°F, 100% Relative humidity
Hot side air temperature	95°F

Table 1b: Secondary technology target specifications for compact cooling systems, which are not based on refrigerants that have GHG potential.

Size	Length = 1.5 ft, width = 1 ft, height/thickness = 9 inches.
Life time	14 years (See subsection C in section B.4)
Retail cost	~ $1000/ton

Area of Interest 1b: ARPA-E realizes that for many new approaches, developing a system with a cooling capacity of 1 Ton and the cost target of $1000/ton may not be realistic. There are many new ideas for which the concept has not yet been categorically proven. However, if proven, their impact could be significant. For such unproven and yet promising ideas, ARPA-E seeks small seedling proposals to conduct experiments to achieve a proof of concept. However, the proof-of-concept experiment must be designed in a way that the results obtained suggest possible paths to approach the specifications of Table 1.

Area of Interest 2: Enhanced energy efficiency of vapor compression based air conditioning systems:

As discussed earlier, more than 90% of the cooling systems today are based on vapor compression. Therefore, ARPA-E has strong interest in increasing the energy efficiency of vapor compression based systems while reducing greenhouse gas emissions and the operating cost to the consumers. Air conditioning is used to both control the temperature (sensible

[12] http://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/Calc_CAC.xls

load) and the humidity (latent load) in the indoor environment. Therefore, air conditioning requirements can vary significantly depending on the building and climate type. For example, the fraction of fresh air intake is a strong function of building type, e.g. hospitals require 100% fresh air vs. a typical office might require less than 20% fresh air intake[13]. In warm and humid climate, this will lead to very high latent heat load (dehumidification load) in the fresh air ventilation part of the cooling load[14]. Even if 100% air is re-circulated, the COP is a strong function of the condenser side ambient air temperature. To account for these different climatic conditions and building types, there are two sub-thrust areas of Interest as shown below. Since ~50% of AC units are of packaged type, the focus will be on packaged air conditioning units. For the US market, most of the opportunity lies in retrofitting concepts whereas for developing markets, new systems can also have a substantial market. To cover both the climate type (warm & humid vs. hot and dry) and fresh air intake vs. re-circulating air, ARPA-E is interested in two areas in this thrust with the expectation that technological advances in these areas will cover any of the possible combinations of climate type and the amount to fresh air intake.

Area of Interest 2a: Efficient control of temperature and humidity in warm and humid climate to increase energy efficiency, and indoor air quality while reducing operating cost

Ventilation load can be significant fraction of cooling load depending on building type and desired indoor air quality in warm and humid climate[14]. The minimum amount of work needed to condition air from state 1 (ambient) to state 2 (supply) is the availability (exergy) of air with respect to the ambient and is given as follows.[15] For sensible cooling,

$$W_s = c_{Pair}(T - T_{amb}) - T_{amb}\left[c_{Pair}\ln\left(\frac{T}{T_{amb}}\right)\right] + x\left(c_{Pvapor}(T - T_{amb}) - T_{amb}\left[c_{Pvapor}\ln\left(\frac{T}{T_{amb}}\right)\right]\right) \quad (1)$$

and for dehumidification (latent load cooling):

$$W_l = R_{air}T_{amb}\ln\left(\frac{P - P_{vapor}}{P - P_{vapor\_amb}}\right) + xR_{vapor}T_{amb}\ln\left(\frac{P_{vapor}}{P_{vapor\_amb}}\right) \quad (2)$$

where W_s is the minimum required work for sensible cooling per unit mass of dry air, W_l the minimum required work for latent load per unit mass of dry air, T the temperature of the output of the air conditioner that is supplied to the building, c_p the specific heat, R the gas constant, P the pressure, P_{vapor} the partial pressure of vapor, and x is the humidity ratio at the supply conditions. Since a conventional vapor compression system can only provide sensible cooling, it reduces the temperature to the dew point so that the relative humidity of the supply air is ~100% to condense the water from the humid air. This significantly increases the work input into the cooling system. Sometimes depending on the relative humidity and the temperature, the dew point temperature can be very low, which in turn requires reheat to reach the desired indoor temperature. This leads to significant decrease in the effective COP of the cooling system, which increases the cost to consumers. However, if the COP of the vapor compression system can be increased then energy required to dehumidify can be significantly reduced.

Another approach that has been investigated is to provide sensible cooling using conventional vapor compression system (or evaporative coolers in some cases) combined with the use of moisture absorbing materials such as desiccants to handle the latent load. Desiccants require heat to desorb (regenerate) the moisture, which can be provided by natural gas combustion or waste heat available at the cooling site. The *COP* of desiccants are typically reported in terms of the primary thermal energy used for regeneration i.e. COP_{latent} = Latent load/primary thermal energy input.

[13] D.R. Kosar et al., 1998, ASHRAE Journal, March 1998, 71- 75
[14] L.G. Harriman III et al., ASHRAE Journal, November 1997, 37-45
[15] E.M. Mina, Int. J. of Refrigeration, 28, 784 – 795 (2005)

Regardless of whether one uses a purely mechanical system or a combination of dessicant use and a mechanical system, it is important to understand the thermodynamic limit and how far we are today from the limit. An ideal system which operates at the thermodynamic limit for a combined vapor compression and desiccant cycle is illustrated in Fig. 1. If the outside air is at T_{amb} = 90 ^{o}F with a relative humidity of 90% and the indoor supply air is at T = 55 ^{o}F with a relative humidity of 55%, W_l from Eq. (2) is 2.06 kJ/kg (per unit mass of dry air). This is the exergy or the minimum work required for the latent heat load. However, we are achieving this regeneration process not by work but by heat, Q_d. The temperature of regeneration for the desiccant, T_r, is in the range[14,16] of 60 to 120 ^{o}C, which has to be higher than both T_{amb} and T. Assuming ambient temperature, T_{amb}, of 90 ^{o}F (32.22 ^{o}C) the Carnot efficiency, η_{Carnot} of an engine running between T_r and T_{amb} will range from 0.083 to 0.22, respectively. Therefore, the minimum heat required for regeneration of moisture when T_r ranges from 60 to 120 ^{o}C is $Q_d = W_l / \eta_{Carnot}$ = 2.06/0.083 to 2.06/0.22 or 24.6 to 9.2 kJ/kg (per unit mass of dry air), respectively. The actual latent load, which is given by $Q_l = h_g \left(x_{amb} - x \right)$ where h_g is the enthalpy of saturated vapor under these conditions, is 59 kJ/kg (per unit mass of dry air). Therefore, the theoretical limit of $\left(COP_{latent} \right)_{\lim} = Q_l / Q_d$ with respect to primary energy will range from 2.4 to 6.4, respectively. In current desiccant systems COP_{latent} typically ranges from[16] 0.5 – 1.0. Therefore, there is a significant potential to improve the COP_{latent}. The losses in desiccant systems arise from mainly two sources: (a) the regenerative heat exchanger between the process air and the regeneration air has an effectiveness less than 1 (i.e. an imperfect heat exchanger); (b) the moisture sorption and desorption processes are irreversible and have hysteresis, as required by kinetics. Furthermore, thermal and mass transport in desiccants take place at finite temperature and vapor pressure differences, which also lead to irreversibilities.

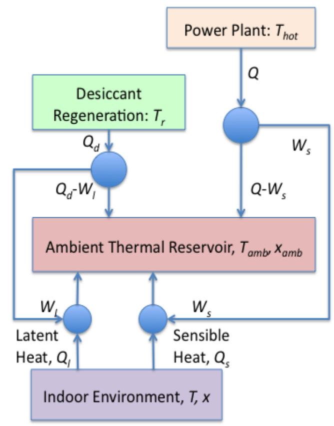

Fig. 1 Schematic diagram showing ideal system with Carnot engines and refrigerators. Note that (Q_d + Q) is the minimum primary energy input.

As discussed above, depending on the technology proposed, both thermal energy and electricity can be simultaneously used, such as in desiccant systems regenerated by thermal energy combined with vapor compression system powered by electricity for cooling. Therefore, the technical specifications have been set in terms of the *COP* with respect to the primary energy source which assumes that electricity comes from a thermal source[‡] i.e. $COP_{primary}$ = cooling-capacity/primary-energy. For simplicity, we require proposers to use the conversion factor[2] between electrical energy and primary energy to be 3.18. For example, if the *COP* of a vapor compression system with no reheat is 4 then $COP_{primary}$ = *COP*/3.18. While ARPA-E fully realizes that ambient conditions depend on time of the day, month and location, for performance benchmark it is assumed that outdoor ambient temperature is 90°F and relative humidity (RH) is 90%. It is also assumed that 100% of the indoor air is supplied at 55°F with a relative humidity of 50%. Under these conditions a conventional mechanical vapor compression system with electric reheat with an assumed *COP* of 4 will have $COP_{primary}$ of 0.75, which also includes the energy used for reheating. ARPA-E seeks proposals to increase the $COP_{primary}$ by 50%. If waste heat from the air conditioning unit is being used (such as heat from the condenser) then it should not be included in the calculation of $COP_{primary}$.

For the particular set of conditions for T_r = 100 ^{o}C, and T_{hot} = 500 ^{o}C (thermal plant), Figure 2 shows the ideal primary energy input as a function of COP_{VC} of the vapor compression system. It also shows the primary energy input for a purely vapor compression system with electrical reheat, and ones with dessicants with COP_{latent} of 0.7 and 1.4. Also shown in Fig. 2, is the region where current packaged units can be placed, where the primary energy input is about 120

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[16] A. Lowenstein, HVAC&R Research, 14, 6, (2008)

[‡] We will only consider electricity generation for thermal plants, with an average efficiency of 31.4%. This yields a multiplier of 3.18 for the primary energy consumption. We will not consider renewable electricity here, since that is small fraction of our 12.8 Quads of annual electricity generation today.

kJ/kg and a COP_{VC} of 2-4. These calculations have been done using the cycle shown in Fig. 2, whereas the thermodynamic limit is obtained from the ideal cycle shown in Fig. 1.

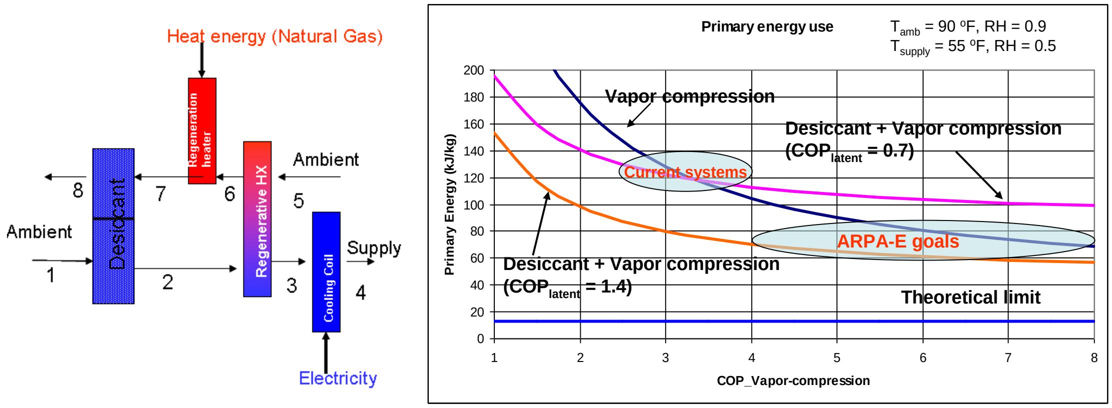

Fig. 2 (Left) A desiccant-based cooling system with regenerative heat exchange. In an ideal system the heat exchange should have an effectiveness of 1 and the desiccant should have no hysteresis during sorption-desorption cycles. (Right) Primary energy input as a function of COP of the vapor compression system for a particular set of ambient and supply conditions. Also shown is an ideal system operating at thermodynamic limit, the current systems and ARPA-E target for the current FOA.

Note that the thermodynamic limit is about 12 kJ/kg, making the current packaged units a factor of 10 away from the thermodynamic limit. For water-cooled systems, the COP_{VC} can be as high as 8 and the primary energy input is about 65 kJ/kg. However, there is significant loss of water due to evaporation in such systems.

The challenge that ARPA-E poses to the technical community is to reach primary energy input to be about 65 kJ/kg without water loss. This is to cut the difference between current energy input and the ideal energy input by a factor of 2.

Table 2 provides the technology target specification for this area of interest. It is expected that while integrating it in a building, various types of regenerative heat exchanges are possible depending on the fraction of fresh air intake. This will further increase the efficiency, however for technology demonstration the device should be tested without considering different integration schemes in an actual building. It is expected that while integrating in a building, those advantages will be availed whenever possible.

Energy efficiency can be significantly increased by use of evaporative coolers; however, significant amount of water is lost to the atmosphere in evaporative coolers. Water scarcity is another major problem that the planet is facing today. Therefore, use of evaporative coolers can be proposed only if 90% of the water mass flow rate that is evaporated can be reclaimed.

Table 2: Technology target specification for efficient control of temperature and humidity in warm and humid climate

COP based on primary energy source = cooling load/primary thermal energy use	1.125
Technology demonstration	5 Ton capacity for packaged systems
Air entering the evaporator	90°F, 90% Relative humidity
Air leaving the evaporator	55°F, 50 % Relative humidity
Condenser side air temperature	90°F
Use of evaporative cooling	Yes if 90% water is reclaimed i.e. 90% of water that is lost due to evaporation and drift has to be reclaimed i.e make up water flow rate is less than 10% of the flow rate of water being lost due to evaporation and drift
Life time	14 years (See subsection C in section B.4)
Retail cost	< $1500/ton for new systems, < $1000/ton for a retrofit to existing vapor compression system

Area of Interest 2b: Increase the cooling efficiency of recirculation air in hot environment

Depending on the building type, a significant fraction of air is simply re-circulated within a building. However, the *COP* of cooling is still a strong function of the ambient temperature because the condenser rejects the heat to the outdoor environment. It is possible to increase the *COP* by wet cooling of condensers by using cooling towers. But a significant amount of water is lost in wet cooling.

ARPA-E seeks innovative proposals to increase the *COP* of packaged AC units. Proposed ideas could include but are not only limited to: wet cooling of condensers where 90% water lost during evaporation and drift is reclaimed; heat pipe based heat exchangers to increase the effectiveness within the footprint of the state-of-the-art condensers, which are widely used for cooling high-power computers; thermal storage of condenser heat during the day and release during the night when the ambient temperature is lower. Table 3 provides the technology target specification for this area of interest.

Table 3: Technology target specification for increasing the cooling efficiency of recirculation air in hot environment

$COP_{vapor\text{-}compession}$	6
Technology demonstration	5 Ton capacity for packaged systems
Air entering the evaporator	75°F, 60% Relative humidity
Air leaving the evaporator	55°F, 100% Relative humidity
Condenser side air temperature	105°F
Use of evaporative cooling	Yes if 90% water is reclaimed i.e. 90% of water that is lost due to evaporation and drift has to be reclaimed i.e make up water flow rate is less

	than 10% of the flow rate of water being lost due to evaporation and drift
Life time	14 years (See subsection C in section B.4)
Retail cost	< $1500/ton for new systems, < $1000/ton for a retrofit to existing vapor compression system

B.4. OTHER TECHNICAL REQUIREMENTS

A. Proposed technology

- Areas of interest 2a and 2b should be treated separately i.e. applicants are not expected to tackle both the areas
- If an applicant wishes to apply under multiple Areas of Interest, a separate and complete application will be required for each Area of Interest submittal, with no need for application reviewers to refer to another application.
- It is anticipated that some applicants may wish to submit proposals that incorporate elements of both areas of Interest 1& 2 (an example of which might be to build an air conditioning system with a refrigerant with GWP < 1 and meets the criteria of areas of interest 2a or 2b) or elements of sub areas of interest 2a and 2b (an example of which could be system with a COP of vapor compression of 6.0 with desiccant dehumidification). Such submissions are allowed, and applicants should consider submitting such applications to the Area of Interest where the greatest amount of ARPA-E funding would be devoted.

B. Manufacturability of Proposed Technology at Scale

ARPA-E understands that not all applicants will have access to sophisticated cost models for these areas of interest. However, it is expected that all applicants will make a strong effort to estimate the potential materials and manufacturing costs of the proposed technology to justify how the technology holds promise to approach, meet or exceed the cost targets given in this FOA for different areas of interest. The applicants must describe the manufacturing approach(es) that will most likely be used to scale up the proposed technologies. The applicant is also encouraged to describe whether or not the proposed cooling technologies offer an opportunity for the U.S. to take a leadership role in manufacturing of the proposed technologies. If rare earth metals are proposed in a technology, then it is expected applicant will discuss how these metals will be available at cost competitive prices for high-volume manufacturing.

C. Reliability of Proposed Technology

The typical lifetime requirement[13] for cooling systems is 14 years. Therefore, it is expected that the proposed technology will have similar life time. ARPA-E recognizes that full-scale reliability testing is not possible by the applicants. However, it is expected that the applicant will perform some level of accelerated lifetime testing to understand critical failure modes and use physics-based understanding to project the reliability of the proposed technology.

D. Integration of retrofits in existing cooling systems

If the applicant is proposing a retrofitting scheme to existing cooling systems then it is expected that applicant will describe possible integration schemes.

E. Technical Strength of the Performance Team

The applicant should describe the unique elements/background of the proposed technical team that makes the team uniquely suited to successfully execute the proposed air conditioning research and development. Preference will be given to multidisciplinary teams where different team members complement each other and have expertise in different aspects of the technology. It is expected the principal investigator (PI) will have both technical and management roles. He/she will make sure that different elements of the project and technology are well integrated, while making decisions based on technical understanding of the problem.

B.5. CONCEPT PAPER STRUCTURE

Applicants are required to first submit a Concept Paper describing the essence and novelty of their new technology concept in order to be considered for award under this FOA. The purpose of the Concept Paper phase of this FOA is to allow applicants to communicate their AC technology concept to ARPA-E, with a minimal level of investment in time and resources, and receive feedback on ARPA-E's level of interest in the concept before ARPA-E requests the submission of a more time and resource intensive Full Application.

General Concept Paper requirements can be found in Section IV.B.2 of this FOA. Specific requirements and key elements that each Concept Paper must address are found in this section (Section I.B.5) and in the rest of Section I.B.

As stated in Section IV.B.2, Concept Paper will consist of a body not exceeding five (5) pages in length containing the following sections: 1.) Abstract and 2.) Technical Section. The Concept Paper will also include a one page "Cost Summary" (described in Section IV.B.2) and a one page completed "End of Project Targets" table that should be included in a single Concept Paper file, but will not count toward the five (5) page Concept Paper body limit. The End of Project Targets table will include the end of project target for the scale and form factor of the prototype device deliverable, as well as the end of project targets for all Primary Technical Requirements and Secondary Technical Targets. The "End of Project Targets" template can be found in Appendix 1 in Section X.

TECHNICAL SECTION

Specific issues/questions that should be considered and addressed in the Technical Section include the following:

- Identification of whether the applicant is applying for an award under the "Proof of Concept Seedling" category or the "Advanced Device Prototyping" category.
- A detailed description of the novel technology approach to be developed in the proposed project, including a description of its basic operating principles of how the proposed approach is unique and innovative.
- A description of the current state-of-the-art in the proposed technology area, including key shortcomings/limitations/challenges, and how the proposed project will seek to significantly improve upon the current state-of-the-art performance and overcome current key shortcomings/limitations.
- The applicant should provide a brief paragraph addressing the following issues for each of the technology target specification
  - What is the current state-of-the-art performance level for the proposed technology area for the specified requirement/target?
  - What level of performance will the project proposed here target for the specified requirement/target? What are the specific technical issues that have limited performance of this technology to date for the specified requirement or target?
  - How does the project proposed here address these specific technical issues to provide enhanced performance relative to the specified requirement or target? The applicant should provide technical justification for why this proposed target can credibly be met.
  - What are the key technical risks/issues associated with the technology development plan related to the specified requirement or target?
- A brief description of the manufacturing approach by which the proposed coolng technology would most likely be scaled and the scalability/cost issues related to this approach.
- A brief description of how the project, if successful, would impact U.S. leadership in cooling technology development and manufacturing.
- A brief description of the project team and why they are uniquely suited to successfully execute the proposed cooling research and development plan.
- A brief description of the impact ARPA-E funding of the proposed project would have relative to other previous or existing funding sources the project team has secured.

B.6. CONCEPT PAPER EVALUATION CRITERIA

General Concept Paper Evaluation Criteria are found in Section V.A. of this FOA. More specific Concept Paper Evaluation Criteria are described in this section.

Concept Papers will be evaluated against the following evaluation criteria in decreasing order of importance:

- To what degree does the Concept Paper present a cooling technology development plan that demonstrates credible and well-justified technical potential to meet or exceed technology target specification of this FOA. Technology approaches will be evaluated in a quantitative fashion, with technology approaches rated according to the degree to which they fall short of, meet, or exceed each technology target specification.
- To what degree does the Concept Paper present a unique and innovative technical approach to significantly improve cooling performance over the current state-of-the-art
- To what degree does the Concept Paper present a clearly demonstrated understanding of the current state-of-the-art and technical limitations of the current state-of-the-art in the relevant technology area.
- To what degree does the cooling technology proposed in the Concept Paper hold potential to enable U.S. manufacturing leadership in building cooling systems.
- To what degree does the proposed technical team have the skills and knowledge to successfully execute the project plan
- To what degree will ARPA-E funding have a leveraged impact on the development of the proposed technology relative to other funding sources for the project team.