Alcatel·Lucent

For:	**"Energy Efficient Information and Communication Technology" DE-FOA-0000107**
Title:	**Advanced Refrigerant-based Cooling Technologies for Information and Communications infrastructure (ARCTIC)**
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Project Objectives

A team led by Alcatel-Lucent (ALU) is pleased to present this proposal, "Advanced Refrigerant-based Cooling Technologies for Information and Communications infrastructure (ARCTIC)". The objective of our Category II proposal is to further develop and dramatically accelerate the commercialization of a game-changing, refrigerant-based, liquid-cooling technology and achieve a revolutionary increase in energy efficiency and carbon footprint reduction for our nation's ICT infrastructure.

ALU has recently developed modular cooling technology based on a central pump that supplies liquid refrigerant via hoses to microchannel heat exchangers that remove heat directly at the shelf level of equipment racks via refrigerant evaporation. Results of a prototype data center installation are so dramatic (Section 2) that the technology is being prepared for release as a first-generation ALU product offering. Successful execution of the proposed ARCTIC project will augment the technology beyond the current capability of the prototype shelf-level configuration by bringing the liquid coolant much closer to the actual heat sources, and accelerate development and commercialization of a next generation product.

The objectives of the ARCTIC proposal are three-fold: i) advanced research innovations EX 4 that dramatically enhance the ability to deal with ever-increasing device heat densities and footprint reduction by bringing the liquid cooling much closer to the actual heat sources; ii) manufacturing optimization of key components EX 4 and iii) ensuring rapid market acceptance by reducing cost, thoroughly understanding system-level performance and developing viable next-gen commercialization strategies.

ARCTIC will deliver substantial benefits in three key areas important for promoting market acceptance:

i) <u>reduced cooling costs</u>: ARCTIC's projected energy savings-- hence cooling cost savings -- are in excess of 90% relative to conventional CRAC-based air cooling, since the heat-carrying capacity relative to pumping power is substantially greater for the refrigerant than for air.

ii) <u>reduced real-estate footprint</u>: As compared to air-cooled approaches, our pumped-refrigerant approach can handle significant increases in rack, shelf, circuit-pack and component level heat loads, allowing the much higher equipment densities required by burgeoning ICT facility needs.

iii) <u>enhanced reliability</u>: ARCTIC's ability to retro-fit live equipment without service interruption is particularly important to our nation's large installed ICT customer base, providing a means of mitigating reliability and performance concerns during the installation, training and validation phases of product integration. Moreover, the refrigerant used in our approach, R134a, is a widely-used, non-toxic dielectric liquid which, unlike water, is non-conducting and non-corrosive and will not damage electronics in the case of a leak—a triple-play win over alternative water-based liquid coolant technologies. Finally, through use of a pumped refrigerant, pressures are modest (~60 psi), and toxic lubricants and oils are not required, in contrast to compressorized refrigerant systems—another environmental win.

Meeting the proposal objectives and achieving full market penetration will allow an estimated reduction in U.S. greenhouse gas emissions of 1.46 MMTCE/year and will reduce data center and ICT facility energy costs by 9.6 billion kWh/year. Higher equipment densities will result in real estate utilization improvements valued at $1.6 billion annually.

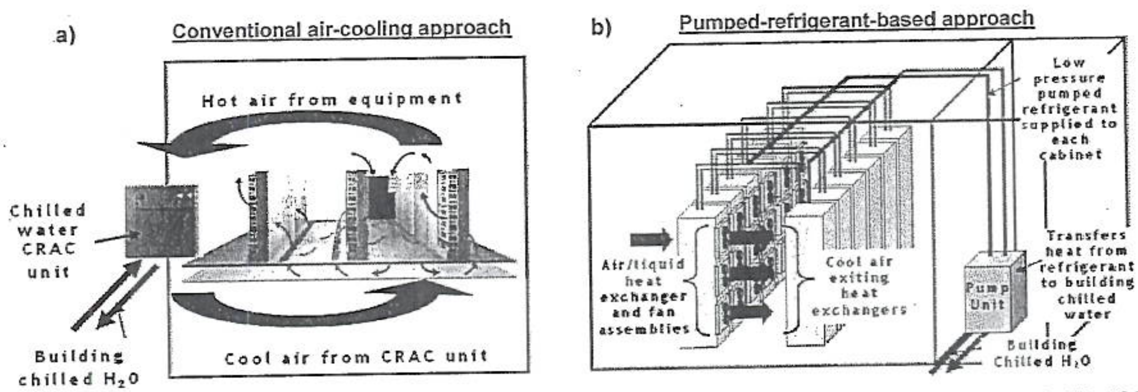

Figure 1: a) Conventional ICT facility cooled by a chilled-water CRAC unit; and b) Shelf-level implementation of the ALU modular liquid cooling system. Note that in contrast to Figure 1a, cool air is exhausted into the aisle, eliminating hot spots and the mixing of hot and cold air.

Criterion 1: Technical Merit

Criterion 1A: Technical Approach and Comparison with Current Technologies

At present, ICT facilities are typically cooled by computer-room air-conditioning (CRAC) units, which provide cold air that is drawn into racks of heat-dissipating equipment by rack- and component-level fans, and with the heated exhaust air recirculated back to the CRAC units via room-level blowers and air movers (see **Figure** 1a). This approach has several drawbacks: i) the transport and cooling of large quantities of air is energy inefficient; ii) mixing of hot- and cold-air streams results in localized hot spots and regions of poor cooling and often necessitates additional sub-cooling of air to overcompensate for inefficiencies; and iii) the heat-carrying capacity of air is limited, so that increasing levels of heat dissipation are stretching air-cooling technologies to their limits, with acoustic noise restrictions and fan reliability concerns often responsible for placing practical limits on the achievable level of air cooling.

The ARCTIC Program

The technology innovation underpinning ARCTIC is the use of a pumped refrigerant to remove heat at the rack, shelf and component levels. The use of a pumped refrigerant has a number of advantages over traditional air- and liquid-based cooling. First, the heat-carrying capacity relative to pumping power is substantially greater for the refrigerant than air due to the refrigerant's large heat of vaporization. This results in projected energy savings in excess of 90% for the pumped refrigerant-based technology relative to conventional CRAC-based air cooling. Second, the pumped refrigerant allows significant increases in device densities at the shelf, circuit-pack and component levels not readily achievable via air-based approaches. Third, the R134a refrigerant is a dielectric liquid which, unlike water, will not damage electronics in the case of a leak. R134a is also non-toxic, and, since the system is based on a pumped refrigerant, it does not require toxic lubricants and oils required by refrigerant systems. Fourth, system pressures are relatively modest (~60 psi) in comparison to a compressorized refrigerant system. Finally, the technology developments in ARCTIC address important issues of reliability and cost that are critical for market acceptance.

In the following, we present details of a range of the pumped-refrigerant-based technologies that will revolutionize cooling at the rack, shelf and component levels, and we describe the next research and development activities that will enable large-scale deployment.

The ALU modular liquid cooling system

A schematic of the ALU modular liquid cooling system is shown in **Figure 1**b. Liquid refrigerant R134a is pumped to finned microchannel heat exchangers placed at the air exhaust in shelves of individual equipment racks. The heat exchangers are similar in form to automobile radiators and consist of alternating stacks of flat, microchannel tubes which carry refrigerant, and strips of fins though which the air passes and is cooled. Fan trays push air through the equipment shelf, where it gains heat dissipated by the electronic components therein. Prior to exiting the rack, the heated air passes through the heat exchangers, where it is cooled back down to the temperature level of the air entering the frame. The vaporized refrigerant is then returned to a condenser where it is liquefied and recirculated by the pump. All the cooling air enters and leaves the shelves/racks at nominally the same temperature.

The ALU modular liquid cooling system has a number of advantages over air-based approaches. First, in a typical system, cool air enters the rack, is heated by the electronic components, and exits at a higher temperature. This is disadvantageous as complex air flows within ICT facilities often result in mixing of hot and cold air streams. Common solutions to this problem are to underutilize equipment racks to eliminate localized hot spots, or overcool the equipment to provide additional margin. Second, in one common rack configuration using air cooling (see **Figure 2**), cool air (blue arrow in **Figure 2**a) enters the base of a rack and is heated as it progresses upwards through each shelf, exiting the rack at a significantly higher temperature (red arrow in **Figure 2**a). Thus, shelves placed higher in the rack receive hotter air than lower shelves. This can result in sub-optimal thermal performance, increased cost, and restricted flexibility in equipment layout. The ALU modular liquid cooling system (see **Figure 2**b) cools the heated air using heat exchangers placed between shelves, thereby ensuring that all shelves receive cool input air.

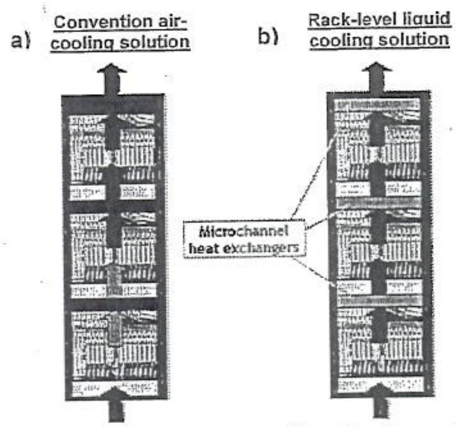

Figure 2: a) Conventional air-cooling solution with no heat exchangers; b) Modular liquid cooling system with heat exchangers placed horizontally between shelves. Arrows show direction of air flow, and arrow colors correspond to cool (blue) and hot (red) air.

The ALU modular liquid cooling system has been implemented and tested at the level of a single shelf, in a 10-rack model data center, and in a lab for evaluating the performance of Internet-Protocol Television (IPTV) equipment with live traffic. The functioning and reliability of the system have been tested and verified. This development program has now reached the point that cost-reduction, efficiency optimization, marketing and wide deployment are the next appropriate steps.

These are the goals of the proposed ARCTIC program of research and development. Our program will focus on the following 5 areas:

<u>1. Enhanced microchannel heat exchanger performance for rack-level liquid cooling.</u> The focus of this work is to further enhance the performance of the ALU modular liquid cooling system by optimizing the microchannel-based air-to-refrigerant heat exchangers. In the present implementation, each shelf is provisioned with an EX 4 microchannel-based heat exchanger and a pair of fans to enhance the airflow provided by the on-board fans in the circuit packs. The current heat exchanger is designed to accommodate EX 4 a heat load characteristic of a range of ICT equipment. A major goal of the proposed program is to optimize the heat-exchanger design to accommodate a much higher cooling capacity, e.g., EX 4 per shelf, with a minimal increase in fan power. A concurrent goal is to minimize the flow resistance of the heat exchangers EX 4 This will enable significant improvements in cost, energy use, and reliability.

The design of the air-side fins determines the efficiency of heat transfer from the hot air into the refrigerant flowing through the microchannel tube. Detailed modeling and experimental studies will be conducted to determine the most efficient fin design. Similarly, optimization of the microchannel tube

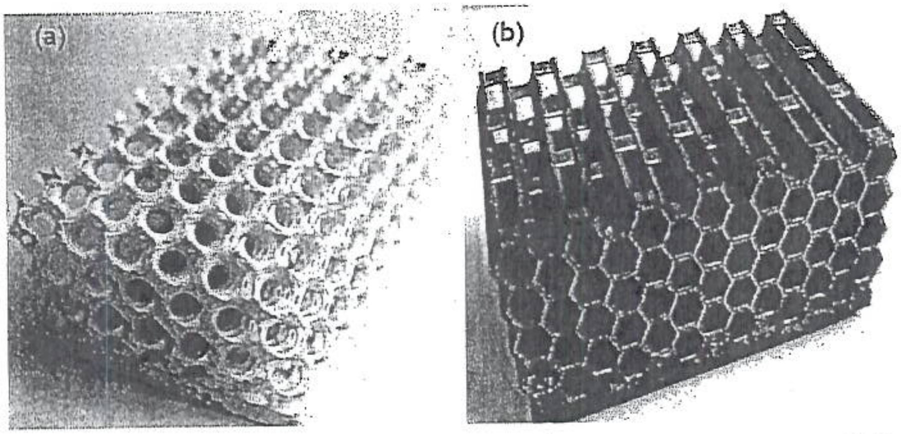

Figure 3 : a) Monolithic foam 3D heat sink cast from silver. (b) Monolithic slotted honeycomb 3D heat sink cast from copper.

geometry will seek to maximize the heat transfer without an excessive liquid-side pressure drop. Optimization of the heat exchangers will be carried out in collaboration with Modine Manufacturing.

2. 3D heat sinks (3DHS) for enhanced component-level air cooling. Power dissipation densities inside telecom circuit packs have increased so much that air cooling is becoming insufficient to keep device temperatures below their maximum allowed values. The essential idea of the 3DHS is to fill the volume normally occupied by the fins of a standard finned heat sink with a porous metal lattice or "foam". This improves the heat-transfer characteristics of the heat sink by modifying the airflow through its volume, by improving conductive heat transfer within the volume, and by considerably increasing the surface area available for heat transfer. Our work expands on that of previous investigators in that, instead of using commercially-available random metal foams, we use regular, lattice-like structures produced by novel fabrication methods. **Figure 3** shows examples of two such structures, which consist of periodic "foams" that replace the fins of a finned heat sink. A key advantage of our technology is that we can reproducibly fabricate optimized 3DHS structures, whereas commercially-available metal foams are stochastic and cannot be optimized or reproduced in detail.

In our preliminary work, three different 3DHS concepts were tested in a wind tunnel facility in fully ducted flow by measuring the thermal resistances against pressure drop, pumping power and velocity. These structures provided up to EX 4 heat-transfer rates than an optimized standard finned heat sink of the same volume. These results constitute a strong basis for the feasibility of enhanced 3DHS designs to make a strong impact in ICT cooling.

Design optimization of standard heat sinks is a well-developed branch of engineering. A comparable basis for the design of 3DHS structures does not yet exist and is sorely needed, since such 3D structures are currently not commercially available. A major goal of the proposed research is to use analytical and numerical methods to investigate and optimize new 3DHS designs. A second major goal is to investigate low-cost manufacturing techniques, possibly based on EX 4

3. EX 4 For higher-power devices in ICT circuit packs, the degree of improvement in air cooling enabled by 3DHS structures is anticipated to be insufficient to allow the ALU modular liquid cooling system to function without external fans.

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4. The ıpproach will not have a low enough thermal resistance to accommodate the highest-density devices in circuit packs. In this case, We propose to investigate the use of ı We will begin bv assessing Next, we will focus on

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5. Cost reduction & manufacturing, system performance and commercialization. Our prototype modular cooling system has revealed several opportunities for dramatic cost reductions. Several of these are straightforward, and others will be enabled as the performance of the system evolves. Additionally, understanding the role of system layout on overall cooling performance, as well as the development of viable commercialization strategies, are critically important. Particular subjects to be investigated include:

Fans and fan control. In our prototype system, fans represent an important component of both cost and energy use. We are working with fan vendors to improve fan efficiency and power management.

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Component-level cooling. A major common goal of the development of the 3-dimensional heat sinks,

Heat-exchanger efficiency.

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As with the work on component-level cooling, will lead to large cost reductions to the extent that this allows

Low-cost manufacturing techniques. Our present designs for 3D heat sinks are manufactured using expensive prototyping methods. methods will dramatically reduce their cost.

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Criterion 1B: Statement of Project Objectives

The objectives of this research program and their expected outcomes are as follows:

Objective #1: Optimize heat exchanger performance to minimize required pumping-station and fan power. We will attack this objective by

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Objective #2: Enhance component-level air cooling using novel three-dimensional heat sinks. A major goal of the proposed research is to use analytical and numerical methods to investigate and optimize new 3DHS designs. The anticipated result will be a computational toolkit for 3DHS design and a number of application-specific prototypes. A second goal is to fabricate and test the resulting optimized prototype 3DHS designs. We already possess the equipment and procedures required for these tests. We expect to be able to design, fabricate, and verify that at least one 3DHS design can achieve a thermal resistance at least EX4 lower than an optimized finned heat sink of the same volume.

Objective #3: Accommodate higher heat densities and reduce required fan powers

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Objective #4:

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Objective #5:

We anticipate that these and other, unanticipated issues will be straightforward to remediate.

Objective #6: Cost reduction. We will reduce costs through an integrated program of supply-chain optimization and technical advances, including:

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(4) We expect that

will make 3D heat sinks a cost-effective thermal solution for component-level cooling.

Objective #7: Develop a successful next-gen product offering for the modular liquid cooling system emphasizing retro-fits of ICT facilities, and incorporate the multiple and synergistic enhancements of component, shelf- and system-level cooling being developed as part of this program into a viable commercialization strategy to accelerate their introduction into next generation products and service offerings.

Criterion 1C: Feasibility of the proposed work and its technical innovation

We have implemented a prototype of the ALU modular liquid cooling system in a test data center (see **Figure 5**) housing 10 racks, each equipped with 10 kW of IT equipment, for a total power of 100 kW. The racks are arranged in a standard hot-aisle/cold-aisle configuration with standard cabinet spacing. Modine heat exchangers are installed on the hot-air exhaust side of each shelf of individual racks, with a fan tray placed on the heat exchanger exterior to pull hot air through (see **Figure 5a, b**).

EX 4 feeds refrigerant to overhead copper plenum piping, while vapor and liquid are returned to the chilled-water condenser by copper return plenum piping. Flexible hoses connect the heat exchangers to the supply and return lines. The lab is completely isolated from the building HVAC system, so that all generated heat is removed exclusively by the ALU modular liquid cooling system.

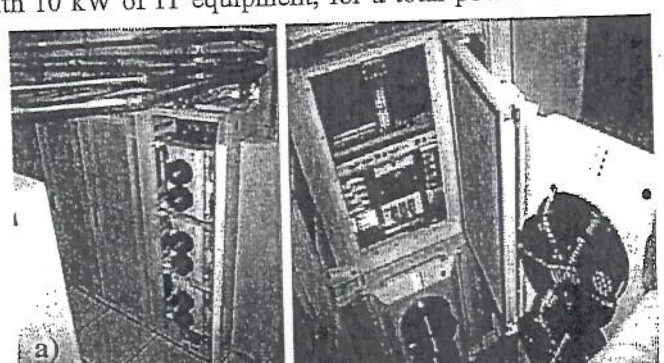

Figure 5: Photographs of 10-rack modular cooling system showing: a) overhead refrigerant piping and equipment racks outfitted with shelf-level heat exchanger / fan assemblies; and b) retractability of heat exchanger / fan assembly for equipment access.

The performance of the prototype clearly demonstrates the feasibility of this approach. The power required to operate the system at full capacity consists of the pump (800 W) and shelf-level fans (1500 W = 2 fans per shelf x 30 shelves x 25 W/fan) for a total of 2.3 kW. For comparison, a comparably-sized chilled-water CRAC unit would require 16.0 kW. This results in coefficients of performance (COP), defined as COP = (cooling capacity / power for cooling), of **43.5** for the liquid cooling prototype and **6.3** for the chilled-water CRAC system

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The various innovations we propose to implement at the system, shelf, and component levels, as well as the REDACTED EXEMPTION 4 synergistic enhancements in cooling performance, scale-ability and cost reduction as per the Objectives outlined in section 1B above.

Criterion 1D: Evidence of "game changing" quality of the proposed technology

The ALU modular liquid cooling system will revolutionize ICT cooling in the following ways:

- The system provides a dramatic jump in overall cooling efficiency and corresponding reductions in energy use and greenhouse-gas emission.
- The system allows an enormous increase of power density at the rack and shelf levels. Because of this, full market penetration will eliminate the need for construction of new ICT real estate for an extended period which we estimate to be on the order of 20 years.
- Installation can be performed "hot" while the ICT facility continues to run live traffic, dramatically enhancing customer confidence and mitigating reliability and up-time concerns during installation, training, implementation and validation of the new cooling technology.
- The increase in equipment density allowed by this system will completely change the nature of data-center design and management. Because all the ambient air in a data center cooled using our technology is at nominally the same temperature, and because high power densities at the rack level can be dealt with, thermal issues will no longer pose constraints on equipment layout.
- The component-level solutions we propose have the potential to deal with much higher device power levels. This will allow equipment designers to break through the barriers that are presently caused by limits on thermal management at the component level.

Criterion 2: Potential Benefits

Criterion 2A: Potential Job Creation Opportunities

ARCTIC will establish a new family of ICT cooling products and services. This will stimulate job creation and direct economic recovery in both the short (12 to 18 months) and long terms. Section 6, "American Recovery and Reinvestment Act (ARRA) Information", has a detailed description.

Criterion 2B: Economic Benefits and Capital Cost Advantages

To illustrate the operating-expense and capital-cost advantages of ARCTIC, we consider the retro-fit of a data center with the ALU modular liquid cooling system. The data center that we consider is a scaled-up version of the prototype system shown in **Figure 5**; details of the configurations and energy usage for the cases of chilled-water CRAC units and the modular liquid cooling system are presented in **Figure 6.** Note that the approach using chilled-water CRAC units requires 3,640,000 kWh of energy annually, whereas the modular liquid cooling system requires only 267,000 kWh, **a 93% reduction** in energy usage. At a cost of $0.10 per kWh, this represents an annual operating-expense reduction of $337k.

Ex 4 To retrofit an air-cooled system using compressor CRAC units, which consume 30 kW instead of the 13 kW required for chilled-water units, Ex 4.

A significant benefit of the ALU modular liquid cooling system is improved real-estate utilization.

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Chilled water CRAC units

- 500 server cabinets at 3 kW per cabinet
- 22,000 square foot service area
- CRAC units cool 47 kW; consume 13 kW
- 32.1 chilled water CRAC units required to cool total equipment load (Supported by actual conditions: 32 of 40 units are running in practice)
- **Energy required: 32 x 13 kW x 8760 hours = 3,640,000 kWh**

Rack-level liquid cooling

- 150 server cabinets at 10 kW per cabinet
  - **Space freed up for 350 cabinets**
- 3 heat exchangers + 6 fans total per cabinet (2 fans per heat exchanger)
- Pump unit uses 800 W
- Each fan uses 25 W (150 W per cabinet)
- Cooling power: 30.5 kW = (10 pumps x 0.8 kW/pump + 150 cabinets x 0.150 kW / cabinet)
- **Energy required: 30.5 kW x 8760 hours = 267,000 kWh**

Figure 6: Comparison of cooling power requirements for a 1.5 MW data center cooled by chilled water CRAC units (left) and ALU modular liquid cooling system (right).

will have a profound effect on the long-term financial and energy costs of ICT cooling as well as on one-time retrofit expense.

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Criterion 2C: Estimated energy savings across U.S. ICT facilities

The estimates in this section are based on the DOE presentation entitled "Routing Telecom and Data Centers Toward Energy Efficient Use" dated May 13, 2009[2], namely:

- Total US energy expenditure for ICT facilities of 120 billion kWh in 2006, with 25% for cooling:
  - total annual US energy expenditure of 60 billion kWh for data centers
  - total annual US energy usage of 20 billion kWh for large communications centers and network trunk lines
  - local equipment, private exchanges and mobile phone towers of 40 billion kWh

Based on these estimates, the total annual U.S. ICT expenditure for cooling in 2006 was

25% * 120.0 billion kWh = 30.0 billion kWh.

We estimate that 25% of this cooling expenditure is used for running CRAC units in existing ICT facilities.

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Environmental Metric (Note: MT ≡ Metric tones)	Emissions per billion kWh (from ICT_Benefits_Spreadsheets.xls)	Annual Emission Reductions for modular liquid cooling
CO displaced (MT)	164.4	1580
CO2 displaced (MM TCE)	0.154	1.48
SO2 displaced (MT)	2070	19870
NOx displaced (MT)	1359	13050
Particulates displaced (MT)	44.1	423
VOCs displaced (MT)	17.7	170

Table 1 Estimated annual U.S. emission reductions (column 3) for modular liquid cooling based on 9.6 billion kWh savings. Column 2 data scaling emissions with energy usage are from [1].

Savings in the energy costs of real-estate expansion are a significant additional component of energy-use reduction enabled by our technology. Estimates for energy savings due to better use of space follow similar reasoning to that discussed in Section 2B for building cost savings.

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where the value of 332 kWh/sq ft is taken from [3]. This is added to the present U.S. ICT cooling energy usage of 30.0 billion kWh to yield a total present yearly energy cost of 32.7 billion kWh. Thus, we estimate that the total yearly energy savings in the United States will ultimately amount to

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Criterion 2D: Estimated reductions in greenhouse gas emissions and other environmental emissions

In **Table 1**, estimates for reductions in U.S. greenhouse gas and other environmental emissions are provided based on an annual energy reduction of 9.6 billion kWh. Data for the emissions per billion kWh (middle column of **Table 1**) were obtained by using values for each metric as provided in the Results sheet in the ICT_Benefits_Spreadsheets.xls spreadsheet provided by the DOE for the proposal[2].

Criterion 3: Commercialization and Market Acceptance

Criteria 3A and 3B: Commercialization strategy and technology viability

The proposed ARCTIC commercialization strategy addresses two main markets: retrofits and new installations. The retrofit market appears particularly viable, as the cooling system is not vendor dependent, and there is a large installed equipment base, with estimates of ~10 million servers in 10,000 data centers in North America. New installations include sales into new ICT facilities, as well as design and integration of shelf- and component-level cooling technology into next-generation equipment that will be particularly challenging to cool. For example, ALU is currently considering this system for cooling a version of REDACTED EXEMPTION 4

According to the recent Uptime Institute *Data Center Capacity and Energy Efficiency Survey*[4], 41.7 percent of data center operators said that their data center would run out of power capacity in 12-24 months. This illustrates the pressing need for the energy-efficient modular liquid cooling technology and speaks to its economic viability. Furthermore, ALU envisions that the modular liquid cooling system will readily meet any potential regulatory and environmental requirements. ALU has extensive experience in ICT equipment testing and expects the modular liquid cooling system to achieve NEBS, UL, CL and CSA compliance. For example, this system recently passed NEBS Zone 4 Earthquake tests, typically not required for data center environments. Finally, we note the ALU modular liquid cooling system offers substantial advantages in meeting energy reduction requirements that may be mandated in the future.

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ALU Services / Sales and Marketing organization is responsible for sales and marketing and bringing the technology to the end user via a service product offering focused around retro-fits and consolidations of existing data centers. ALU Services / Sales and Marketing's role includes: i) feasibility/market research; ii) cost analysis; iii) vendor/supplier qualification; iv) customer business-case development; v) establishment of price, total addressable market (TAM) and market share; vi) development of sales/marketing plan (enabled by sales guides, sales training, brochures, trade shows and conferences); vii) development of ALU Services Business Case (inputs include cost, R&D effort, sales and marketing effort, capital expenses, price, volume, margin targets); viii) management review with go/no-go decision based on direct margin, contribution margin, payback period, market share and projected revenue; and ix) productization scheduling and execution.

Modine and **U.S. Hose** are key suppliers in the commercialization strategy and are responsible for performance and cost improvements for major components of the modular liquid cooling system. These efforts are critical, as cost and performance will be two key factors affecting the marketability of the technology.

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U.S. Hose's development of new materials and manufacturing processes for low-cost, high-reliability connectors and hoses will further reduce the overall system cost.

ALU Network Systems and Integration Test (ALU NSIT) Lab will be an end-user providing feedback on the system-level feasibility of different technologies.

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ALU Bell Labs will focus on research and development of component-level cooling technologies (3D heat sinks, EX 4 for addressing continued increases in device heat densities. These efforts are critical as the modular liquid cooling system still relies on air to transfer heat from within the shelf to the microchannel heat exchanger, and restrictions on fan power, noise and reliability will become limiting at higher heat densities. Modeling, prototyping and testing will provide valuable information on the ability of these technologies to meet market needs, as well as to define requirements for commercialization and manufacturing.

Consolidated Edison (Con Ed) will provide insights from the perspective of a commercial end-user, in this case an electrical power provider's insights into the needs and requirements of its data center customers. Con Ed has a mandate to assist its customers in seeking out and implementing technologies that enable energy efficiencies and power use reduction.

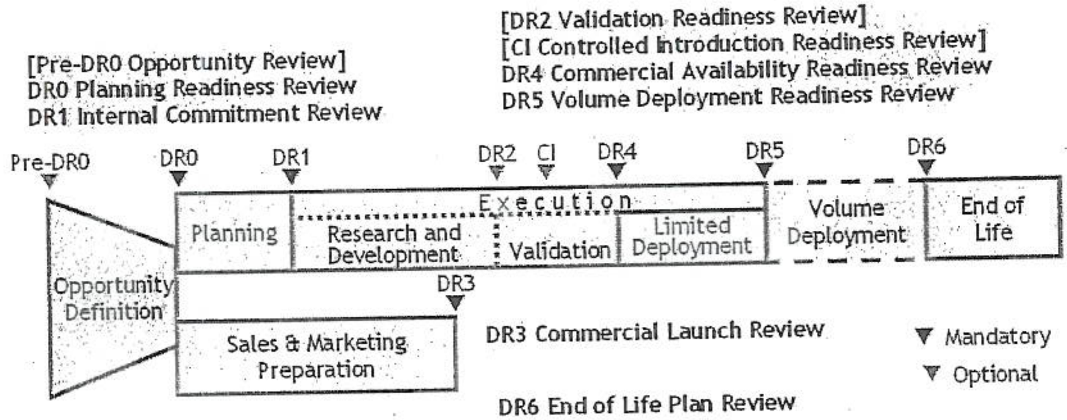

Figure 7: Alcatel-Lucent product life-cycle review process.

Stage Gate Criteria

The key Stage Gate criteria, as defined by DOE's Industrial Technologies Program[5], that are to be used for planning tasks, monitoring progress, and identifying critical milestones in ARCTIC are the following: Stage 3 (Concept Development); Gate 3 (Proof of Technical Feasibility); Stage 4 (Technology Development and Verification); Gate 4 (Proof of Commercial Feasibility); and Stage 5 (Information Dissemination and Commercialization). The important tasks and associated go/no-go decisions based on these criteria are discussed in the Project Management plan.

Design Review (DR) Gate Process

An overall Design Review (DR) gate process will be used to incubate the design concepts, define the opportunity, develop and deploy the product. The DR gates are shown in **Figure 7**. The Stage Gate criteria become part of the process between DR1 (internal commitment) and DR4 (limited deployment).

Criterion 3C: Corporate Commitment

ALU has a deep corporate commitment to environmental sustainability - and most notably investing in the research and development to conceive of and commercialize high-impact concepts throughout the product/solution lifecycle. This is driven from both a corporate social responsibility (CSR) perspective to minimize our impact on the environment and recognition that being environmentally conscious (most notably energy efficient) is the right business decision. It is essential to demonstrate leadership and innovation in our competitive environment. Our commitment is evidenced by our past accomplishments in this area, which span across our portfolio from device level to network element level to rethinking how networks operate from an energy efficiency perspective. Examples include: innovative cooling methods, energy-efficient base stations, dynamic powering (and low-power states) of network elements based on traffic/load, topological optimization of networks, and powering equipment with renewable energy sources. Our commitment to commercialize these developments and energy-efficiency advances yet to be developed are also demonstrated in our 2009 CSR goals (e.g. Improve the functional energy efficiency of key products by at least 20% by 2010 compared with 2008) and our corporate wide program "Transforming Communications for a Sustainable World". More information about Alcatel-Lucent leadership in eco-sustainable networking can be found on our corporate website at the following URL: http://www.alcatel-lucent.com/csr/htm/en/caringForEnvironment.html.

As is evidenced by the above, the energy-savings benefits of ARCTIC align extremely well with Alcatel-Lucent's CSR initiatives and business activities around eco-sustainable products and solutions. In particular, because of the tremendous potential for reducing energy use associated with cooling, the ALU

Services Business Division is committed to offering the modular liquid-cooling solution as a future service product for retro-fits and consolidations of data centers.

Criterion 4: Technical Approach / Project Management Plan

Criterion 4A: Viability, Completeness and Likelihood of Success

Our technical approach benefits from a broad-based ALU commitment to modular cooling technology as a product platform that makes business and environmental sense. In this exciting commercialization initiative, we are making the final intensive strides towards general availability (G.A.) of our first modular liquid cooling product offering. Consistent with this goal,

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Our proposed Category II research program builds directly on the planned commercial platform but with an augmented approach comprising multiple and synergistic enhancements of component, shelf and system level concepts for next-generation product optimization, consistent with the time frame and scope of the DOE FOA. As highlighted throughout this narrative, our focus is not only on optimizing cooling at each of these levels, but also on cost-reduction through substantial follow-on elimination of expensive air-cooling hardware and power requirements of the overall system as well as flexibility in component, shelf, and system level layout.

Our Bell Labs team members offer expertise in research and development, including design, simulation, prototyping, and testing of thermal management concepts ranging from the exploratory to the pragmatic.

Our manufacturing partners bring specific and varied expertise to the team in the areas of thermal management and fluidics, enabling key supply-chain enhancements.

Our sales and marketing team has already been actively engaged with emerging customers for the G.A. product roll-out. Simultaneously they have been calibrating the marketplace for attractive enhancements for the next-generation product, many of which are included in this proposal. As the proposed research unfolds, their expertise and insight into customer observations and emerging requirements will inform and hone alignment of our program initiatives with next-gen product placement.

Our two-stage end-user team structure will similarly enhance the alignment of our research activities. The two types of end user are: 1) the in-house ALU NSIT lab for testing and validation of new technical concepts, and 2) external observation, consultation, critique, and validation by Con Ed in light of its ongoing work to enable energy efficiencies among a large and diverse population of ICT customers.

By emphasizing customer-inspired enhancements gleaned through sales and marketing of the initial G.A. product, and establishing aggressive but realizable goals predicated on both fundamentals-based research and manufacturing refinements to craft the optimized next-generation modular cooling platform, our proposed research program ensures both time-wise and feature-wise alignment with the commercial and environmental needs of the marketplace and the nation.

Criterion 4B: Project Management Plan (see attachment "pmp.pdf")

Criterion 4C: Work and Budget Distribution

The objectives of ARCTIC will advance the ALU prototype modular cooling system and address further energy efficiencies by attacking thermal issues at the system, shelf and device levels. The team will make conceptual and manufacturing advances, while continuously interacting with the test facility and customers, to create solutions that are technically superior and market-ready. Team members are uniquely placed to satisfy the ARCTIC objectives by skills, resources, and budget.

Objective #1: Optimized heat exchanger for shelf-level cooling. EX4 to optimize heat transfer without increased air-flow resistance in collaboration with Bell Labs. EX4

Objective #2: Three-dimensional heat sinks (3DHS). Bell Labs will extend its current work modeling 3DHS with three rounds of design and wind-tunnel tests. Concurrently, Bell Labs will find cost-effective manufacturing techniques for the 3DHS. Cost:

Objective #3:

REDACTED
EXEMPTION 4

Objective #4:

Objective #5:

REDACTED
EXEMPTION 4

Objective #6: New designs, materials and manufacturing process. EX 4 and US Hose will develop appropriate connector fittings and hoses.

Objective #7. Sales and marketing plan. ALU Services/Sales and Marketing will develop business cases and sales plans, in consultation with the test and research team members. EX 4

While the above objectives have been broken out separately, continuous feedback and interactions between partners and tasks ensures that technical advances respond in optimum directions to test lab results and commercialization imperatives. More details are found in the project management plan.

Criterion 5: Qualifications and Resources

Criterion 5A: Capability and Experience

Alcatel-Lucent Bell Laboratories ALU is the world's pre-eminent communications solutions company. Bell Laboratories plays a number of different, yet equally important roles for ALU including: serving as part of Alcatel-Lucent's innovation foundation; contributing expertise to current and future products and services; impacting national technical priorities; and exerting global influence on science and technology. Bell Labs' innovations cover physical, computer, software and mathematical sciences; wireless and wireline networking; and network security, standards, and planning. Bell Labs researchers have received six Nobel Prizes in Physics, nine U.S. National Medals of Science and seven U.S. National Medals of Technology®. Our scientists and engineers have played a pivotal role in inventing or perfecting most of the key communications technologies in use today. With more than 25,000 patents, Bell Labs' research centers have experience in all aspects of network design and support and play a central role in responding to requests for information and requests for proposals (RFI/RFP's) from the world's largest service providers. Bell Labs is recognized as a global leader in devising, testing, developing and deploying state-of-the-art hardware and software systems for carrier-class communication networks. This requires expertise ranging from physical technology for high-capacity networks to scientific computing for simulating system performance to combinatorial optimization for high-level design.

Modine Manufacturing Co. Modine specializes in thermal management, bringing heating and cooling technology to diversified markets. Modine's products are used in light-, medium-, and heavy-duty vehicles, HVAC equipment, industrial equipment, refrigeration systems, fuel cells and electronics. In FY 2008, Modine's sales reached $1.8 billion dollars. Modine is known throughout the automotive and non-automotive sectors as an innovative company with more than 1,000 patents awarded worldwide since its founding in 1916. Key technologies invented by Modine that are now used worldwide in heat exchanger design include the serpentine louvered fin and the microchannel heat exchanger, both helping the US to become more energy efficient and globally competitive.

US Hose Corp. US Hose has over 100 years of experience in the manufacture of corrugated metal, fluoropolymer, and composite hose and hose assemblies for a wide array of markets. US Hose has approximately 100.000 sq. ft. of fabrication, warehouse, and office space. [redacted] EX 4 [redacted] Hose has three product lines: corrugated metal hose, PTFE hose, and composite hose in diameters ranging for 1/8" to 12" and beyond.

ALU Services / Services Business Division With more than 18,000 network experts supporting the top 30 service providers in over 130 countries, ALU Services is the industry's most experienced and knowledgeable services partner, providing a broad and comprehensive set of services that encompass the entire network lifecycle, including consultation & design, integration & deployment, and maintenance & operation. ALU Services designs, builds, implements and manages facilities to help meet the demands of business and residential customers, saving costs and reducing time to revenue.

ALU NSIT Lab The ALU Network Systems and Integration Test (NSIT) lab supports the testing of the ALU Internet Protocol Television (IPTV) solution, as well as new network and IPTV hardware and software releases for all current and future ALU customers. The lab maintains a test environment which features [redacted] EX 4 [redacted]. This area and its configuration of server cabinets closely emulate, and in several cases exceed, the cabinet capacity of deployed IPTV server solutions for [redacted] EX 4 nd other ALU customers in the U.S. and Canada.

Consolidated Edison The Con Ed team will serve as a consulting end-user with unique insights and perspective into the challenges and needs of data centers, stemming from their mandate as an electrical power provider, to enable their customers to achieve energy efficiencies and power usage reduction. They will be active consultants in the design aspects of our research program and installation and characterization aspects of the ALU NSIT laboratory, as well as provide customer introductions.

Criterion 5B: Organizational Experience

Bell Laboratories has a history of successfully innovating, managing, and completing large internal and external research projects, for commercial and government end-use. The outcomes of these programs are evident in commercial telecom practice. Several examples are given below.

Bell Labs (then under Lucent Technologies) was the co-leader of the DARPA-sponsored *Multi-wavelength Optical NETworking* (MONET) program (1995-1999), which involved a consortium including Lucent Technologies, Telcordia Technologies, AT&T, Bell Atlantic, Bell South, SBC, and Pacific Telesis. MONET was an ambitious program to develop transparent and scalable optical networking to include inter-operating long-haul, regional, and local optical telecom networks. The program addressed market analysis, network architecture, control and management component and network-element research and development, laboratory verification and analysis, and end-user validation with a field trial in the Washington, DC area. The key results of MONET led to understanding of architectures, systems, and components for dense wavelength-division multiplexed (DWDM) systems, including optical amplification and related transients, optical switching fabrics, nonlinear interactions between wavelength channels, and control algorithms. The MONET team included over 100 researchers, funding of ~$50M, and a 5-year duration. The Bell Labs leadership team was successful in managing and coordinating the project to significant outcome. The results and understanding from MONET underlie numerous commercial DWDM systems and products.

Name	Training	YPE	Expertise	Role	Availability
[PI] Todd Salamon	PhD, Chem. Engineering	19	Fluid mechanics, thermal management, numerical simulations	REDACTED EXEMPTION 4	
Paul Kolodner	PhD, Physics	34	Fluid mechanics, thermal management		
William Scofield	MS, Aerospace Engineering	15	Thermal/environmental design and implementation		
Peter Hayden	MS, Industrial Engineering	24	Marketing, product management and deployment		
Tony Hanstedt	BS, Industrial Engineering	5	New product development and process flow improvement		
Mark Johnson	MS, Mech. Engineering	17	Heat exchanger design and testing		
Doug Krimmer	BS, Mech. Engineering	17	Metal fabrication and assembly		
Brad Engel	BS, Applied Technology,	16	Metal joining, manufacturing process development		
Mickey Himel	BS, Applied Mathematics	30	Central office management; prototype deployment coordination		
Susanne Arney	PhD, Elec. Engineering	28	Research/project management		
Arthur Kressner	MS, Chem. Engineering	41	Central office management		
Joseph Carbonara	BS, Physics	32	Advanced technology prototype deployment		

Table 2: Key personnel information.

Currently, Bell Labs is leading the DARPA-sponsored program *Integrated Router Interconnected Spectrally* (IRIS), under the Data in the Optical Domain-Networks solicitation. IRIS's accomplishment is the development of a 100-Terabit/s optical router node that processes optical data packets without optical-to-electrical-to-optical conversion. Achievements include developing a load-balanced architecture for optical packet processing, highly integrated photonic circuits, regenerative switches and optical buffers, and integrated optical packet header processing structures. The team, with tens of researchers and which includes three universities, brings together expertise in photonic device design and fabrication, optical networking, data networking, and electronics. The resulting optical data router significantly reduces electrical power consumption in the routers and nodes by greatly reducing electronic processing. This very much aligns with the goals of the present DOE FOA to reduce network energy consumption. Bell Labs has the capabilities and interdisciplinary expertise to produce the innovative accomplishments for IRIS, which is now in its final phase.

As an example of tight collaboration between Lucent Technologies' Bell Labs and its Optical Networking business unit, the LambdaRouter™ All-Optical Switch was a highly acclaimed world-leading product based on micro electro mechanical systems (MEMS) developed to accommodate rapid Internet growth in the late 1990s. Researchers at Bell Laboratories worked with networking development teams to make a carrier-grade MEMS-based optical switch, with the entire development cycle taking only 18 months. Many breakthroughs at the component, sub-system, shelf and rack-level were needed in order to succeed: dielectric engineering, charge mitigation strategies, and spring and actuator optimization for stable open-loop operation not requiring active feedback; 10,000x speedup of array test and "training" through new adaptive optimization algorithms; thermally-stable, low-stress reflector metallization for fast-response reflectors; and 5,000-pin, hermetic optical chip packaging, to name a few. No other organization has shown an equivalent breadth of design expertise or successful product completion with optical MEMS. The LambdaRouter was commercialized and sales were completed with industry customers and the United States Government. A record switch capacity was achieved—2 petabit/s traffic switching capacity in a 1296-port optical cross-connect, 100 times greater than any other switch fabric. The critical skills needed to bring research concepts to the marketplace remain core competencies of the Bell Labs team presenting this ARCTIC proposal.

More recently, the internal research team at Bell Laboratories is successfully advancing the technological frontier for optical networks and, with business-unit partners, driving its commercial adoption. The current commercialization frontier is for 100 Gigabit/s Ethernet optical transport. The research and business teams are working to commercialize the technology, which has been validated by a field trial with the end-user Verizon in November, 2007.

Criteria 5C and 5D: Key Personnel and Adequacy of Facilities and Equipment

Table 2presents information for key program personnel. The facilities for the various team members are:

Bell Labs. Our Murray Hill, NJ laboratory is equipped with a 30-node Linux cluster consisting of 2- and 4-processor CPUs for intensive computing. We have licenses for a number of commercial software packages for CAD/CAE, including Fluent, CFX, ANSYS and Icepak. We possess a laboratory equipped for making thermal measurements and a large, well-equipped machine shop for prototype production. At our Blanchardstown, Ireland laboratory, we have access to heated and unheated wind tunnels for characterizing 3D heat sinks, 3D printers and an established fabrication process for making prototype 3D heat sinks, as well as a state-of-the-art apparatus for characterizing thermal interface materials.

Modine Manufacturing Co. Our thermal testing laboratory has extensive capabilities for evaluating the microchannel heat exchangers: single-phase calorimetry (up to 300kW of cooling), two-phase refrigeration calorimetry (up to 12kW of cooling) and isothermal pressure drop testing (flow rates up to 3240 m^3/hr). Our structural laboratory provides full mechanical test capabilities: multi-, single- and high-frequency vibration testing, drop testing, burst testing (up to 55,200 kPa), and pressure (7-17,240 kPa) and thermal cycling (24-110°C). We also have an extensive suite of virtual design tools that will be applied to the proposed research, including CAD and thermal design software, statistical analysis software, and multiple tools for computational fluid dynamics simulation and finite-element analysis. We have also developed two proprietary thermal prediction codes.

US Hose Corp. US Hose has extensive support for hose fabrication and welding: TIG/MIG welding, orbital welding, 5 welders certified to ASME Section IX BPVC. Test facilities include helium and nitrogen leak testing to 5,000 psig, mass-spectrometer helium leak testing to 1.0 x 10^{-10} sccs, water-free hydrogen leak testing to 400 psig, hydrostatic testing to 20,000 psig, and partnerships with NDT sources for additional testing requirements. Other capabilities include CGA G4.1 approved oxygen delivery cleaning and CNC machining. US Hose is ISO 9000 compliant and has earned a wide array of industrial approvals, including nuclear, aerospace, industrial, and defense specifications.

ALU CTO Lab The CTO facility includes a 10-rack version of the modular liquid-cooling system hosting a range of operational servers with 100-kW total power and with a 160-kW capac[redacted]pumping facility.

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EXEMPTION 4

ALU NSIT Lab The ALU NSIT lab has facilities for rigorous system-level testing of enhancements to the modular liquid cooling system. The baseline first generation shelf-level modular cooling technology is currently installed in an existing NSIT server farm which houses 17 frames equipped with ~400 servers of various vendor makes and models and total power dissipation of ~100 kW. The area, which uses a

REDACTED
EXEMPTION 4

We also have the facilities to configure a second environment to test the next-generation version of the modular cooling system with REDACTED EXEMPTION 4 This lab houses ~500 servers in 22 frames, with a total power dissipation of ~130 kW.

American Recovery and Reinvestment Act (ARRA) Information

Job creation and/or preservation and direct economic recovery impacts in 12 to 18 months

Alcatel-Lucent / Bell Labs: The Research component of the effort will create 2 Post-Doctoral candidate positions funded at EX 4 er year for the 2-year duration of the program.

Modine: Modine will create the following positions: i) Retain a Manufacturing Engineer EX 4 ii) Contract a Sample Technician for an 8-12 week period iii) Contract a Designer for a 3 to 6 ½ week period and iv) Contract a Designer for a 10-week period REDACTED EXEMPTION 4

U.S. Hose: One new engineering technician position will be created at REDACTED EXEMPTION 4 for the two-year duration of the project.

Other direct economic impact: The installation of prototype systems will require the use of installers and contractors EX 4 and for a duration of 24 weeks.

Long-term job creation and/or preservation and direct economic recovery impacts

Successful commercial implementation of the liquid-cooling technology in ARCTIC will create a new service offering for retro-fitting and consolidating ICT facilities, as well as incorporating the technology into new installations. Specific jobs supported include:

ALU: Full-time positions include: i) Research and Development; ii) Sales and Marketing; iii) Managers and Support Personnel for installation, operation and maintenance; and iv) Design Engineers supporting retro-fits and integration of the technology directly into Alcatel-Lucent products.

Modine: The long-term commercial aspects of this concept will allow Modine's OEM Coil Group to support manufacturing jobs in North America and fund other development work that allow this group to be a viable supplier in the HVAC&R market. This will support the following jobs: i) Development Engineering and Manufacturing Engineering (3 Engineers at an REDACTED EXEMPTION 4 ii) Drafting; iii) Heat exchanger manufacturing (5 to 10 personnel and iv)

r

U.S. Hose: New full-time positions include: i) Engineering Technician at REDACTED EXEMPTION 4 overseeing product manufacturing; and ii) 4 Manufacturing Employees at responsible for assembly, welding, testing, and manufacturing of hose assemblies.

Other direct economic impact: The following positions will also be required to support the liquid-cooling technology: i) Trained installers and contractors for retro-fit installations; ii) Designers, engineers and manufacturing personnel for supplying component-level cooling technologies (3D heat sinks, EX 4 and iii) Facilities personnel at end-user locations trained in the installation, operation and maintenance of the technology.

[1] P. Kolodner. M. Hodes, I. Ewes, and P. Holmes, "Mechanical gap fillers: concepts and thermal resistance measurements", IEEE Transactions on Components and Packaging Technologies, **30**, 813 (2007)

[2] http://sites.energetics.com/ICT_roadmap09/pdfs/ICT_Vision_and_Roadmap_051309_draft.pdf

[3] http://architecture2030.org/current_situation/building_sector.html

[4] http://www.uptimeinstitute.org/wp_pdf/(TUI3025A)DataCenterCapacityandEnergy.pdf

[5] http://www1.eere.energy.gov/industry/financial/pdfs/itp_stage_gate_overview.pdf

MODINE
APPLIED THERMAL INNOVATION™

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Racine, Wisconsin 53403-2552

Tel. 262.636.1200
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July 21, 2009

Todd Salamon
Member of Technical Staff
Alcatel-Lucent
600 Mountain Avenue
Murray Hill, NJ 07974

Subject: Advanced Refrigerant-based Cooling Technologies for Information and Communications Infrastructure (ARCTIC)"

Dear Todd:

Modine is pleased to submit a proposal to participate in the Advanced Refrigerant-based Cooling Technologies for Information and Communications Infrastructure (ARCTIC) project with Alcatel-Lucent. We are committed to contributing EX 4 n cost sharing to this project. This amount includes EX 4 n cost for validation testing on new heat exchangers developed for this program.

We look forward to working with your company on this exciting new opportunity. Please keep us informed of the status of this proposal.

Sincerely,

Craig Grohman
Commercial Products Group
Coils Business Manager

Cc: Mark Johnson

7/15/2009

USHOSE CORPORATION
METAL-COMPOSITE-FLUORPOLYMER

U.S. Hose Corporation
815 Forestwood Drive
Romeoville, Illinois 60446
Tel: (815) 886-1140
(800) 671-0033
Fax: (815) 886-4550
www.ushosecorp.com

Letter of Commitment

To Whom It May Concern:

U.S. Hose Corp has a vested interest in researching and developing products that could provide more energy efficient information and communication technologies. In order to meet the federal funding requirement of 20% cost sharing as identified in FOA number DE-FOA-0000107, U.S. Hose Corp is committed to providing EX 4. Our cost sharing funds will be composed of personnel costs, travel costs, and equipment/manufacturing costs. These proposed project and objectives will require dedicated time and effort from new and existing internal and external resources. We look forward to the possibility of participating in this U.S. Department of Energy opportunity.

Sincerely,

John Devine
President - U.S. Hose Corp

conEdison
a conEdison, inc. company

Consolidated Edison Company
of New York, Inc.
4 Irving Place
New York NY 10003
www.conEd.com

July 17, 2009

Susanne Arney, Director
Microsystems and Nanotechnology Research Dept
Bell Labs, Alcatel-Lucent
600-700 Mountain Ave, Rm 1D-339
Murray Hill, NJ 07974

Re: Letter of Commitment to participate in the "Advanced Refrigeration-Based Cooling Technologies for Information and Communications Infrastructure (ARCTIC)" proposal to DOE

Consolidated Edison Company of New York, Inc. (Con Edison), a subsidiary of Consolidated Edison, Inc., is a regulated utility that provides electric delivery service to more than three million customers throughout New York City and Westchester County.

Data centers are both an increasingly large electric energy user in our service area and also represent a potentially significant opportunity for new advanced energy efficiency measures. The energy consumption in data centers has been nearly doubling every five years and is projected to continue to increase.

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EXEMPTION 4

Con Edison will collaborate with ALU in its proposal "Advanced Refrigeration-Based Cooling Technologies for Information and Communications Infrastructure (ARCTIC)" to DOE in response to the Funding Opportunity Announcement "Recovery Act: Energy Efficient Information and Communication Technology" (DE-FOA-0000107). Con Edison supports the subject application to develop and demonstrate an innovative server cooling technology for data centers. The innovative cooling technology will permit substantial improvement in data center energy efficiency and the environment.

Con Edison proposes to provide end-user perspective, as well as providing technical and practical support from the utility perspective regarding energy efficiencies and demand reduction for data centers.

In particular, Con Edison proposes to:

1) Participate in the development as a technical resource and reviewer of the technology being proposed for the data center installation of the modular cooling technology developed under DOE-funded research in ALU's Plano, Texas facility; and

2) Host and make introductions for presentations to our customers of the modular cooling technology and potentially a demonstration at a Con Edison data center at the point this technology becomes commercially available.

If the Alcatel-Lucent team is successful in obtaining an award on this proposal, Con Edison would be willing to provide in-kind services on this project in the form of our company labor and other in-kind services up to a maximum value of EX 4 ncluding overhead.

We look forward to working with you on the development of this data center technology.

Sincerely,

Arthur Kressner, Director
Research and Development

Impact Projections Model

Project Name:	Advanced Refrigerant-based Cooling Technologies for Information and Communications infrastructure (ARCTIC)
Preparer: Name and Organization	Todd Salamon; Alcatel-Lucent USA Bell Labs

Technology Description

Please provide a concise description (more than one-half page is unncessary) of the new technology you are proposing, addressing:

- Its function, and benefits to the industrial user of the technology
- The state-of-the art technology it replaces
- The target of the technology and potential limitations to its applications and barriers
- Plant modifications necessary to incorporate the new technology
- Competing technologies
- The definition of one technology unit-year

The proposed new technology consists of an extremely efficient way to provide shelf-level cooling of equipment racks in a telecom central office or data center. In this new system, a heat exchanger which functions the same way as an automobile radiator is mounted on each shelf. The air that is driven through the shelf to carry off the waste heat exits the shelf through the heat exchanger, which cools it back down to ambient temperature. A fluid handling system pumps R134a refrigerant through the heat exchangers to provide the cooling. Heat is removed from the refrigerant by heat exchange with building chilled water. A great advantage of the proposed technology is that all the air that enters and exits the racks is at the same ambient temperature. Thus, no shelves are cooled by air that is so cold that wasteful overcooling occurs, [redacted] EX 4 This advantage allows for a correspondingly higher equipment density and correspondingly lower real-estate costs. It also allows data-center designers to lay out the equipment as best dictated by function, without having to worry about local overheating.

Cooling is presently accomplished in this industry by circulating cooled air through the office in such away that it is drawn from the room into the shelves for cooling. The heated air is vented back out into the room and is then ducted into an air-conditioning (CRAC) unit for heat exchange and recirculation. The present technology has many disadvantages. The air is heated as it passes from shelf to shelf before returning to the CRAC; thus, in order for the last shelves in the air stream to receive adequately cool air, the CRAC set point has to be set so low that the first shelves in the air stream are uselessly and wastefully overcooled. Without extremely careful design, the cool air partially mixes with heated air outside the racks, leading to further energy waste. Because of these inefficiencies, shelves cannot be filled with equipment to their maximum, capacity - this would produce too much heat in each shelf. Thus, real estate is wasted. These are precisely the deficiencies that the proposed new system avoids.

[redacted] We estimate the payback [redacted] EX 4 Since the fluid-circulation component consists simply of a pump, [redacted] we expect substantially better reliability than a CRAC-based system.

Deployment of the new technology requires the installation of a fluid-handling system and the mounting of heat exchangers and possibly external fans on each rack to be cooled. Physical space for these components appears to be generally available. A pump and heat exchanger are also required; these take up part of the space normally occupied by the CRAC unit.

[redacted]

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EXEMPTION 4

Impact Projections Model

Unit Inputs

Advanced Refrigerant-based Cooling Technologies for Information and Communications infrastructure (ARCTIC)

Per Unit Impacts per year	New Technology	Current Technology	Net Impact
Energy Use			
Electricity (billion kWh)		REDACTED EXEMPTION 4	0.00E+00
Natural Gas (trillion Btu)			0.00E+00
Petroleum - Residual Fuel (million barrels)			0.00E+00
Petroleum - Distillate Fuel (million barrels)			0.00E+00
Petroleum - Liquefied Petroleum Gas (million barrels)			0.00E+00
Coal (million short tons)			0.00E+00
Feedstock (trillion Btu, please specify)			0.00E+00
Biomass (trillion Btu, please specify)			0.00E+00
Waste (trillion Btu, please specify)			0.00E+00
Other (please specify, trillion Btu)			
	Comments		

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EXEMPTION 4

Market Inputs

Advanced Refrigerant-based Cooling Technologies for Information and Communications Infrastructure (ARCTIC)

Total Market

\# of installed units

year for data ab REDACTED

annual marke EXEMPTION 4

Comments

x

Ultimate Potential Market Share

Ultimate Potential A[illegible]ible Market (%)

Likely Techn REDACTED

EXEMPTION 4

Comments

x

Market Penetration

	(10+ years)	(4-8 Years)			(2-3 Years)		
Case	Initial R&D Completed	Initial System Prototype	Refined Prototype	Commercial Prototype	Commercial Introduction	Technology Class	Years to Saturation
With ITP	[redacted]						

REDACTED
EXEMPTION 4

Comments

REDACTED
EXEMPTION 4

REDACTED
EXEMPTION 4

Impact Projections Model

Impacts: New Technology vs Current Technology							
Advanced Refrigerant-based Cooling Technologies for Information and Communications infrastructure (ARCTIC)							
Impact By Year	2010	2015	2020	2025	2030	2035	2040
Cumulative Units installed			REDACTED EXEMPTION 4				
Annual New Units Installed							
Annual Replacement Units Installed							
Annual Installations Total							
Market penetration							
ANNUAL SAVINGS							
Energy Metrics							
Total primary energy displaced (trillion Btu)	0.80	8.09	51.70	124.54	182.92	247.48	331.58
Direct electricity displaced (billion kWh)	0.09	0.98	6.55	15.78	23.18	31.36	42.02
Direct natural gas displaced (bcf)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct petroleum displaced (million barrels)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Direct coal displaced (million short tons)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Feedstock energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Waste energy displaced (trillion BTU)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other energy displaced (trillion Btu)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Financial Metrics							
Energy-cost savings ($MM/yr)	5.81	58.46	386.74	953.32	1411.18	1909.17	2558.02
Environmental Metrics							
CO Displaced (Metric tonnes)	15.49	163.40	1076.97	2594.21	3810.33	5154.97	6906.92
Carbon Dioxide emissions displaced (MM TCE)	0.02	0.16	1.01	2.42	3.56	4.81	6.45
Other greenhouse emissions displaced (MM TCI	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO2 displaced (Metric tonnes)	252.87	2293.38	13561.48	32666.97	47980.73	64912.70	86973.73
NOx displaced (Metric tonnes)	150.13	1443.76	8903.96	21447.92	31502.37	42619.27	57103.73
Particulates displaced (Metric tonnes)	5.40	49.02	288.68	695.38	1021.36	1381.79	1851.40
VOCs displaced (Metric tonnes)	1.67	17.55	116.00	279.41	410.39	555.22	743.91
Hydrocarbons displaced (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Solid Waste (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other environmental benefits (Metric tonnes)	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Instructions and Summary

Award Number:
Award Recipient: Alcatel-Lucent USA

Date of Submission:
Form submitted by: Alcatel-Lucent USA
(May be award recipient or sub-recipient)

Please read the instructions on each page before starting.
If you have any questions, please ask your DOE contact. It will save you time!

On this form, provide detailed support for the estimated project costs identified on the SF-424A form (Budget).

- The dollar amounts on this page must match the amounts on the associated SF-424A.
- The award recipient and each sub-recipient with estimated costs of $100,000 or more must complete this form and a SF-424A form.
- The total budget presented on this form and on the SF424A <u>must include both Federal (DOE), and Non-Federal (cost share) portions</u>, thereby reflecting TOTAL PROJECT COSTS proposed.
- For costs in each Object Class Category on the SF-424A, complete the corresponding worksheet on this form (tab at the bottom of the page).
- All costs incurred by the preparer's sub-recipients, vendors, contractors, consultants and Federal Research and Development Centers (FFRDCs), should be entered only in section f. Contractual. All other sections are for the costs of the preparer only.

SUMMARY OF BUDGET CATEGORY COSTS PROPOSED

(Note: The values in this summary table are from entries made in each budget category sheet.)

CATEGORY	Budget Period 1 Costs	Budget Period 2 Costs	Budget Period 3 Costs	Total Costs	Project Costs %	Comments (Add comments as needed)
a. Personnel						
b. Fringe Benefits						
c. Travel						
d. Equipment						
e. Supplies			REDACTED EXEMPTION 4		REDACTED EXEMPTION 4	
f. Contractual						
Sub-recipient						
FFRDC						
Vendor						
Total Contractual						
g. Construction						
h. Other Direct Costs						
i. Indirect Charges						
Total Project Costs						

Additional Explanations/Comments (as necessary)

Instructions and Summary

Award Number: ______
Award Recipient: Alcatel-Lucent USA Bell Labs

Date of Submission: ______
Form submitted by: Modine Manufacturing
(May be award recipient or sub-recipient)

Please read the instructions on each page before starting.
If you have any questions, please ask your DOE contact. It will save you time!

On this form, provide detailed support for the estimated project costs identified on the SF-424A form (Budget).

- The dollar amounts on this page must match the amounts on the associated SF-424A.
- The award recipient and each sub-recipient with estimated costs of $100,000 or more must complete this form and a SF-424A form.
- The total budget presented on this form and on the SF424A must include both Federal (DOE), and Non-Federal (cost share) portions, thereby reflecting TOTAL PROJECT COSTS proposed.
- For costs in each Object Class Category on the SF-424A, complete the corresponding worksheet on this form (tab at the bottom of the page).
- All costs incurred by the preparer's sub-recipients, vendors, contractors, consultants and Federal Research and Development Centers (FFRDCs), should be entered only in section f. Contractual. All other sections are for the costs of the preparer only.

SUMMARY OF BUDGET CATEGORY COSTS PROPOSED
(Note: The values in this summary table are from entries made in each budget category sheet.)

CATEGORY	Budget Period 1 Costs	Budget Period 2 Costs	Budget Period 3 Costs	Total Costs	Project Costs %	Comments (Add comments as needed)
a. Personnel						
b. Fringe Benefits						
c. Travel					REDACTED EXEMPTION 4	
d. Equipment		REDACTED EXEMPTION 4				
e. Supplies						
f. Contractual						
Sub-recipient						
FFRDC						
Vendor						
Total Contractual						
g. Construction						
h. Other Direct Costs						
i. Indirect Charges						
Total Project Costs						

Additional Explanations/Comments (as necessary)

Applicant Name: Alcatel-Lucent USA   Award Number: ______

Budget Information - Non Construction Programs

OMB Approval No. 0348-0044

Section A - Budget Summary

Grant Program Function or Activity (a)	Catalog of Federal Domestic Assistance Number (b)	Estimated Unobligated Funds: Federal (c)	Estimated Unobligated Funds: Non-Federal (d)	New or Revised Budget: Federal (e)	New or Revised Budget: Non-Federal (f)	New or Revised Budget: Total (g)
1. DE-FOA-0000107	81.086			$1,346,873	REDACTED EXEMPTION 4	
2.						
3.						
4.						
5. Totals		$0	$0	$1,346,873		

Section B - Budget Categories

6. Object Class Categories	Grant Program, Function or Activity (1)	(2)	(3)	(4)	Total (5)
a. Personnel		REDACTED EXEMPTION 4			REDACTED EXEMPTION 4
b. Fringe Benefits					
c. Travel					
d. Equipment					
e. Supplies					
f. Contractual					
g. Construction					
h. Other					
i. Total Direct Charges (sum of 6a-6h)					
j. Indirect Charges					
k. **Totals** (sum of 6i-6j)					
7. Program Income					

Previous Edition Usable

SF-424A (Rev. 4-92)
Prescribed by OMB Circular A-102

Section C - Non-Federal Resources

(a) Grant Program	(b) Applicant	(c) State	(d) Other Sources	(e) **Totals**
8. DE-FOA-0000107				
9.				
10.		REDACTED EXEMPTION 4		
11.				
12. **Total** (sum of lines 8 - 11)				

Section D - Forecasted Cash Needs

	Total for 1st Year	1st Quarter	2nd Quarter	3rd Quarter	4th quarter
13. Federal	$1,346,873	$502,034	$342,802	$286,888	$215,149
14. Non-Federal			REDACTED EXEMPTION 4		
15. **Total** (sum of lines 13 and 14)					

Section E - Budget Estimates of Federal Funds Needed for Balance of the Project

(a) Grant Program	Future Funding Periods (Years)			
	(b) First	(c) Second	(d) Third	(e) Fourth
16. DE-FOA-0000107				
17.				
18.				
19.		REDACTED EXEMPTION 4		
20. **Total** (sum of lines 16-19)				

Section F - Other Budget Information

21. Direct Charges	22. Indirect Charges

23. Remarks

Instructions for the SF-424A

Public Reporting Burden for this collection of information is estimated to average 3.0 hours per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Please do not return your completed form to the Office of Management and Budget; send it to the address provided by the sponsoring agency.

General Instructions
This form is designed so that application can be made for funds from one or more grant programs. In preparing the budget, adhere to any existing Federal grantor agency guidelines which prescribe how and whether budgeted amounts should be separately shown for different functions or activities within the program. For some programs, grantor agencies may require budgets to be separately shown by function or activity. For other programs, grantor agencies may require a breakdown by function or activity. Sections A, B, C, and D should include budget estimates for the whole project except when applying for assistance which requires Federal authorization in annual or other funding period increments. In the later case, Sections A, B, C, and D should provide the budget for the first budget period (usually a year) and Section E should present the need for Federal assistance in the subsequent budget periods. All applications should contain a breakdown by the object class categories shown in Lines a-k of Section B.

Section A. Budget Summary Lines 1-4 Columns (a) and (b)
For applications pertaining to a **single** Federal grant program (Federal Domestic Assistance Catalog number) and **not requiring** a functional or activity breakdown, enter on Line 1 under Column (a) the catalog program title and the catalog number in Column (b).

For applications pertaining to a **single** program **requiring** budget amounts by multiple functions or activities, enter the name of each activity or function on each line in Column (a), and enter the catalog number in Column (b). For applications pertaining to multiple programs where none of the programs require a breakdown by function or activity, enter the catalog program title on each line in **Column** (a) and the respective catalog number on each line in Column (b).
For applications pertaining to **multiple** programs where one or more programs **require** a breakdown by function or activity, prepare a separate sheet for each program requiring the breakdown. Additional sheets should be used when one form does not provide adequate space for all breakdown of data required. However, when more than one sheet is used, the first page should provide the summary totals by programs.

Lines 1-4, Columns (c) through (g)

For new applications, leave Columns (c) and (d) blank. For each line entry in Columns (a) and (b), enter in Columns (e), (f), and (g) the appropriate amounts of funds needed to support the project for the first funding period (usually a year).

For continuing grant program applications, submit these forms before the end of each funding period as required by the grantor agency. Enter in Columns (c) and (d) the estimated amounts of funds which will remain unobligated at the end of the grant funding period only if the Federal grantor agency instructions provide for this. Otherwise, leave these columns blank. Enter in columns (e) and (f) the amounts of funds needed for the upcoming period. The amount(s) in Column (g) should be the sum of amounts in Columns (e) and (f).

For supplemental grants and changes to existing grants, do not use Columns (c) and (d). Enter in Column (e) the amount of the increase or decrease of Federal funds and enter in Column (f) the amount of the increase or decrease of non-Federal funds. In Column (g) enter the new total budgeted amount (Federal and non-Federal) which includes the total previous authorized budgeted amounts plus or minus, as appropriate, the amounts shown in Columns (e) and (f). The amount(s) in Column (g) should not equal the sum of amounts in Columns (e) and (f).

Line 5—Show the totals for all columns used.

Section B. Budget Categories
In the column headings (a) through (4), enter the titles of the same programs, functions, and activities shown on Lines 1-4, Column (a), Section A. When additional sheets are prepared for Section A, provide similar column headings on each sheet. For each program, function or activity, fill in the total requirements for funds (both Federal and non-Federal) by object class categories.

Lines 6a-i—Show the totals of Lines 6a to 6h in each column.

Line 6j—Show the amount of indirect cost.

Line 6k—Enter the total of amounts on Lines 6i and 6j. For all applications for new grants and continuation grants the total amount in column (5), Line 6k, should be the same as the total amount shown in Section A, Column (g), Line 5. For supplemental grants and changes to grants, the total amount of the increase or decrease as shown in Columns (1)-(4), Line 6k should be the same as the sum of the amounts in Section A, Columns (e) and (f) on Line 5.
Line 7—Enter the estimated amount of income, if any, expected to be generated from this project. Do not add or subtract this amount from the total project amount. Show under the program narrative statement the nature and source of income. The estimated amount of program income may be considered by the federal grantor agency in determining the total amount of the grant.

Section C. Non-Federal Resources

Lines 8-11—Enter amounts of non-Federal resources that will be used on the grant. If in-kind contributions are included, provide a brief explanation on a separate sheet.

Column (a)—Enter the program titles identical to Column (a), Section A. A breakdown by function or activity is not necessary.

Column (b)—Enter the contribution to be made by the applicant.

Column (c)—Enter the amount of the State's cash and in-kind contribution if the applicant is not a State or State agency. Applicants which are a State or State agencies should leave this column blank.

Column (d)—Enter the amount of cash and in-kind contributions to be made from all other sources.

Column (e)—Enter totals of Columns (b), (c), and (d).

Line 12—Enter the total for each of Columns (b)-(e). The amount in Column (e) should be equal to the amount on Line 5, Column (f) Section A.

Section D. Forecasted Cash Needs

Line 13—Enter the amount of cash needed by quarter from the grantor agency during the first year.

Line 14—Enter the amount of cash from all other sources needed by quarter during the first year.

Line 15—Enter the totals of amounts on Lines 13 and 14.

Section E. Budget Estimates of Federal Funds Needed for Balance of the Project

Lines 16-19—Enter in Column (a) the same grant program titles shown in Column
(a), Section A. A breakdown by function or activity is not necessary. For new applications and continuation grant applications, enter in the proper columns amounts of Federal funds which will be needed to complete the program or project over the succeeding funding periods (usually in years). This section need not be completed for revisions (amendments, changes, or supplements) to funds for the current year of existing grants.
If more than four lines are needed to list the program titles, submit additional schedules as necessary.

Line 20—Enter the total for each of the Columns (b)-(e). When additional schedules are prepared for this Section, annotate accordingly and show the overall totals on this line.

Section F. Other Budget Information

Line 21—Use this space to explain amounts for individual direct object-class cost categories that may appear to be out of the ordinary or to explain the details as required by the Federal grantor agency.

Line 22—Enter the type of indirect rate (provisional, predetermined, final or fixed) that will be in effect during the funding period, the estimated amount of the base to which the rate is applied, and the total indirect expense.

Line 23—Provide any other explanations or comments deemed necessary.

Principal Investigator

Resume – Todd Salamon

Education and Training.

University of Connecticut, Chemical Engineering, B. S., 1989
University of Connecticut, Chemistry, B. S., 1989
Massachusetts Institute of Technology, Chemical Engineering, Ph. D., 1995

Professional Experience.

1995 – present: Member of Technical Staff, Bell Laboratories, Alcatel-Lucent, Inc. Numerical simulations applied to research and development in optical fiber manufacturing processes, electronics cooling, microfluidics, transmission and control in transparent optical networks, and wave propagation in photonic-crystal fibers.
1989: Summer Fellow, Imperial Chemical Industries. Investigated source of instabilities in a chemical process for manufacturing dimethylaniline/ethylaniline.
1988: Engineering Technician, American Cyanamid. Supervised pilot plant production of thermoplastic polymers.

Publications.

1. D. Hernon, T. Salamon, R. Kempers, S. Krishnan, A. Lyons, M. Hodes, P. Kolodner, J. Mullins and L. McGarry, "Thermal Management Technologies for Enhanced Functionality and Reduced Carbon Footprint Telecommunications Hardware", to appear in *Bell Labs Technical Journal*, vol. 14, no. 4 (2010).
2. A. Ahuja, J. A. Taylor, V. Lifton, A. A. Sidorenko, T. R. Salamon, E. J. Lobaton, P. Kolodner and T. N. Krupenkin, "Nanonails – A Simple Geometrical Approach to Superlyophobic Surfaces", *Langmuir* **24,** 9 (2008).
3. T. Krupenkin, J. A. Taylor, E. Wang, P. Kolodner, M. Hodes and T. Salamon, "Reversible Wetting-Dewetting Transitions on Electrically Tunable Superhydrophobic Nanostructured Surfaces", *Langmuir* **23**, 9128 (2007).
4. E. J. Lobaton and T. R. Salamon, "Computation of Constant Mean Curvature Surfaces: Application to the Gas-Liquid Interface of a Pressurized Fluid on a Superhydrophobic Surface", *Journal of Colloid and Interface Science* **314**, 184 (2007).
5. T. R. Salamon, W. Lee, T. Krupenkin, M. Hodes, P. Kolodner, R. Enright and A. Salinger, "Numerical Simulation of Fluid Flow in Microchannels with Superhydrophobic Walls", *Proceedings of the ASME International Mechanical Engineering Congress and Exposition,* IMECE2005-82641, Orlando, Nov. 5-11, 2005.
6. T. R. Salamon, J. A. Rogers and B. Eggleton, "Numerical Analysis of Heat Flow in Optical Fiber Devices That Use Microfabricated Thin Film Heaters", *Sensors and Actuators A* **95**, 8 (2001).
7. T. R. Salamon, D. E. Bornside, R. C. Armstrong and R. A. Brown, "Local Similarity Solutions for the Stress Field of an Oldroyd-B Fluid in the Partial-Slip/Slip Flow", *Physics of Fluids* **9**, 2191 (1997).
8. T. R. Salamon, D. E. Bornside, R. C. Armstrong and R. A. Brown, "Local Similarity Solutions Using a Slip Boundary Condition", *Physics of Fluids* **9**, 1235 (1997).
9. T. R. Salamon, D. E. Bornside, R. C. Armstrong and R. A. Brown, "The Role of Surface Tension in the Dominant Balance in the Die Swell Singularity", *Physics of Fluids* **7**, 2328 (1995).

10. M. J. Szady, T. R. Salamon, A. Liu, D. E. Bornside, R. C. Armstrong, R. A. Brown, " A New Mixed Finite Element Method for Viscoelastic Flows Governed by Differential Constitutive Equations", *J. of Non-Newtonian Fluid Mechanics* **59**, 215 (1995).

Patents.

1. M. S. Hodes, P. R. Kolodner, T. N. Krupenkin, W. Lee, T. R. Salamon, J. A. Taylor and D. P. Weiss, "Techniques for Microchannel Cooling", U. S. Patent No. 7204298, issued on April 17, 2007.
2. J. A. Rogers and T. R. Salamon, "Heat Tunable Optical Devices with Linearity Compensation", U.S. Patent No. 6856731, issued on February 15, 2005.
3. L. L. Blyler, A. C. Hart, T. R. Salamon and M. Viriyayuthakorn, "Process for Fabricating Plastic Optical Fiber", U.S. Patent No. 6254808, issued on July 31, 2001.

Synergistic Activities.

Photonic Integrated Circuit (PIC) - provided experimental, analytical and numerical modeling support to develop cooling strategies for packaged laser arrays.

Thermal interface materials (TIMs) - developed computational models for thermal transport and mechanical deformation to understand the relation between geometry and thermal performance for a new class of TIMs based on micro-patterned metal foils.

Superhydrophobic nano-structured surfaces – developed and applied analytical and numerical models of fluid flow and heat transport to evaluate the use of superhydrophobic nanostructured surfaces in microchannel cooling applications.

Optical fiber manufacturing – developed and applied detailed computational models to improve the performance of a range of processes for making optical fiber. These included high-speed fiber coating, high-temperature fiber drawing, the modified chemical vapor deposition (MCVD) process for making fiber preforms, the sol-gel process for using inexpensive starting materials to make high-purity glass preforms, and an extrusion process for the manufacture of graded-index plastic optical fiber (GIPOF).

High-performance computer simulations – developed a number of software tools for simulation of complex physical phenomena, including: i) lead developer of a C- and MPI-based parallel finite element code (40,000+ lines) for solving fluid flow, heat and mass transfer problems; ii) lead developer of a C-based simulation tool (60,000+ lines) for modeling power propagation and amplifier control dynamics in a nationwide optical network; and iii) lead developer of a C and Fortran code (100,000+ lines) for calculating leaky modes in photonic crystal fibers by solving the vector Maxwell equations. The code was applied to understanding Bragg fibers consisting of an air core with alternating layers of high-refractive-index-contrast material comprising the cladding of the fiber.

Resume – Paul Kolodner

Education and Training.

Princeton University, Physics, A. B., 1975
Harvard University, Physics, A. M., 1977
Harvard University, Physics, Ph. D., 1980

Professional Experience.

2002 – present: Distinguished Member of Technical Staff, Bell Laboratories, Alcatel-Lucent, Inc. (formerly AT&T Bell Laboratories). Research and development in fiber-optic devices, heat transfer, thermal management.
1980 – 2002: Member of Technical Staff, Bell Laboratories. Pure and applied research in fluid dynamics, pattern formation, biophysics, fiber-optic devices.

Publications.

1. T. Salamon, W. Lee, T. Krupenkin, M. Hodes, P. Kolodner, R. Enright, and A. Salinger, "Numerical simulation of fluid flow in microchannels with superhydrophobic walls", in *Proceedings of IMECE2005,* paper IMECE2005-82641 (2005).
2. P. Kolodner, M. Hodes, I. Ewes, and P. Holmes, "Thermal-resistance measurements on mechanical gap fillers", in *Proceedings of InterPack2005,* paper IPACK2005-73084 (2005).
3. P. Kolodner, C. Bolle, and M. Hodes, "Efficient cooling of multiple components in a shielded circuit pack", in *Proceedings of InterPack2005*, paper IPACK2005-73071 (2005).
4. R. Enright, C. Eason, T. Dalton, M. Hodes, T. Salamon, P. Kolodner, and T. Krupenkin, "Friction factors and Nusselt numbers in microchannels with superhydrophobic walls", in *Proceedings of ICNMM2006,* paper ICNMM2006-96134 (2006).
5. P. Kolodner. M. Hodes, I. Ewes, and P. Holmes, "Mechanical gap fillers: concepts and thermal resistance measurements", IEEE Transactions on Components and Packaging Technologies **30,** 813 (2007).
6. M. Hodes, C. Bolle, and P. Kolodner, "Efficient cooling of multiple components in a shielded circuit pack", Journal of Electronics Packaging **129**, 216 (2007).
7. R. Kempers, P. Kolodner, A. Lyons, and A. Robinson, "Development of a high-accuracy thermal interface material tester", in *Proceedings of ITherm2008,* pp. 221-226 (2008).
8. R. Kempers, P. Kolodner. A. Lyons, and A. J. Robinson, "A High-Precision Apparatus for the Characterization of Thermal Interface Materials", Review of Scientific Instruments (in press).
9. N. Kumari, V. Bahadur, M. Hodes, T. Salamon, A. Lyons, P. Kolodner, and S. V. Garimella, "Numerical analysis of mist-cooled high-power components in cabinets", in *Proceedings of Interpack2009*, paper IPACK2009-89269 (2009).

Patents.

4. P. Kolodner, "Method and apparatus for measuring the temperature profile of a surface", US patent number 4,819,658, issued April 11, 1989.
5. P. Kolodner and D. L. Rousseau, "High efficiency optical switching and display devices", US patent number 5,781,330, issued July 14, 1998.
6. P. L. Gannel, K. G. Hampel, and P. Kolodner, "Fluorescent thermal imaging using rare-earth-chelate films", US patent number 5,971,610, issued October 26, 1999.