



# Final Report

## “Consolidated Research and Development for Pipeline Safety”

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Submitted by: Electricore, Inc.  
27943 Smyth Drive, Suite 105  
Valencia, California 91355  
Phone: (661) 607-0260, Fax: (661) 607-0264  
Program Manager: Mr. Ian Wood



With support from: AeroVironment, Inc.  
1960 Walker Avenue  
Monrovia, California 91016  
Principal Investigator: Ms. Deborah Jelen



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## EXECUTIVE SUMMARY

Small Unmanned Air Vehicles (UAVs) are used extensively by the military for a variety of aerial surveillance missions. In April 2005, Electricore, in teaming with AeroVironment Inc., began work on a U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration (PHMSA) co-funded project to conduct a proof of concept demonstration using small UAVs for a variety of pipeline surveillance missions currently being conducted with manned aircraft and on the ground personnel.

The project identified available UAVs and commercially available sensor technologies to allow the program team to rapidly converge on a cost effective system solution to conduct aerial surveillance for pipeline monitoring and leak detection. **The program objective is to determine the feasibility of using UAVs for detecting leaks associated with natural gas and hazardous liquid pipelines, and identifying and recording encroachment violations in pipeline rights of way.** These practical solutions are attempting to address Department of Transportation priorities to close gaps in safety, inspection and enforcement while reducing the cost of state-of-the-art pipeline surveillance.

In addition to pipelines, UAV technology can be applicable to a broad spectrum of other uses, including power line inspection, **rail line inspection**, digital mapping, water and sewer monitoring, and leak detection.

The program team has recently completed the Feasibility Phase, which entailed:

- Identifying aerial surveillance missions that could potentially be serviced by UAVs
- Identifying UAV platforms and sensors best suited for flying these missions
- Conducting a series of demonstration test flights as a “proof of concept” for the technology
- Providing data and system analysis following the demonstration tests.

Multiple demonstration test flights were flown as part of this program. These tests have shown that small UAV technology currently in use with the U.S. military has potential commercial application for a variety of pipeline surveillance missions. In particular, UAVs can serve as a portable aerial surveillance platform to monitor pipelines for third party encroachment, monitor pipelines for oil and gas leaks, and conduct a variety of mapping and GIS missions.



Small UAV Launch



3rd Party Encroachment



Infrastructure Surveillance

## MISSION REQUIREMENTS

The program investigated the feasibility of using remotely piloted aircraft with appropriate sensors to detect leaks from transmission pipelines, locate right of way encroachments, video record encroachment violations, and reduce the cost of aerial pipeline surveillance.

### ***Mission***

The program is comprised of four phases: Feasibility, Application Development, Testing, and Commercialization to be completed over a period of four years. The use of available Unmanned Aerial Vehicles (UAVs) and commercial sensor technologies is allowing the team to rapidly converge on a cost effective system solution for conducting aerial surveillance for pipeline monitoring and leak detection. The UAV and sensor suite was used to determine the feasibility of utilizing an airborne remote sensing system for detecting leaks associated with natural gas and hazardous liquid pipelines, and identifying and recording encroachment violations in pipeline rights of way. A significant reduction in survey costs of aerial pipeline surveillance is an important aspect of this program.

These practical solutions are addressing the Department of Transportation priorities to close gaps in safety, inspection and enforcement while reducing the cost of state of the art pipeline surveillance. In addition to pipelines, UAV technology is applicable to a broad spectrum of other uses including power line inspection, rail line inspection, digital mapping, water and sewer monitoring, and leak detection.

### ***Specific Types of Pipeline Monitoring Required***

#### Encroachment Detection

The first objective was to detect pipeline right of way encroachments, map their location on a GPS map and provide a real time visual image of the problem area. A combination of forward-looking and side-looking visual (color video camera) and infra red imaging was used.

Data was be obtained by performing flight tests in coordination with DOT/OPS using real and simulated encroachments. Altitude was determined by payload scan requirements, insuring that at least 1000 feet on either side of right of way is recorded. Photographs were taken with GPS coordinates to demonstrate recording capabilities for use in addressing violations. Analysis on the ability to count houses was identified.

#### Leak Detection

The second major objective was to determine the system's reliability and accuracy in locating and mapping leaks associated with pipelines, map their location on a GPS map and provide a real time visual image of the problem area.

Data was obtained by performing flight tests in coordination with DOT/OPS and the pipeline industry. Over a series of demonstration flights, the detection of leaks of varying magnitudes (ranging from 15 scfh to 5000 scfh) was attempted through simulated leakages.

#### Frequency of Pipeline Monitoring Required by Regulations

The entire pipeline right-of-way must be patrolled **two to four times each year**, depending on how densely populated the area around the pipeline is (the higher the population, the more frequent the patrol). Leak detection surveys are conducted at least annually in unpopulated areas and four times each year in populated areas.

The operator of a pipeline in **densely populated** areas is required to observe the Right-of-way at intervals not **exceeding 3 weeks**, but at least 26 times a year (49 CFR Part 195.412 (a)). This requirement is normally met by aerial surveillance conducted bi-weekly.

Pipeline owner operators are required to **annually review house counts** surrounding pipelines to insure the classification has not changed.

### **Cost Reduction**

The third objective of the program is to achieve survey data at a cost much less than other methods currently available. The predominate method of surveying pipelines is by manned flight using fixed wing and rotary aircraft.

Surveying cost is directly related to the time taken to complete the survey and the geographical region of the survey site. Costs increase as precision and comprehensiveness are required. Recording survey results also increases costs. Other factors that complicate surveying include rugged terrain, heavy vegetation, accessibility of the site and existing survey landmarks (existing evidence).

Existing fixed wing surveillance is conducted by small, commercial aircraft operated by a commercial pilot. The crew may also include a camera operator and a GPS technician. The vehicle is outfitted with a precise navigation system interfaced to a camera, inertial measurement units, GPS units, or laptop computers.

Mission planning includes coverage required, the pipeline to be flown, forward or side looking cameras, altitudes required for proper scale, digitizing of flight lines, and identifying restricted flight areas. Factors affecting surveying missions include weather, sun angle (for proper camera performance) and vegetation.

Costs per mile will be identified and compared for urban and rural conditions for manned and unmanned flight as part of this program.

## ***Applicable Regulations***

### Applicable Federal Regulations

Federal regulatory agencies overseeing pipelines include: the U.S. Department of Transportation (DOT) Office of Pipeline Safety; the Federal Energy Regulatory Commission (FERC); and the Department of Interior's Minerals Management Service. Operations may also be subject to regulations of the Environmental Protection Agency; the Occupation Safety and Health Administration; the U.S. Coast Guard; the U.S. Army Corps of Engineers; and various state public service or public utility commissions and other state agencies may add further requirements to address local issues. The [National Transportation Safety Board](#) investigates pipeline accidents and makes recommendations for improvements in operations.

The interstate natural gas pipeline industry has two principle federal regulators: the FERC is responsible for the economic regulation of pipelines, while the DOT oversees the industry's safety efforts. The FERC is the regulatory agency that oversees the 180,000 miles of U.S. interstate natural gas pipelines. does so under the authority of the Natural Gas Act (NGA), the Natural Gas Policy Act (NGPA), the Outer Continental Shelf Lands Act (OCSLA), the Natural Gas Wellhead Decontrol Act and the Energy Policy Act (EPAct). FERC regulates tariffs on interstate pipelines that are subject to its jurisdiction. The FERC is a five-member commission, each of whom is nominated by the President of the United States and confirmed by the U.S. Senate. The commission regulates both the construction of interstate natural gas pipelines and the transportation of natural gas in interstate commerce. Companies wishing to build interstate pipeline facilities or operate pipelines first must obtain a Certificate of Public Convenience and Necessity from FERC. This is done to ensure that pipeline facilities benefit consumers, are compatible with the environment and minimize interference with the public and landowners along pipeline rights-of-way. In regulating the transportation of natural gas in interstate commerce, the commission sets rates, terms and conditions for operation of interstate gas pipeline facilities.

According to documents published by the Association of Oil Pipe Lines (AOPL) and the American Petroleum Institute, high consequence areas along pipeline rights of way require inspection by regulation. "High consequence" includes those areas that could affect drinking water, ecologically sensitive areas (including the habitats of threatened and endangered species) and navigable waterways. Between 2001 and 2004, some 37,990 miles of pipeline were categorized as high consequence areas. An additional 33,890 miles outside of high consequence areas could affect high consequence areas.

DOT has the lead on safety regulations for the pipeline industry. 49 CFR Parts 194 and 195 regulate maintenance, safe operations and prevention of leaks in the nation's pipeline network. 49 CRF Part 192 regulates natural gas pipelines.

Many regulations have the potential to drive the need for aerial surveys. The regulations that are most applicable are provided herein. Full text of the regulations is available at: [http://www.access.gpo.gov/nara/cfr/waisidx\\_04/49cfrv3\\_04.html](http://www.access.gpo.gov/nara/cfr/waisidx_04/49cfrv3_04.html)

- Inspection after a known environmental incident requires inspection:
  - 49CFR191.23
    - Unintended movement or abnormal loading by environmental causes, such as an earthquake, landslide, or flood, that impairs the serviceability of a pipeline or the structural integrity or reliability of an LNG facility that contains, controls or processes gas or LNG.
- Class locations are driven by the number of buildings and occupants in proximity to the pipeline. So called “house counts” are conducted, often aerially to determine the number of buildings near a pipeline.
  - 49CFR192.5
    - A “class location unit” is an onshore area that extends 220 yards (200 meters) on either side of the centerline of any continuous 1-mile (1.6 kilometers) length of pipeline.
    - Each separate dwelling unit in a multiple dwelling unit building is counted as a separate building intended for human occupancy. (b) Except as provided in paragraph (c) of this section, pipeline locations are classified as follows:
      - A Class 1 location is: An offshore area; or Any class location unit that has 10 or fewer buildings intended for human occupancy.
      - A Class 2 location is any class location unit that has more than 10 but fewer than 46 buildings intended for human occupancy.
      - A Class 3 location is: Any class location unit that has 46 or more buildings intended for human occupancy; or An area where the pipeline lies within 100 yards (91 meters) of either a building or a small, well-defined outside area (such as a playground, recreation area, outdoor theater, or other place of public assembly) that is occupied by 20 or more persons on at least 5 days a week for 10 weeks in any 12-month period. (The days and weeks need not be consecutive.)
      - (4) A Class 4 location is any class location unit where buildings with four or more stories above ground are prevalent.
      - (c) The length of Class locations 2, 3, and 4 may be adjusted as follows:
        - A Class 4 location ends 220 yards (200 meters) from the nearest building with four or more stories above ground.
        - When a cluster of buildings intended for human occupancy requires a Class 2 or 3 location, the class location ends 220 yards (200 meters) from the nearest building in the cluster.
- Continuing surveillance is required to maintain correct classifications.
  - 49CFR192.613
    - Each operator shall have a procedure for continuing surveillance of its facilities to determine and take appropriate action concerning changes in class location, failures, leakage history, corrosion, substantial changes in

cathodic protection requirements, and other unusual operating and maintenance conditions.

- Leakage surveys must be conducted regularly to insure safety.
  - 49CFR192.706
    - Leakage surveys of a transmission line must be conducted at intervals not exceeding 15 months, but at least once each calendar year.
    - In Class 3 locations, at intervals not exceeding 7 ½ months but at least twice each calendar year.
    - In Class 4 locations, at intervals not exceeding 4 ½ months, but at least four times each calendar year.
  - 49CFR192.721
    - The frequency of patrolling mains must be determined by the severity of the conditions that could cause failure or leakage, and the consequent hazards to public safety. Mains in places or on structures where anticipated physical movement or external loading could cause failure or leakage must be patrolled;
    - In business districts, at intervals not exceeding 4½ months, but at least four times each calendar year; and
    - Outside business districts, at intervals not exceeding 7½ months, but at least twice each calendar year.
  - 49CFR192.723
    - Each operator of a distribution system shall conduct periodic leakage surveys.
  - 49CFR195.412
    - (a) Each operator shall, at intervals not exceeding 3 weeks, but at least 26 times each calendar year, inspect the surface conditions on or adjacent to each pipeline right of way. Methods of inspection include walking, driving, flying or other appropriate means of traversing the right of way.

Many other agencies influence the operation and inspection of pipelines. An example of another federal agency influencing regulations is U.S. Forest Service regulated travel management and limited access of U.S. Forest land to designated routes. The routes did not adequately provide access to the many pipelines on Forest land that require inspection. New rules threatened to require written authorization prior to accessing to Forest lands. This rule would have significantly increased the paperwork associated with pipeline inspection and slowed the frequency of inspection as written authorization was awaited. Industry groups have petitioned to address the issue.

#### Applicable State Regulations

According to the Association of Oil Pipelines (AOPL), State's have a key role to play in achieving pipeline safety. The federal government's Office of Pipeline Safety has overall responsibility for safety regulations, in much the same way as the FAA regulates airline safety. However, state and local governments have other very significant powers and responsibilities that are not available to the federal government, and these powers can contribute in significant



ways to improving pipeline safety. It is beyond the scope of this document to review regulations of each state.

### Industry Standards

According to the Association of Oil Pipelines (AOPL), in addition to this core technical document, the industry adheres to a number of other standards that apply to all phases of pipeline safety:

- Tank operation and construction (15 standards maintained by a committee operated by API, the American Petroleum Institute)
- Underground storage caverns (2 API standards)
- Manufacture of line pipe (4 API standards)
- Cathodic protection against corrosion (8 NACE standards and guides)
- Welding (15 AWS and 1 API standards)
- Pipeline awareness (2 API standards)
- Pipeline integrity (API Recommended Practice 1129, Assurance of Hazardous Liquid Pipeline System Integrity)
- Pipeline wall thickness (API Standard B31.G).

These industry standards did not influence the planned demonstrations of this program.

Several industry organizations exist to consolidate and focus the voice of the pipeline industry and to develop appropriate standards for operation.

The Interstate Natural Gas Association of America (INGAA) is a trade organization that advocates regulatory and legislative positions of importance to the natural gas pipeline industry in North America. INGAA represents virtually all of the interstate natural gas transmission pipeline companies operating in the U.S., as well as comparable companies in Canada and Mexico. Its members transport over 95 percent of the nation's natural gas through a network of 180,000 miles of pipelines. INGAA actively works on pipeline safety integrity, recommending operations methods that are rational, cost effective and flexible.

The American Petroleum Institute (API) represents more than 400 members involved in all aspects of the oil and natural gas industry. This association draws on the experience and expertise of its members and staff to support a strong and viable oil and natural gas industry.

The Association of Oil Pipe Lines (AOPL) provides on its website an industry vision: an oil pipeline industry that conducts operations safely and with respect for the environment, respects the privilege to operate granted to it by the public, and provides reliable transportation of the crude oil and refined products upon which America relies.

The American Gas Association (AGA) mission statement advocates the interests of its energy utility members and their customers, and provides information and services promoting demand and supply growth and operational excellence in the safe, reliable and cost-competitive delivery of natural gas.

### Pipeline Owner/Operator Operational Requirements

In addition to regulatory and industry requirements, pipeline owners and operators require air visual support to complete a wide range of operational missions. The frequency of patrols varies from daily during times of concern (construction, weather related damage, vandalism, terrorism, etc.) to annually to meet regulatory requirements. Frequently, an aircraft is called in to verify a report derived from other sources. Aerial surveying provides a comprehensive and objective view of a large area over a short period of time. Aerial surveillance also offers the opportunity to acquire data in regions that are inaccessible to ground crews.

A few operational missions include:

- ❑ Annual counting of houses adjacent to pipelines.
- ❑ Monitoring for current and previous excavation in right of way areas.
- ❑ Identifying pipeline washouts.
- ❑ Documenting construction errors.

A review of Land Surveyors' offerings results in a group of surveying missions in demand by operations, but not due to regulations:

- ❑ Boundary Survey – Locating corners and boundary lines of a parcel of land.
- ❑ Topographic Survey – Natural and man-made topographical feature mapping.
- ❑ Site Planning Survey – Combination of boundary and topographic surveys for improvements.
- ❑ Control Survey – Horizontal position and elevation points for use in mapping, including GIS.
- ❑ Court Exhibit Survey – Visual displays for use in court proceedings
- ❑ Construction Survey – Layout of control for construction purposes.

Other possible surveying missions include:

- ❑ Photogrammetry – To acquire imagery, data and spatial information.
- ❑ Airborne remote sensing – including photography (see below), remote sensing derives information about an object, area or phenomenon from a distance.
- ❑ Aerial photography – from simple out of the window photography to precision oblique and vertical photography using special cameras and modified airplanes.
- ❑ Hydrographic, aerial image processing, spatial data, and GIS data collection.

Ground surveying is used when aerial surveillance is not accurate enough. Dangerous areas present a difficult situation, which is currently solved by the use of low altitude helicopter services. Ground surveillance carries the extra burden of road closures and traffic diversion, and often puts the surveyor in harms way.

## PAYLOAD TECHNOLOGY EXALUATION

### ***Commercially Available Payload Assessment***

#### Payload Requirements

Payloads must be capable of integration into existing SUAVs. The payload must meet the size, weight, and dimensions available for payloads on SUAVs. Future development and SUAV system upgrades may make more space, power and weight available for payloads.

The UAV system had to be capable of carrying a range of commercially available payloads, including black and white, color and infrared still and video digital imaging cameras, a host of environmental sensors, and a Global Positioning System (GPS).

#### Sensor and Data Requirements for Mission

The first objective of this program was to detect pipeline right of way encroachments, map their location on a GPS map and provide a real-time visual image of the problem area. Payload scan requirements, insuring at least 1,000 feet on either side of the right of way, were recorded. A combination of visual (color video camera) and infrared imaging was used, with the ability for the user to switch the camera being used. Forward looking and side looking payloads were employed. Images, along with GPS coordinates, were captured digitally.

The second major objective was to determine the system's reliability and accuracy in locating and mapping leaks associated with pipelines, map their location on a GPS map and provide a real-time visual image of the problem area. Detecting leaks of varying magnitudes (ranging from 15 scfh to 5000 scfh) was attempted through simulated leakages.

Table 1.0 outlines commonly used ground-based leak detection methods and their application on the "Consolidated Research and Development for Pipeline Safety Unmanned Air Vehicle Program":

***Table 1.0 – Sensor Methods & Applications***

Method	Ground Vehicle	SUAV	On Foot
Odor	Possible	Possible	Yes
Vegetation Discoloration	Yes	Yes	Yes
Insect Infestation	Yes	No	Yes
Fungus Growth	No	No	Yes
Sound	Yes	No	Yes
Unaccounted Gas	No	No	No
Electro-optical Camera	Yes	Yes	Yes
Infrared Camera	Yes	Yes	Yes
LIDAR	Yes	Possible	Yes
RADAR	Yes	Possible	No
Chemical/Biological Sensors	Yes	Possible	Yes

A number of commercially available sensors are available to address operational missions. Table 2.0 identifies payloads and their characteristics along with applicability to the “Consolidated Research and Development for Pipeline Safety Unmanned Air Vehicle Program”.

*<sup>i</sup>Table 2.0 – Available Sensors, Characteristics & Applicability to Program*

Payload/Technology	Appropriate for SUAV?	Manufacturer	Power Source	Benefits	Drawbacks	Approx Price	Comments
Altimeter	Yes	Various	Vehicle				Barometric
Compass	Yes	Various	Vehicle				
Electro-optic color camera	No	Swiss Federal Institute of Technology System Config		Day use.	Contrast dependent.	\$ 100,000	Large scale photogrammetry. Used in conjunction with GPS/INS. Used for mapping of landslides/avalanches.
Electro-optic color camera	Yes	Various	Vehicle	Used in vehicle now. Day use.	Resolution not adequate for surveying.		Spectral Sensitivity 300-700nm, Resolution NTSC, Illumination 2.0 Lux min.
Electro-optic low light, black & white camera	Yes	Various	Vehicle	Used in vehicle now. Low light usage.	Resolution not adequate for surveying.		Spectral Sensitivity 300-700nm, Resolution NTSC, Illumination 0.2 Lux min.
Global Positioning System	Yes	Various	Vehicle	Used in vehicle now.			
LIDAR - Light Detection and Ranging	No	Swiss Federal Institute of Technology System Config		Day and night use.		\$ 1,500,000	LIDAR integrated with GPS/INS
LIDAR - Light Detection and Ranging	No		7A	Measures topographical differences.	Cost. Weight. Volume. Cost.		LIDAR integrated with GPS/INS
LIDAR - Light Detection and Ranging	No	ITT		Airborne detection feasible	Weight, volume and cost require additional development.		
RADAR	No	Various	Vehicle		Weight		
Thermal camera, uncooled	Yes	Raytheon Corp	Independent, battery powered	Day and night use.	Designed for handheld use.	\$ 20,000	Model PalmIR Pro. Tested in use for harbor spills.
Thermal camera, uncooled, passive, mid IR, multi spectral scanning.	No	En'Urga, Inc.			Designed for use within 50 ft of leak		Tested by DOT
Thermal camera, uncooled, passive, mid IR, multi spectral scanning.	Yes	Various	Vehicle	Day and night use.			Spectral Sensitivity 8000-13000nm, Resolution 320x240.
Chem/Bio Sensors	No	SRI, Intl.		Day and night use.	Weight. Prototype System	Very Expensive	
Methane Sensor	Possible	Univ of Glasgow	Independent, battery powered	Day and night use.	Senses methane only. Prototype only.		
Methane Sensor	Possible	Physical Sciences Inc.	Independent, battery powered	Day and night use.	Sensing up to 100 to 150 ft	\$16,000	Tested by DOT
Combustible Gas Indicator	No	Various	Independent, battery powered	Low cost. Developed technology. Day and night use.	Broadly adopted for use.		For use in confined spaces.

### Electro-Optical Cameras

Electro-optical technology is a technology that uses the conversion of optical radiation into electrical signals. Electro-optical cameras installed in satellites that circle the globe at altitudes of several 100 kilometers have been used for sensing and mapping purposes for more than 20 years. These cameras have lenses that are entirely electronically controlled; there are no mechanical levers for focus or aperture control. This means that focus and aperture control motors are both built into the lens and not the camera body.<sup>ii</sup>

Electro-optical cameras are available and appropriate for deployment on this program. Electro-optical cameras were used to distinguish vegetation discoloration, disturbed soil and some liquid spills. The cameras used include:

*Color Camera:*

- ❑ Spectral Sensitivity: approximately 300 to 700 nanometers (nm)
- ❑ Resolution: NTSC or greater
- ❑ Minimum Illumination: 2.0 Lux

*Low Light Camera:* (black and white image)

- ❑ Spectral Sensitivity: 300 to >700 nm
- ❑ Resolution: NTSC
- ❑ Minimum Illumination: 0.2 Lux

Infrared Cameras

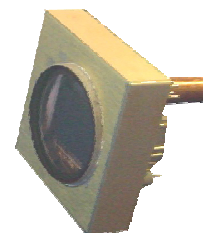
An infrared camera is a non-contact device that detects infrared energy (heat) and converts it into an electronic signal, which is then processed to produce a thermal image on a video monitor while performing temperature calculations. Heat sensed by an infrared camera can be very precisely quantified, or measured, allowing the user to not only monitor thermal performance, but also identify and evaluate the relative severity of heat-related problems. Recent innovations, particularly in detector technology, the incorporation of built-in visual imaging, automatic functionality and infrared software development, deliver more cost-effective thermal analysis solutions than ever before.<sup>iii</sup>

For instance, uncooled microbolometer detectors are sensitive in the long wavelength spectral range of 7 to 13 microns. Uncooled imagers are solid state and require very little maintenance. Several fixed focal length lens options are offered for each array format. Each format is configured into a camera system with the appropriate features to meet optimized installation and operational criteria. The 160x120 (Omega) format allows for the smallest size and weight thermal camera, which is ideal for short-range surveillance, while the 320 arrays provide higher resolution at a lower price in equivalent volumes.

*Uncooled Thermal Camera:*

- ❑ Spectral Sensitivity: 8000 to 13000 nm
- ❑ Resolution: up to 320x240
- ❑ Polarity Switch Option (white hot/ black hot)
- ❑ Color Infusion Option

The infrared camera used is manufactured by FLIR Systems and their sister company INDIGO. The product brand is Omega. Omega is the smallest, lightest, fully integrated, long-wavelength infrared camera available. Omega exhibits excellent sensitivity, with typical



performance of 50mK NE $\Delta$ T using f/1.6 optics. The camera resolution is 160x120. A pixel doubling and interpolation scheme is used in the camera to generate an effective video display resolution of 320x240. The camera also embodies a unique, patented combination of on-focal-plane circuitry and non-uniformity compensation processing that eliminates the need for temperature stabilization of the sensor. This results in very low power consumption and an “instant-on” capability. Omega outputs NTSC or PAL analog video, as well as 14-bit digital video.<sup>iv</sup>

Indigo commenced full-scale production of the Omega camera in October 2002. Since then, Indigo has built and delivered over 10,000 Omega cameras. Approximately 65 percent of Omega cameras delivered are used in a firefighting instrument known as the E5000, manufactured by Mine Safety Appliances (MSA). The remaining 30 percent (3,000+ Omegas) have been delivered for use in small UAVs. The predominant usage has been as an infrared camera payload on the Raven UAV manufactured by AeroVironment.

Indigo offers 10 different versions of the Omega camera, resulting from the availability of five different lens options and two input power supply options. The Raven uses an Omega with a 11mm lens, and the Extended Input Voltage option. The part number of this Omega configuration is 412-0106-07. The field of view furnished by the 11mm lens is 40x30 degrees.

Omega is a commercial, off-the-shelf (COTS) IR camera.

### LIDAR (Light Detection and Ranging)

LIDAR (light detection and ranging) uses the same principle as RADAR. The LIDAR instrument transmits light out to a target. The transmitted light interacts with and is changed by the target. Some of this light is reflected / scattered back to the instrument where it is analyzed. The change in the properties of the light enables some property of the target to be determined. The time for the light to travel out to the target and back to the LIDAR is used to determine the range to the target.

LIDAR, laser radar, optical radar and LADAR are all names used for “radar” systems utilizing electromagnetic radiation at optical frequencies. The radiation used by laser radars is at wavelengths that are 10,000 to 100,000 times shorter than those used by conventional radar. Radiation (photons) scattered by the target is (are) collected and processed to yield information about the target and/or the path to the target. Early conventional and laser radars observed only the intensity of the collected radiation and the time delay from transmission to collection. Modern laser radars also observe intensity and time delay.<sup>v</sup>

The Department of Transportation Office of Pipeline Safety conducted the “Field Testing of Remote Sensor Gas Leak Detection Systems” in Casper, Wyoming in September 2004. The program field-tested the abilities of five (5) systems to find real leaks. The most successful system results were displayed by a LIDAR system manufactured by Physical Scientific, Inc. (PSI). PSI uses a handheld laser-based LIDAR with a swept laser frequency to detect the presence of methane. The effective range of this





system is 100 to 150 feet. Initial discussions with PSI indicated that it might be possible to operate the handheld LIDAR in conjunction with a SUAV. Current technology readiness however does not allow for the PSI system to be integrated onto the SUAV.

### GPS – for mapping of areas of concern and documentation of areas of encroachment

The Global Positioning System (GPS) satellites transmit signals to equipment on the ground. GPS receivers passively receive satellite signals. Each GPS satellite transmits data that indicates its location and the current time. All GPS satellites synchronize operations so that these repeating signals are transmitted at the same instant. The signals, moving at the speed of light, arrive at a GPS receiver at slightly different times because some satellites are further away than others. The distance to the GPS satellites can be determined by estimating the amount of time it takes for their signals to reach the receiver. When the receiver estimates the distance to at least four GPS satellites, it can calculate its position in three dimensions. GPS receivers require an unobstructed view of the sky, so they are used only outdoors and they often do not perform well within forested areas or near tall buildings. GPS operations depend on a very accurate time reference, which is provided by atomic clocks on board.

There are at least 24 operational GPS satellites at all times plus a number of spares. The satellites, operated by the U.S. Department of Defense, orbit with a period of 12 hours (two orbits per day) at a height of about 11,500 miles, traveling at near 2,000 mph. Ground stations are used to precisely track each satellite's orbit.

The accuracy of a position determined with GPS depends on the type of receiver. Most handheld GPS units have about 10 to 20 meter accuracy. Other types of receivers use a method called Differential GPS (DGPS) to obtain much higher accuracy. DGPS requires an additional receiver fixed at a known location nearby. Observations made by the stationary receiver are used to correct positions recorded by the roving units, producing accuracy greater than 1 meter.<sup>vi</sup>

The SUAV uses commercial grade GPS signals. At least four satellite inputs are used. Reliability varies depending upon the reception and conditions. Typical accuracy of the GPS location for this commercial grade system is within 10 meters.

### Combustible Gas Indicator (CGI)

A Combustible Gas Indicator (CGI) consists of a meter, probe and an aspirator bulb. The bulb is pumped by hand to bring a sample of air into the probe and the instrument. The dial on the instrument indicates the percentage of flammable gas in the air (percent gas scale) or percent of the lower explosive limit (LEL) scale. These instruments must be calibrated for the type of gas in the system. The CGI should be calibrated for natural gas for use on a natural gas system.<sup>vii</sup>

Below are pictures of CGIs. PHMSA recommends that a two-scale meter be purchased (LEL and percent gas). CGI systems initially assessed were found to not be suitable for use with a

SUAV. However, further investigation revealed a CGI could be integrated with the SUAV. Demonstration tests were conducted with a CGI mounted on the SUAV.

**Figure 1.0 - CGI**



### Available Digital Imagery

The SUAV utilizes a NTSC (National Television System Committee) standard analog signal to download information from the air vehicle to the ground control unit. The ground control unit displays the data and provides a video feed to either a videocassette-recording device or to a personal computer. The standard computer is a military issued "Tough Book." The computer digitizes the images and displays them on the computer screen. The digitized image may then be used in conjunction with commercially available software packages for real time and interactive mapping and geographic information systems.

Photographs were taken with GPS coordinates to demonstrate recording capabilities for use in addressing violations. Available imagery was obtained to determine success in the following tasks:

- ❑ Video and still images of encroachment violations
- ❑ Enough information to determine the resolution of imagery and the scale of the images
- ❑ Conduct house counts – GPS coordinates and mapping of area
- ❑ Video with GPS coordinates
- ❑ Ability to identify structures through tree cover
- ❑ Capture and store images for review and analysis

### Available Data Processing

Images transmitted from the SUAV are output from the ground control unit to a "Tough Book" computer. The computer can be configured to run with a commercially licensed version of FalconView software manufactured by the Georgia Tech Research Institute (GTRI).



FalconView is a multimedia-mapping package for personal computers that displays various types of maps and geographically referenced overlays. Developed to support flight planning for the U.S. Air Force, Navy and Special Forces, FalconView is now employed by more than 16,000 users in every branch of the armed forces. The mapping package's low cost and portability allows pilots to complete their flight planning almost anywhere by retrieving and displaying maps on their computer screens.

Researchers at GTRI have enhanced the original, text-based planning program by writing software to display maps, imagery, digital terrain elevation data and a variety of aeronautical flight information. Pilots can now develop flight plans by pointing and clicking on terrain features and navigational aids along the way. FalconView users can view overlays with live intelligence data, airspace boundaries and possible flight hazards; they also may use GPS tracking information while airborne to increase situational awareness.<sup>viii</sup>

The FalconView software is integrated with custom AeroVironment SUAV software to supply the user with an interactive environment. The SUAV location is shown on a map. Users may fly a specified route or easily customize the flight by moving waypoints on the map to see specific areas of interest.

### Geographic Information Systems

Geographic Information Systems (GIS) offer a database for pipeline owners and operators to store data, maps and other site-specific information. The images collected by the SUAV and optical payloads are good candidates for inclusion in the GIS database. The GIS market is well developed with several clear leaders in technology and products. Though outside the scope of this initial project, the long-term goal will include the images output from the SUAV be designed to be collected by a GIS system. Initial discussions with GIS industry leaders provided several standard formats for data. Additional data processing will be required to configure the SUAV output to the form required for GIS input.

### **Vehicle Requirements**

AeroVironment's Unmanned Aerial Vehicles business is focused on the design, development and production of high-efficiency, unmanned aircraft for communications relay, remote sensing and research applications. The company is widely recognized as the world leader in stratospheric and small/micro UAVs, with over two decades of experience in developing, manufacturing and operating UAV systems. AV is the world's largest supplier of SUAV systems. The Raven, Dragon Eye, Pointer and Swift SUAV systems are used extensively by the Department of Defense and increasingly by other U.S. government agencies and the allied military.

The original SUAVs were designed as tactical reconnaissance vehicles for military and law enforcement applications. An onboard camera (color, or IR day/night vision) relays live video images to the pilot and mission navigator, to a video recorder, or even to other remote ground receivers.

AeroVironment's SUAVs has several key features for this application:

- ❑ Quiet and unobtrusive
- ❑ Operators not exposed to hostile situations
- ❑ Quick set-up, hand-launch and auto-land recovery
- ❑ Minimal training with no previous flight experience
- ❑ Minimal maintenance or logistical support required
- ❑ Rugged, lightweight, all-composite fabrication for multi-mission re-uses
- ❑ Low cost permits expendability, when appropriate.

The SUAV systems have been demonstrated in additional applications requiring other payloads. Potential applications include:

- ❑ Air sampling for pollution monitoring
- ❑ Chemical weapons detection
- ❑ Unexploded ordnance detection.

Global Positioning Systems (GPS) AutoNavigation is a standard feature.

The proposed SUAV, *PUMA*, is a battle-hardened design consisting of an air vehicle and ground station. The system is man portable, or light enough to be carried by two people. The system is designed for ease of use when employed by a trained operator, and can be set up and deployed within five minutes.

*PUMA* was able to carry the weight of two color or lowlight cameras, as well as two thermal cameras in the payload bay. Power consumption is lower on the color and lowlight cameras than on the thermal cameras. AeroVironment had previously verified operation of the proposed "2+2 configuration" mentioned above on the *PUMA* platform.

***Table 3.0 – Puma Vehicle Performance Requirements***

Range	15 miles
Duration	4 hours
Speed	35 – 60 miles per hour

***Table 4.0 – Puma Vehicle Specifications***

Wingspan	9 feet
Payload	X pounds
Length	6 feet
Weight	11 pounds or less

***Table 5.0 – Puma Vehicle Features***

Switchable Frequency
Computer Mapping
GPS

Autonavigation
Link Loss Default
Day and Night Operations
Hand Launched
AutoLand
Light Weight
Small Size
Man Portable

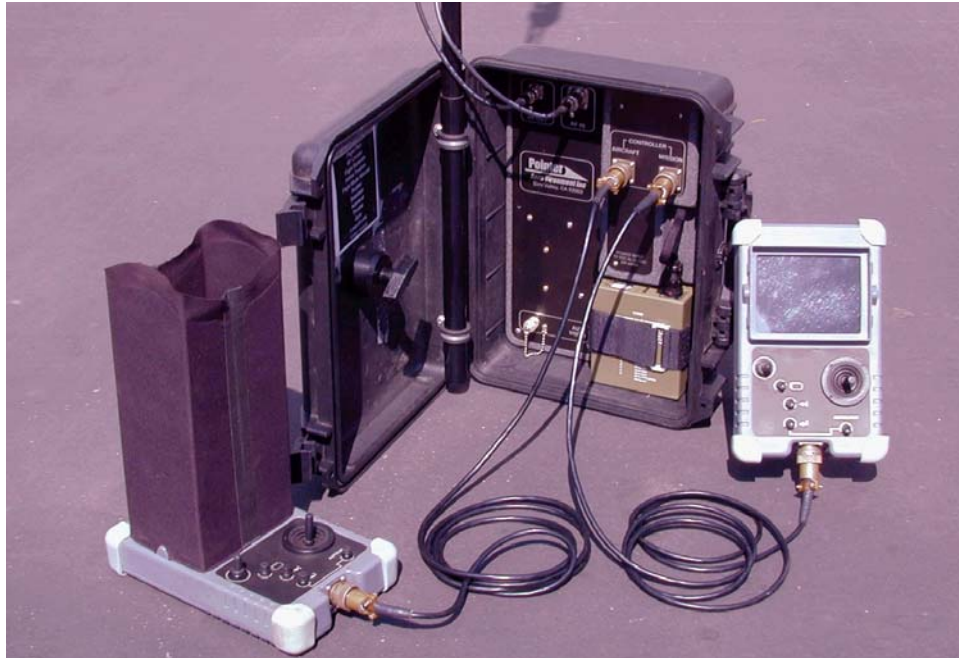
***Table 6.0 - Payloads***

Color Video
Infrared camera
Forward Imaging
Side-looking Imaging
Camera Switch Function
GPS
Compass Heading
Altimeter
Other Environmental Sensors (TBD)

***Figure 2.0 - Unmanned Air Vehicle***



*Figure 3.0 – Unmanned Air Vehicle Ground Control Unit*



## DEMONSTRATION TEST DATA ANALYSIS

### ***Unmanned Air Vehicle Demonstration Summary***

Proof of concept demonstration tests were conducted from December 2005 through June 2006 to determine the ability to use small unmanned air vehicles (UAVs) outfitted with available commercial sensors for pipeline surveillance missions. Demonstration tests were successful in identifying those missions the UAV could service as well as those missions that require additional development.

This section details the results of the demonstration tests.

### ***Data Analysis***

This section of the reports details the results of the project demonstration tests conducted from December 2005 through June 2006. A brief discussion of the results will be given in the conclusion section of this report. A detailed discussion of the demonstration results, from a system standpoint, will be given in a separate section titled: "System Analysis and Planning."

#### Gas Leak Detection

Gas Leak Detection demonstration tests were conducted using both infrared and combustible gas indicator (CGI) sensors.

##### *Infrared Camera*

##### Test

Gas leak demonstration tests were conducted on March 9, 2006 in Fillmore, California. Methane was released from compressed tanks at a rate of 15-, 100-, 500-, 1000-, 2000-, 2500- and 5000-scf. Testing began at the highest concentration and was reduced until the leak could no longer be detected from the small UAV. The UAV was flown over the known leak location and the video image taken by the infrared camera was analyzed. Both "black hot" and "white hot" settings were used on the infrared camera. The methane release was cleared by both the Ventura County Fire Department and the Ventura County Air Pollution Control.

##### Test Setup

Figures 4 and 5 below show the methane tank and valve assembly setup.



*Figure 4 (left) shows the methane tanks used for the gas leak demonstration testing. Figure 5 (right) shows the methane release apparatus.*

Test Results

Test Number	Leak Magnitude (scft/min)	Go / No-Go	Notes
1	5000	No-Go	a) Multiple passes flown over leak site b) Unable to detect any temperature change from methane release with infrared camera c) No further testing at lower concentrations was attempted
2	2500	N/A	Not attempted
3	2000	N/A	Not attempted
4	1000	N/A	Not attempted
5	500	N/A	Not attempted
6	100	N/A	Not attempted
7	15	N/A	Not attempted

Multiple attempts were made to detect the methane release. Figure 6 (below) shows an infrared image taken during the methane release. The white object is the outlet nozzle that the methane was released through. Its bright white color is due to the low temperature of the nozzle. No temperature change can be seen from methane in the air directly above the nozzle, however.



*Figure 6: Infra-red image of methane release*

Combustible Gas Indicator (CGI)

Test

Gas leak demonstration tests were conducted on March 9, 2006 in Fillmore, California. Methane was released from compressed tanks at a rate of 5000-scft per minute. The UAV was flown over the known leak location and the combustible gas indicator attempted to detect the presence of organic vapors from the methane release. Full integration of the sensor into the UAV was not accomplished and thus there was no real-time monitoring of the detector. The CGI sampled every second but only recorded readings every 15 seconds. The mission was flown and the sensor was analyzed after the UAV landed. The methane release was cleared by both the Ventura County Fire Department and the Ventura County Air Pollution Control.

Test Setup

The test for the CGI was set up in the same manner as the gas leak test for the infrared camera (see section 2.1.1 above).

Test Results

Test Number	Leak Magnitude (scft/min)	Go / No-Go	Notes
1	5000	Go	Methane leak was detected, however, there was no real-time relay of CGI sensor data to the ground station. Leak location therefore would be unknown without further development and integration into the UAV.

Several passes were made over the gas release and then returned to the ground station. Post processing showed that the CGI did detect the methane release. It could not be determined on which pass the CGI detected the airborne methane without real-time data downlink.

## Liquid Leak Detection

Liquid leak detection tests were conducted using an Indigo infrared camera and a standard color camera looking for dead vegetation.

### Infrared Camera

#### Test

Liquid leak demonstration tests were conducted on February 22, 2006 in Simi Valley, California. An inert liquid was heated to 90 degrees F and poured into two controlled “spill” areas. The UAV was flown over the known “spill” location with an infrared camera. The test determined the ability for the infrared camera to detect the heated liquid against the ground.

#### Test Setup

An inert liquid was heated to 90 degrees F (to approximate liquid crude in a pipeline) and poured into two controlled “spill” areas. The “spill areas” were small holes dug into the ground and lined with plastic. One hole held approximately 3 gallons of fluid and the second held approximately 6 gallons of fluid. Figure 7 (below) shows the test setup from the ground.



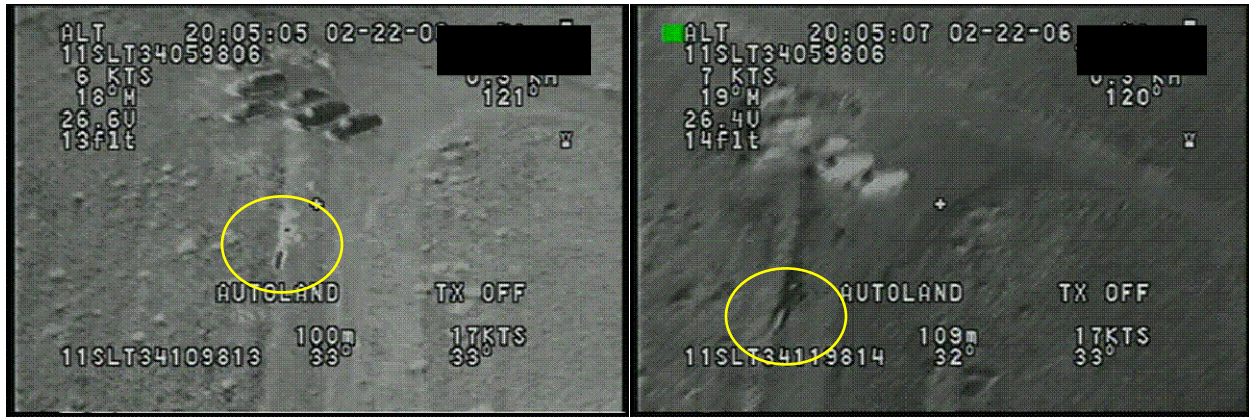
*Figure 7: Liquid leak “spill” setup*

#### Test Results

Test Number	Leak Magnitude (gallons)	Go / No-Go	Notes
1	3	Go	Leak easily seen in both white hot and black hot settings.
2	6	Go	Leak easily seen in both white hot and black hot settings.

The infrared camera could easily detect both the small (3 gal.) and large (6 gal.) simulated spills as the UAV flew over the site. Figures 8 and 9 below show the spill image in white hot and black hot settings.





*Figure 8 (left) shows the simulated liquid leak in “black hot” setting with the infrared camera. Figure 9 (right) shows the simulated liquid leak in “white hot” setting with the infrared camera.*

Dead Vegetation

Test

Leak demonstration tests were conducted on February 22, 2006 in Simi Valley, California. Sample dead vegetation was placed near a pipeline and surrounded by live vegetation. The demonstration test determined the ability of the color camera to detect dead vegetation as a possible indicator of a pipeline leak.

Test Setup

Six square feet of dead vegetation was placed on the ground surrounded by fourteen square feet of live vegetation. The UAV was flown above the known location of the dead vegetation.

Test Results

Test Number	Amount of Dead Vegetation	Go / No-Go	Notes
1	6 ft <sup>2</sup>	Go	Vegetation could be distinguished from the UAV camera image. (May have been difficult had the location been unknown.)

The dead vegetation could be seen from the UAV using the color camera. Figure 10 (below) shows the dead vegetation as seen from the UAV color camera.



*Figure 10: Dead vegetation as seen with the UAV color camera*

### Building Counts

Building count demonstration tests were conducted using the standard UAV color camera.

#### House Counts

##### Test

House count demonstration tests were conducted on February 22 and June 7, 2006 in Simi Valley, California. Video imagery of houses was taken using the UAV color camera and then compared to existing overhead map information.

##### Test Setup

The UAV was flown adjacent to a select area of homes with the color camera recording the flight. Video imagery was then compared to overhead imagery from Google Earth. A qualitative and quantitative comparison was made between the two systems.

Figure 11 (below) is an aerial photograph of the area selected (from Google Earth). 42 homes can be seen from the overhead image.



*Figure 11: Overhead image of housing complex. 42 structures can be seen.*

Test Results

Test Number	Structures Seen from Google Earth	Structures Seen from UAV	Go / No-Go	Notes
1	42	42	Go	All structures could be seen with the UAV. The imagery from the UAV was higher quality and offered an orthographic view.

The flight over the test area showed that the color camera mounted on the UAV has more than sufficient resolution to easily pick out individual structures. Figure 12 (below) is a sample of the imagery taken of the housing development.



*Figure 12: Sample imagery of housing complex taken by the UAV*

## Identification of High Consequence Structures

### Test

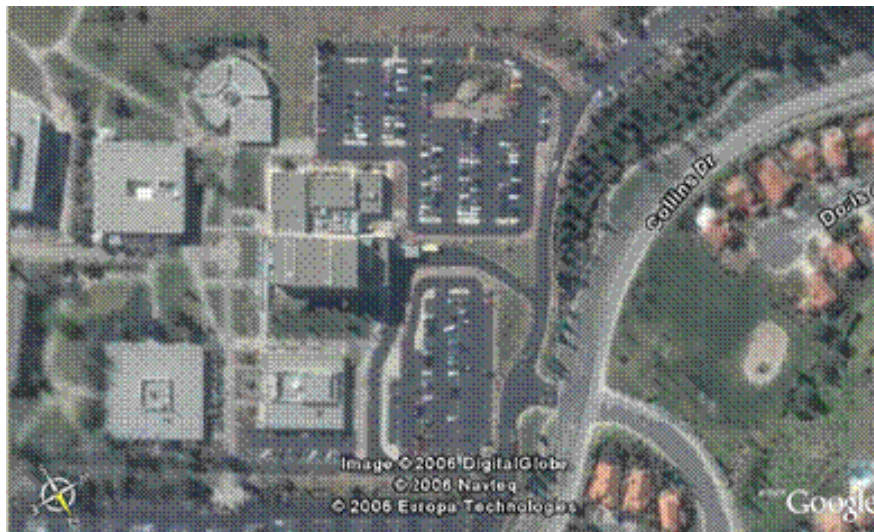
The UAV was flown adjacent to a known high consequence structure (Moorpark Community College). The imagery from the UAV was compared to imagery taken of the same location on Google Earth.

### Test Setup

The UAV was flown adjacent to the known location of Moorpark Community College (using GPS coordinates). Imagery taken with the UAV utilizing a color camera was compared to overhead aerial imagery (from Google Earth) of the same location. A qualitative comparison was made between the two images.

### Test Results

Test Number	Image from Google Earth	Image from UAV	Go / No-Go	Notes
1	Figure 13	Figure 14	Go	Image from UAV had better resolution and gave an orthographic view of the structure as compared to the Google Earth image.



*Figure 13: Overhead aerial imagery of Moorpark Community College (from Google Earth)*



*Figure 14: Image of Moorpark Community College taken from UAV*

Pipeline Right-of-Way

Test

This test determined the ability of the UAV to fly a pipeline right-of-way track based on a series of set GPS coordinates.

Test Setup

A series of 12 waypoints were loaded into the UAV flight plan. The UAV was flown autonomously over the 12 GPS points. Right of way markers were placed at each GPS waypoint. A qualitative analysis of the ability to follow the right-of-way was then made.

Test Results

Test Number	GPS Waypoint (military system: 11SLT-)	Waypoint Reached? (Yes/No)	Marker Visible? (Yes/No)	Go / No-Go	Notes
1	34149 97981	Yes	No	Go	Waypoint reached but marker not seen from UAV.
2	34280 97961	Yes	No	Go	Waypoint reached but marker not seen from UAV.
3	34487 97955	Yes	No	Go	Waypoint reached but marker not seen from UAV.
4	34674 97884	Yes	No	Go	Waypoint reached but marker not seen from UAV.

5	34658 97798	Yes	No	Go	Waypoint reached but marker not seen from UAV.
6	34544 97675	Yes	No	Go	Waypoint reached but marker not seen from UAV.
7	34419 97518	Yes	No	Go	Waypoint reached but marker not seen from UAV.
8	34141 97120	Yes	No	Go	Waypoint reached but marker not seen from UAV.
9	34163 97074	Yes	No	Go	Waypoint reached but marker not seen from UAV.
10	33959 97030	Yes	No	Go	Waypoint reached but marker not seen from UAV.
11	33763 96922	Yes	No	Go	Waypoint reached but marker not seen from UAV.
12	33679 96874	Yes	No	Go	Waypoint reached but marker not seen from UAV.

All 12 waypoints were reached without difficulty. The aerial markers placed at each point were not visible from the air. Overall the test showed that the UAV can fly autonomously along a pipeline right-of-way if accurate GPS coordinates are entered into a flight path.

#### Encroachment Detection

##### Test

This test determined the ability of the UAV to identify encroachment on pipeline rights of way.

##### Test Setup

The UAV was flown over areas with vehicles and personnel to determine the ability of the UAV color and infrared cameras to detect right-of-way encroachment.

##### Test Results

<b>Test Number</b>	<b>Encroachment Type</b>	<b>Camera Type</b>	<b>Go / No-Go</b>	<b>Notes</b>
1	Vehicular	Color	Go	Vehicles clearly visible. GPS locations given by UAV.
2	Vehicular	Infrared	Go	Vehicles clearly distinguishable. GPS locations given by UAV.
3	Personnel	Color	Go	Personnel clearly visible. GPS locations given by UAV.

4	Personnel	Infrared	Go	Personnel clearly distinguishable. GPS locations given by UAV.
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Figure 15 (below) is a color image taken from the UAV clearly showing vehicles and personnel near the simulated pipeline right-of-way. Figure 16 (bottom) is an infrared image taken from the UAV showing vehicles and personnel near the simulated pipeline right-of-way.



**Figure 15: Color image of pipeline right-of-way encroachment. Both vehicles and personnel are clearly seen.**



**Figure 16: Infrared image of pipeline right-of-way encroachment. Both vehicles and personnel are clearly seen.**

GPS Accuracy

Test

A selection of GPS coordinates taken from the UAV are compared to GPS coordinates taken from the same points on the ground. This test determined the accuracy of using the UAV to pinpoint GPS locations.

Test Setup

Three ground points were selected and ground GPS coordinates taken. The UAV was flown over each point and the GPS coordinate was taken. The GPS taken from the UAV was then compared to the coordinates taken from the ground.

Test Results

			MGRS	Decimal		DMS		Error
				Lat (N)	Lon (W)	Lat	Lon	
1	Road Intersection	Handheld	11SLT3417298144	34.311	118.802	34° 18' 39.6"	118° 48' 7.2"	None
		UAV	11SLT3418098120	34.311	118.802	34° 18' 39.6"	118° 48' 7.2"	
2	Truck	Handheld	11SLT3466597007	34.301	118.797	34° 18' 3.6"	118° 48' 49.2"	None
		UAV	11SLT3464097010	34.301	118.797	34° 18' 3.6"	118° 48' 49.2"	
3	Construction Equipment	Handheld	11SLT3560996445	34.296	118.786	34° 17' 45.6"	118° 47' 9.6"	90 m
		UAV	11SLT3551096380	34.296	118.787	34° 17' 45.6"	118° 47' 13.2"	
4	Simulated Liquid Leak	Handheld	11SLT3413498131	34.311	118.803	34° 18' 39.6"	118° 48' 10.8"	90 m
		UAV	11SLT3419098110	34.311	118.802	34° 18' 39.6"	118° 48' 7.2"	

The UAVs currently display their GPS coordinates in the Military Grid Reference System (MGRS) or in decimal format. MGRS was chosen for standardization between the UAV and the handheld GPS device.

MGRS was converted to decimal using a web-based converter on the National Geospatial Intelligence Agency website:

[http://geoengine.nga.mil/geospatial/SW\\_TOOLS/NIMAMUSE/webinter/rast\\_roam.html](http://geoengine.nga.mil/geospatial/SW_TOOLS/NIMAMUSE/webinter/rast_roam.html)

The decimal coordinates were converted to Degrees-Minutes-Seconds using a web-based converter on the Federal Communication Commission website:

<http://www.fcc.gov/mb/audio/bickel/DDDMSS-decimal.html>

The 90 meter error calculated is significantly larger than the manufacturer's error (less than 10 meters). Therefore, the larger 90 meter error is likely due to errors converting MGRS to Degrees-Minutes-Seconds.

**Conclusion**

The demonstration tests were successful in showing that small UAVs with commercial sensors can be used for a variety of pipeline surveillance missions. Current sensor technology and UAV configurations can conduct the following pipeline missions:

1. Liquid leak detection
2. Gas leak detection by spotting dead vegetation
3. House counts
4. Identifying high consequence structures
5. Autonomously flying a pipeline right-of-way
6. Encroachment detection
7. GIS data production and validation.



The UAV additionally showed promise in several areas that will require further development to make completely successful. These include:

1. Gas leak detection using infrared cameras
2. Gas leak detection using a combustible gas indicator
3. GIS integration into user systems.

## SYSTEM ANALYSIS

This section provides analysis, from a system level, of the ability of small unmanned air vehicles (UAV) to perform pipeline inspection missions. A series of proof of concept demonstration tests were conducted from December 2005 through June 2006. These tests were used to determine the ability of a UAV, using commercially available sensors, to perform a variety of pipeline surveillance missions.

These tests demonstrated that a small UAV can perform a variety of pipeline surveillance missions currently being conducted by other means. The UAV, in many cases, improves upon the current methods by being more flexible, user friendly, less labor intensive, and safer than other aerial and ground surveillance methods.

### ***Small Unmanned Air Vehicle Platform***

This program looked at the feasibility and applicability of utilizing current U.S. military small unmanned air vehicles (UAVs) to conduct a variety of pipeline surveillance and monitoring missions. A UAV system is comprised of three major components: the aircraft, the ground control unit, and support equipment (including batteries, battery charger, and video recorder). The proof of concept tests conducted in February 2006 showed that a small UAV can be used to conduct many of the missions currently being serviced by fixed and rotary wing assets.

#### Aircraft

Two different aircraft platforms were tested to compare the relative benefits and drawbacks for each type. Both systems are electric motor driven powered by rechargeable batteries (primary batteries are also an option but were not used in this testing). The two platforms selected were the AeroVironment “Puma” and AeroVironment “Raven.” Figures 17 and 18 below show the Puma and Raven.



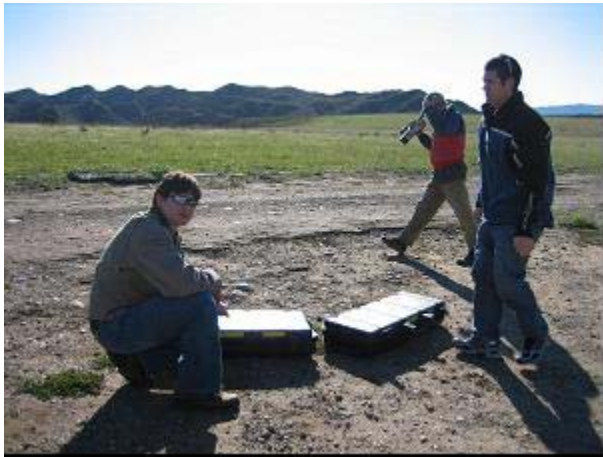
***Figure 17: AeroVironment “Puma” UAV***



***Figure 18: AeroVironment “Raven” UAV***

Both systems are broken into component pieces and stored into hardened plastic cases for storage and transport. The entire system, including aircraft, ground control unit, and support equipment

is easily transported in the back of a truck or car. The smaller Raven can be backpackable. Figure 19 shows the stored UAV and Figure 20 show the assembled Puma system.



*Figure 19: UAV cases*



*Figure 20: Final Assembly*

### Puma

The Puma is a 10 to 12 pound UAV with a 8.5 foot wingspan. The Puma is the larger of the two platforms and is capable of carrying two batteries (for extended flight time) and up to four sensors (two forward looking and two side looking). Flight times can be maximized at four hours with the use of two primary batteries. The range is currently 10 kilometers line-of-sight, however, this could be extended by using repeater stations.

The advantage of the Puma system is the larger payload and increased flight endurance. This allows the operator to carry both color and infrared cameras on a single flight. The aircraft is a little larger and heavier than the Raven, however, not to a degree as to make it difficult for the operator to assemble, launch, use, or recover.

### Raven

The Raven is a 4.2 pound UAV with a 4.5 foot wingspan. The smaller Raven can only carry one forward and one side looking payload. Flight times are 60 to 90 minutes with a range of 10 kilometers line-of-sight.

The smaller payload capability and shorter endurance is a drawback to using this system for pipeline surveillance. The Raven was designed for use by U.S. military units and is compact and lightweight. The requirement for a smaller and lighter weight system is not as important for commercial applications, and thus the Raven does not provide any significant advantages over the Puma.

### Analysis

Based on the flight testing performance, the Puma platform appears to offer the best commercial applications for pipeline surveillance. The increased endurance and the larger payload capacity

(ability to carry color and infrared cameras (or another type of sensor) simultaneously) offer an advantage over the Raven.

### **Ground Control Unit**

The ground control unit (GCU) consists of controllers (for piloting the aircraft), an antenna to communicate with the UAVS, and a laptop for mission planning and tracking. The GCU is common to both the Puma and Raven systems. The GCU is small and easy to use. The GCU is easily useable for commercial applications and will require no modification for pipeline surveillance missions. Figures 21 and 22 (below) show pictures of the GCU.



*Figure 21: Ground Control Unit*



*Figure 22: GCU with laptop, operators and test observers*

### **Support Equipment**

Other support equipment used included a battery charger and a video recorder. These items are critical for operations in support of pipeline surveillance missions. Two types of batteries are required for the UAV system. One type to power the aircraft and one type to power the GCU. The GCU battery is a military type BB-390 rechargeable battery. The two types of batteries currently require separate battery charging infrastructure. The video recorder is a commercial off-the-shelf item and can be chosen by the operator based on desired recording features. Recording directly to a laptop is another acceptable option.

The standard military small UAV support equipment was easily adapted to the pipeline surveillance mission. Additional development to reduce the size and weight of the ground support equipment will greatly assist a commercial customer.

### **Sensors**

#### Electro-Optical Cameras

The small UAV can be outfitted with color and black and white electro-optical cameras. The project team utilized only the superior color cameras during the demonstration testing. The

black and white cameras are used for low light conditions and may have some applicability in areas that experience long periods of low light conditions.

Specifications for each type of camera are:

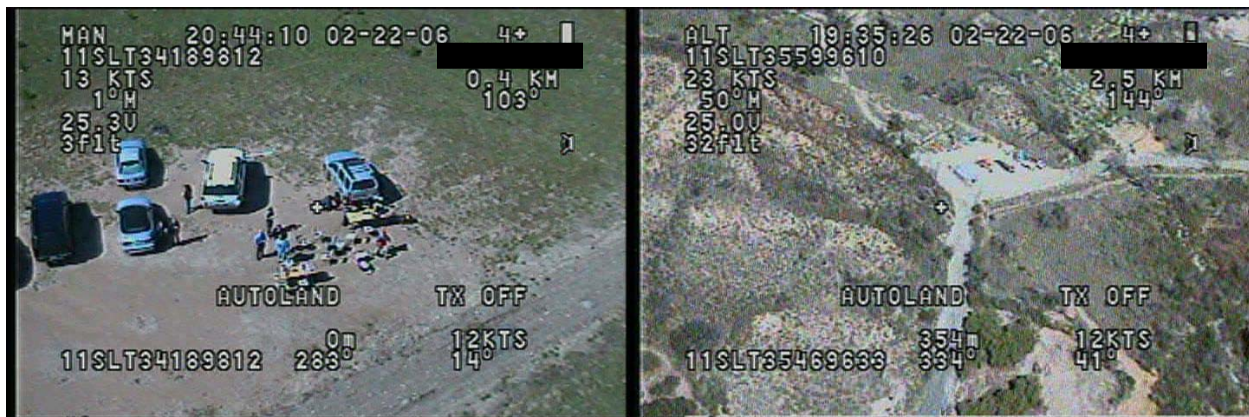
*Color Camera:*

- Spectral Sensitivity: approximately 300 to 700 nanometers (nm)
- Resolution: NTSC or greater
- Minimum Illumination: 2.0 Lux

*Black and White Camera: (low light conditions)*

- Spectral Sensitivity: 300 to >700 nm
- Resolution: NTSC
- Minimum Illumination: 0.2 Lux

Figures 23 and 24 (below) are sample images taken by the UAV utilizing the standard military grade small UAV color camera. The camera resolution is clear enough to distinguish people, vehicles, structures, and other moderately sized to large objects. The resolution was not good enough to identify smaller objects (less than 12" diameter) including aerial pipeline markers.



**Figure 23: Demonstration of color camera resolution**

**Figure 24: Demonstration of color camera resolution**

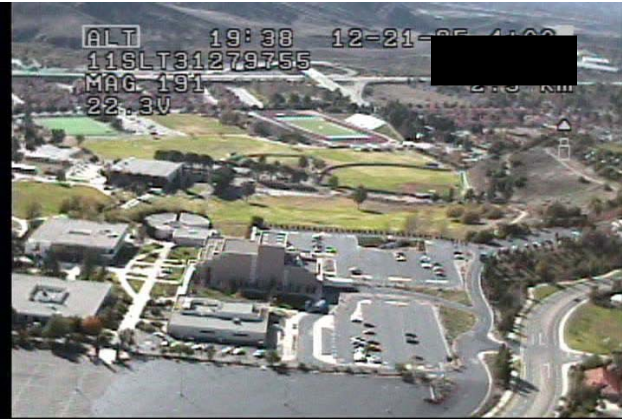
Color camera performance for different missions is discussed below:

House Counts

The standard color camera has the resolution to easily identify individual houses and other buildings that could influence the classification of an area. Figures 25 and 26 below show images of houses and a school taken during the demonstration tests.



**Figure 25: House count demonstration**



**Figure 26: Identification of a community college in high consequence area**

### Encroachment Detection

Vehicles, people and other large objects are easily distinguished with the color camera. Based on the demonstration tests, encroachment detection can be readily accomplished with the color camera mounted on the small UAV. Figure 23 above clearly shows vehicles and people.

### Leak Detection (spotting dead vegetation)

Dead vegetation was visible under the demonstration conditions. The demonstration placed six square feet of dead vegetation on the ground surrounded by live vegetation. While this can be seen for the UAV, it would have been difficult to distinguish if the location of the vegetation was not previously known. Figure 27 below shows an image of the dead vegetation taken from the UAV. A larger area of dead vegetation may have been much easier to see.



**Figure 27: Image of dead vegetation detection test**

Overall the color camera is an excellent sensor for use in daylight surveillance missions. One drawback is that currently the camera is not stabilized within the UAV. Therefore, under high wind conditions, the UAV's pitch, roll, and yaw can result in an unsteady image.

The current color camera technology is assessed to be more than sufficient for most pipeline surveillance missions. While the pipeline industry could take advantage of developments made in defense on these products, no further immediate development work is required for pipeline surveillance missions.

### Infrared Cameras

The infrared camera used in the demonstration testing is manufactured by FLIR Systems and their sister company INDIGO. The product brand is Omega. Omega is a Commercial, Off-The-Shelf (COTS) IR camera.

Three missions were flown with the infrared camera, including: right-of-way monitoring, liquid leak detection and gas leak detection.

#### Right-of-Way Monitoring

The Omega infrared camera was successful at identifying people and vehicles near a pipeline right-of-way. This can be useful in monitoring encroachment in low light or night flying conditions. This feature could also be used for security of pipelines at night. Figure 28 below is an image of vehicles taken from the Omega infrared camera during the demonstration tests.



*Figure 28: Infrared image of vehicles and people*

#### Liquid Leak Detection

The sensor was able to see both a small and large test spill of a heated inert liquid. The liquid was heated to approximately 100 degrees F and poured into lined pits in the ground. The small spill was approximately 3 gallons of liquid and the large spill was approximately 5 gallons of liquid. Figure 29 below shows an image of the small and large spills.

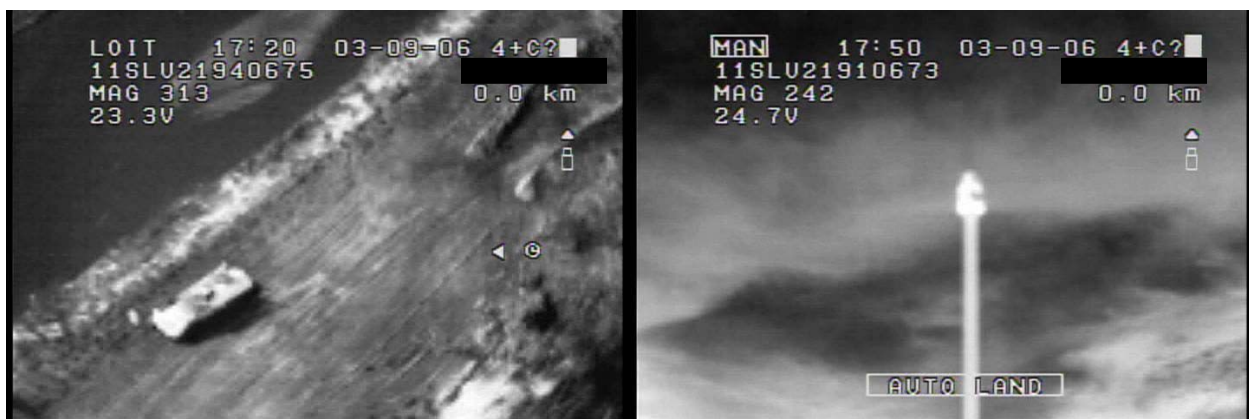


**Figure 29: Infrared image of controlled heated inert liquid spill**

### Gas Leak Detection

The infrared sensor was unable to see the temperature change caused by released airborne methane. Prior calculations indicated that the infrared sensor used for the testing would be unlikely to capture the methane released as the wavelength of the methane gas was at the very edge of the spectrum for the infrared sensor available. The infrared sensor was designed for sensing hot objects such as heated liquid, engines, and people.

The demonstration test confirmed that the standard UAV infrared sensor used could not detect the methane wavelength or a localized air temperature change from the methane release. Two tests of the sensor were conducted. The first involved flying the sensor on the UAV over a known methane release point. The second test consisted of holding the infrared sensor 4 feet from the known methane release point. The sensor could not detect the methane under either condition. Figures 30 and 31 below show the infrared signature of the methane release from the airborne UAV and from the ground.



**Figure 30: Infrared image of methane release area**      **Figure 31: Methane release from ground perspective**

The demonstration tests of the Omega infrared camera showed that it can be used for encroachment monitoring and liquid leak detection without further modification. Gas leak



detection appears to be impossible with the Omega sensor. Further testing of other available infrared sensors that are tuned to different wavelengths may find an infrared sensor capable of detecting a methane gas release and would be worth pursuing.

### LIDAR

The project team initially looked at testing a handheld LIDAR system from Physical Sciences, Inc. Unfortunately, this system was not immediately available for integration with the small UAV for the current proof of concept phase of testing. The LIDAR system has potential for gas leak detection from a small UAV platform. Tests utilizing the hand-held LIDAR technology should be conducted after further development, including ruggedization, is complete.

### GPS

The current military configuration gives GPS in either Military Grid Reference System (MGRS) or decimal. A certain degree of error is introduced when MGRS is converted to degrees-minutes-seconds (DMS). Additionally, the UAV only gives an 8 digit MGRS versus a 10 digit MGRS from a handheld GPS device. This further decreases the accuracy. The demonstration tests showed that this introduced an error 50% of the time. The conversion error typically introduced a 90 meter difference in DMS coordinates. However, this error is small enough so that an operator would easily be able to get to the general area identified by a UAV. Further development is required to ensure the UAV gives GPS coordinates in the format to be used by pipeline operators without inducing the translation error in the method used in this testing.

### Combustible Gas Indicators (CGI)

Tests were conducted using a combustible gas indicator that could detect concentrations of methane. Two tests were conducted under similar conditions as the infrared sensor tests. The sensor could not detect the leak while airborne on the UAV. However, the sensor was able to detect the gas leak under the controlled conditions on the ground. This is most likely due to the mechanics of how the combustible gas sensor reports what the sensor detects. While the sensor takes a reading every 0.5 seconds, it only records that reading every 15.0 seconds. Due to the speed of the UAV in flight, it is unlikely that a UAV flying over a pipeline leak would be over the leak at the same time the sensor is recording a reading. Additional development to increase the number of recorded sampling points by the combustible gas indicator could solve this problem.

## ***Data Processing***

### Digital Imagery

Currently, the small UAV sends the video image real time to the GCU. The UAV pilot sees what the UAV sees. This image can be shown on a second small screen, laptop, or full size monitor. The image can also be recorded on a standard commercial off-the-shelf recorder on Mini DV tapes. Figure 32 below shows the recorder used for this demonstration.



*Figure 32: Mini DV recorder*

Post processing of the video is required to transfer the video on Mini DV to a digital format. Once digitized, still screen shots can be taken. Image enhancement is also possible through post processing.

The system is designed for military use where soldiers need the images real-time and react immediately to the information. Pipeline surveillance missions have a greater need for saving the digitally recorded video so that it can be accessed by users. Further development is required to determine which format and processing method would be most beneficial to the pipeline industry.

#### Other Data Processing

##### Combustible Gas Indicator

The combustible gas indicator sensor used during the testing was modified from a handheld sensor. The data from the sensor was not transmitted real time to the operator on the ground. Under the current configuration, the sensor records readings while the UAV is in flight and then the sensor data is analyzed after the UAV lands. The major drawback to this is that the UAV pilot is not able to immediately fly back to a point if the combustible gas indicator gets a positive reading. It would be beneficial to use the different sensors (color camera, infrared and combustible gas indicator) in conjunction with each other to assist in confirming any positive gas leak readings one sensor receives.

Further development is recommended to enable real-time transmission of the combustible gas indicator reading to the GCU. Combining the combustible gas indicator readings to the GPS coordinated and visual images would allow for better confirmation of any positive readings for gas leaks.

## GPS

The GPS location of the small UAV and the calculated GPS location of the target are displayed on the GCU and recorded to the Mini DV. This information can also be displayed on a laptop computer real-time using FalconView. FalconView is a Windows mapping system that displays various types of maps and geographically referenced overlays, and is an integral part of the Portable Flight Planning Software (PFPS). Currently, FalconView is the mapping system in widest use by the US military for small UAVs and other applications.

Further development and testing is required to determine if the GPS data from the small UAV can easily be integrated into the GIS mapping systems currently in use by the pipeline industry.

## SYSTEM PLANNING

This section outlines recommended follow-on phases to this program to build on and address application development issues identified in the proof of concept phase.

### ***Completion of Phase I Objectives***

The objectives of Phase I of this project were to first identify the various pipeline surveillance missions that could be serviced by a small UAV and second to conduct proof of concept demonstration testing to determine the ability of the small UAV to accomplish these missions.

#### Mission Identification

The project team identified two main missions that could be serviced by small UAVs. The first was aerial surveys and the second was leak detection. Under the aerial survey mission, Electricore identified right-of-way monitoring, encroachment detection, and house counting as individual tasks to be conducted by aerial assets. The leak detection mission was subdivided into gas leak detection and liquid leak detection as individual tasks. Based on the mission profiles and requirements, different sensors were identified and selected for testing.

#### Proof of Concept Demonstration Testing

A series of ground and flight tests were conducted to determine the ability of the small UAVs and selected sensors to accomplish the pipeline aerial surveillance missions identified above. These tests were conducted over a three-month period from December 2005 through February 2006. The tests were able to determine which missions could be met by current small UAV platforms, commercially available sensors, and little further development cost.

### ***System Benefits***

The small UAVs and commercial sensors provide the pipeline operator with a cost effective, easily transportable, and reliable alternative to fixed- and rotary-wing aerial assets. As opposed to conventional fixed- or rotary-wing assets that require an airfield, aviation fuel, and extensive maintenance; the small UAVs are hand launched, battery powered (rechargeable), easily transported in the back of a vehicle, and require little maintenance. The color imagery (video) has sufficient resolution to identify and locate pipelines, vehicles, people, houses, high consequence buildings, road crossings and other items of interest. **The infrared camera is able to easily show vehicles, people, and heated liquid from a spill.** The data is relayed real-time to the operator and can be recorded using a simple commercial off the shelf Mini DV system.

Additional benefits include the fact that the small UAVs operate off of rechargeable batteries instead of fuel. **After landing, the UAV operator can replace the low battery with a fully charged battery and be back in the air in less than 2 minutes.** The UAV is also extremely durable (designed for use in combat operations being conducted by the U.S. Special Forces under

extreme conditions) and can easily survive multiple take offs and landings with minimal maintenance requirements.

### ***System Improvements***

The main system shortfall is that available SUAVs are currently configured to specifically address the needs of the military. Specific issues include:

- Post processing required to convert recorded video into a digital format
- Lack of integration of GPS data into a civilian GIS program
- No confirmed commercial off-the-shelf gas leak detection sensor
- No common battery charging infrastructure.

The issues regarding post-processing and GIS integration will require further development in conjunction with an industry partner in order to address their specific industry requirements and formats. Continued searches of the current state of sensor technology will assist in determining if there is other potential methane sensors available that have the specifications required to be flown on a small UAV. Additional lab and demonstration testing on any identified sensors would confirm any search results.

### ***Recommended Phase II Project***

Electricore recommends a follow-on Phase II series of Application Development be conducted in conjunction with a pipeline operator to optimize the small UAV for pipeline missions. This phase would include additional development, system modification, and demonstrations testing and analysis. These proposed additional tasks are in accordance with the follow on activities originally proposed to the DOT to continue to develop this promising aerial surveillance technology and quickly bring a valuable product to market.

Application Development: will focus on refining the aircraft, sensor, software, associated hardware, and user interfaces to meet the requirements of pipeline operators. Current technology is taken from an exclusively military application and additional development work is required to tailor the UAV and sensor technology to the commercial pipeline mission. This phase will be conducted in close coordination and cooperation with a pipeline operator to provide expert advice on industry needs.

Potential tasks include:

- Integrate advanced sensor payloads including but not limited to:
  - Combustible Gas Indicators
  - Handheld LIDAR
  - Infrared sensors (tuned to the wavelength of methane).
- Develop GPS navigated (waypoint to waypoint, non-line-of-sight) flight capability to fly long distance (100 miles +) pipeline routes. Potential subtasks include:

- Engineering feasibility study
  - Data transmission/storage options study
  - Proof of concept testing.
- 
- Integrate GIS data from UAV into existing GIS architecture used by pipeline operators.
  - Develop pilot user interface on Ground Control Unit tailored for the pipeline mission.
  - Develop “direct to digital” recording in order to eliminate the post-processing requirement.
  - Reduction of battery charging infrastructure through use of common charging techniques.

Demonstration Testing: will provide a realistic, test and demonstration phase to measure the performance of small UAVs against fixed- and rotary-wing assets. This phase will be conducted under real-world conditions at an operating pipeline (with the support of a pipeline operator). Potential tasks include:

- Conduct test demonstrations and performance measurements for the small UAVs under real-world conditions. Tests will include:
  - Leak detection, including:
    - Gas leaks
    - Liquid leaks
  - Aerial surveillance, including:
    - Right-of-way monitoring
    - Encroachment detection
    - House counting
  - GIS/Video integration.

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