GAS BEARING CENTRIFUGAL COMPRESSOR SYSTEM FOR RADIOXENON MONITORING

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ABSTRACT

Radioxenon monitoring systems are an important tool for detecting nuclear weapon tests around the world. These systems must be reliable and have low contamination potential because detection opportunities are brief and accurate measurements are critical. A compressor is a key component in these systems, and commercial compressors cannot satisfy system requirements for contamination-free operation and reliability. However, Creare Incorporated has been developing miniature, gas-bearing, centrifugal compressors for over three decades for long-life space cryocoolers, including one unit that operated on the Hubble Space Telescope for over 6.5 years without maintenance or performance degradation. The maintenance-free reliability and low contamination requirements for these systems have produced components with very attractive characteristics for radionuclide monitoring. Distinguishing characteristics include: (1) hydrodynamic gas bearings and clearance seals eliminate wear and maintenance, (2) spaceflight heritage provides high reliability, (3) all-metal seals eliminate leakage and permeation, (4) limited organic materials and virtual leaks minimize outgassing, (5) high rotational speeds help minimize size and mass, and (6) small, precisely balanced, high-speed rotor assemblies reduce vibration below measurable levels. For a recently started NNSA project, we plan to apply our compressor technology to radioxenon monitoring systems. This paper provides a detailed description of our planned approach.

OBJECTIVES

The focus of our project is to develop a compact, lightweight, oil-free compressor system to enhance radionuclide monitoring. Our approach utilizes miniature, gas-bearing, centrifugal compressor technology that Creare has developed over three decades for turbo-Brayton cryocoolers that support space-based infrared detectors and other critical applications. The reliable maintenance-free operation and low contamination requirements for these systems have produced components with very attractive characteristics for radionuclide monitoring. Successful completion of this program will improve nuclear explosion monitoring capabilities and enhance global safety and security.

Figure 1 provides a conceptual design for the compressor system we are developing, and Figure 2 is a schematic representation. The system includes two centrifugal compressors with integral heat exchangers, an inlet filter, power and control electronics, and a small air blower. For this design, we assumed the compressor flow rate is 0.80 g/s (40 slpm) of air, the inlet pressure is 101 kPa, and the outlet pressure is 608 kPa. Our preliminary estimates indicate the overall dimensions will be 13 cm (5.0 in.) by 17 cm (6.6 in.) by 29 cm (11.4 in.), the mass will be 7.7 kg (17 lb), and the required electric power will be 312 W at 120 VAC. These size and mass estimates include a protective enclosure, support structures, and wire harnesses, which are not shown in Figure 1. An alternative embodiment of our design could use an externally supplied liquid flow stream for cooling, which would reduce the size of the heat exchangers, eliminate the blower, and reduce electric power consumption.

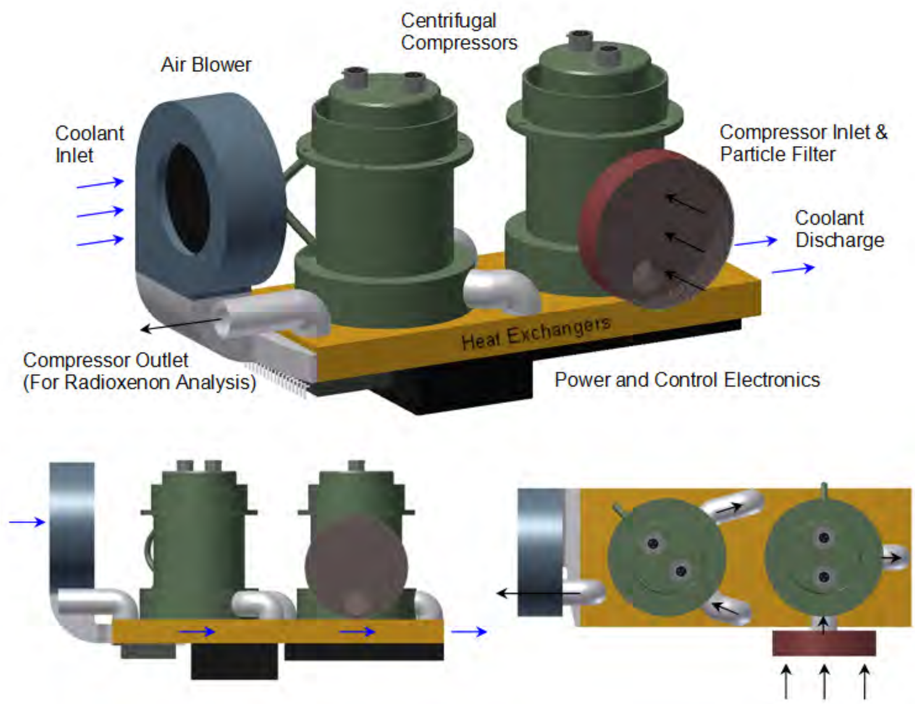

Figure 1. Compressor system conceptual design.

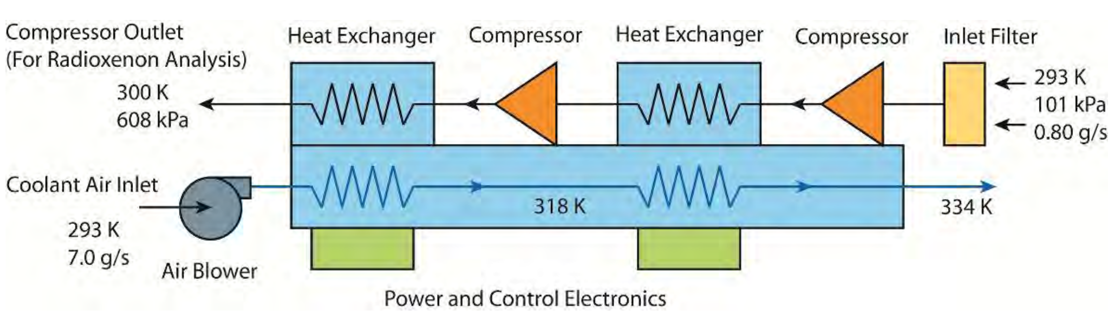

Figure 2. Compressor system schematic.

Our compressor system builds on proven technology for miniature, high-performance turbomachines and turbo-Brayton systems that Creare has developed for critical aerospace and terrestrial applications. These components and systems have satisfied rigorous National Aeronautics and Space Administration (NASA) and Department of Defense (DoD) requirements for reliability, endurance, vibration emittance, launch tolerance, electromagnetic interference and susceptibility, and environmental cycling (Breedlove et al., 2001; Dolan et al., 1997). One such system is a turbo-Brayton cryocooler that operated on the Hubble Space Telescope for over 6.5 years without maintenance or performance degradation while meeting all mission requirements (Swift et al., 2008). More recently, we made significant improvements in the manufacturing readiness level of our technology for a classified DoD application (Zagarola et al., 2008). These systems have demonstrated compressors at the size, power level, and rotational speed required for radionuclide monitoring systems. Figure 3 contains photographs of existing Creare technology that is appropriate for the planned compressor system.

Figure 3. Existing Creare technology appropriate for planned compressor system.

Reliability is Critical for Radionuclide Monitoring

Radionuclide monitoring is an extremely important tool for detecting nuclear explosions. A variety of space-based and ground-based sensors provide optical, radiation, seismic, hydroacoustic, and infrasound data that identify, measure, and locate events consistent with nuclear detonation. However, radionuclide measurement is the only technique that provides irrefutable proof of a nuclear explosion and specific information about the nuclear reaction employed. Pacific Northwest National Laboratory has led the development of two measurement systems that detect different types of radionuclides. The Radionuclide Aerosol Sampler/Analyzer (RASA) collects airborne particles and determines whether they contain fission products (Miley et al., 1998), while the Automated Radioxenon Sampler/Analyzer (ARSA) collects xenon gas from the air and measures the ratio of radioactive isotopes (Bowyer et al., 1996). Although the ARSA system is more complex, it is essential because most underground detonations do not liberate radionuclide particles.

The reliability of radionuclide monitors is critical. Measurement must be continuous because nuclear detonations can occur without warning, and a radionuclide plume from an underground test can pass by a monitoring station in just a few hours (Perkins and Casey, 1996). In addition, some radionuclides that are important to measure have relatively short half-lives such as ^{135}Xe (9.1 hr). Continuous measurement also provides accurate background levels, which can be important for detonations with low discharge levels. Although nuclear explosions produce unique xenon isotope ratios, the ability to measure these ratios accurately can be impaired at low levels. For these events, it may only be possible to measure an increase above background levels, which are also influenced by nuclear reactor operations, nuclear fuel reprocessing, and medical isotope production and usage.

The ARSA001 engineering prototype used a piston compressor to sample air from the atmosphere. System testing during the International Noble Gas Experiment in Guangzhou, China, identified several reliability shortfalls. Specifically, Rynes et al. (2004) report the system was inoperable 34% of the test time, and the system was off line 9.3% of the test time because of compressor failures. Electronics modifications should be able to address some of the reliability problems observed. However, alternative compressor technology is also needed to eliminate the 9.3% down time attributed to the piston compressor.

Commercial Compressors Are Not Appropriate for Radioxenon Systems

The required compressor characteristics for a radioxenon monitoring system are severe. In particular, the requirements for size, mass, reliability, and lack of contaminants that can migrate into the process gas make current commercial technology unsuitable. Commercial piston, diaphragm, and scroll compressors can meet the flow and pressure rise requirements. However, piston and scroll compressors typically use oil- or grease-lubricated bearings. Although design strategies can help isolate the bearings from the gas flow, these measures only reduce the amount of contamination in the process gas, and do not eliminate it entirely. Diaphragm compressors can eliminate oil contamination completely, which is why they are often used in the food and medical fields where contamination of the process fluid is unacceptable. These compressors are typically quite large due to limitations of speed and compression volume. An additional drawback with all of these compressor types is that they use reciprocating forces that create vibration, typically in the 30 to 120 Hz range. Additional components can be included to isolate or cancel this vibration, but these devices add size and mass, which is undesirable for a compact, lightweight system.

Centrifugal compressors are ideal for radioxenon systems. High operating speeds make them compact and lightweight. In addition, many units have been developed for long-life, maintenance-free applications (e.g., air-cycle machines on aircraft). These units use non-contact gas bearings, and they can be manufactured from materials that will not contaminate the process gas. In addition, well-balanced rotors and high rotational speeds can make vibration negligible. The one drawback of centrifugal compressors for the current application is associated with their high energy density. For the relatively low flow rates required, the corresponding rotor is extremely small, having an impeller diameter that is less than 13 mm. At this small scale, operating speeds around 10,000 rev/s are required to meet the pressure rise requirements. To date, there has been no high-volume market for turbomachines with these characteristics. Consequently, appropriate commercial products do not exist. The few motor-driven centrifugal compressors that have been produced at the appropriate size, speed, and power level have been developed by Creare for space applications. The requirements that drove these designs also provide ideal characteristics for radioxenon systems. These characteristics include low volume and mass, low power consumption, maintenance-free reliability, and low contamination potential.

Gas-Bearing Centrifugal Compressor System

A gas-bearing centrifugal compressor system will provide the best combination of maintenance-free reliability, size, mass, and cleanliness for radionuclide monitoring. Creare developed the fundamental compressor technology required for this system largely to support long-duration (>10 year) space missions where reliability is critical and maintenance is not possible. The requirements for these applications caused us to eliminate wear and reduce particulate and condensable contamination to extremely minute levels. The resulting components and systems have completed a large number of rigorous qualification tests and long-term mission operations to establish their reliability and endurance. Table 1 provides a summary of the most significant demonstrations. The primary challenge for the current project is to optimize our technology for the specific requirements of a radioxenon monitoring system.

Table 1. Turbo-Brayton life and endurance demonstrations at Creare

Assembly or Hardware Description	Demonstration
Durability test rig (1982-1996) • 3.2 mm shaft • 11,000 rev/s	• 123,000 hours (14 years) in filtered air at 300 K • 2600 start/stop cycles during initial 10-year period with no maintenance
Turboexpander start/stop tests (1987) • 3.6 mm shaft	• 10,000 start/stop cycles in helium at 300 K • No anomalies or wear detected
Induction-motor compressor and inverter (2005) • 6.4 mm shaft	• 10,000 start/stop cycles in neon at 300 K • No anomalies or wear detected
5 W, 65 K Engineering Model cryocooler (1996-2000) • Compressor at 6,500 rev/s • Turboexpander at 8,500 rev/s • Single-stage CCE with manual controls	• 30,000 hours overall at nominal operating conditions • Known diffusion of moisture through O-ring seals caused minor performance degradation
Low-temperature cryocooler (2002-2003) • Two compressors in series at 9,200 rev/s • Dual-temperature turboalternator • Brassboard electronics	• 6,500 hours overall with no performance degradation • Temperatures down to 17 K
Orientation testing (2007) • Induction-motor compressor • Permanent magnet turboalternator	• 500 to 1,000 start/stop cycles in neon in each of four orientations • Ambient and 80 K tests for turboalternator
NICMOS circulator and inverter (1999) • 3.6 mm shaft	• 2,000 start/stop cycles in 300 K and 80 K neon • Flight unit and qualification units tested & inspected • No anomalies or wear detected
NICMOS cryogenic system (1998-2008) • Induction-motor compressor • Permanent magnet turboalternator • Cryogenic circulator • Cryocooler electronics	• 2 shuttle launches and one landing • 1,900 hours of ground testing • >200 start/stop cycles during ground testing • ~6.5 yrs operating time on Hubble Space Telescope

We created a thermodynamic model of our compressor system and developed conceptual component designs to specify preliminary characteristics, estimate size and mass, determine power requirements, and assess the top-level feasibility of our approach. The resulting component sizes, flow rates, temperatures, pressures, and operating speeds are consistent with prior units developed and demonstrated at Creare. Table 2 quantifies the most critical parameters in our conceptual design, and Table 3 provides mass estimates for the individual components and the overall assembly. In summary, we predict the overall dimensions will be 13 cm (5.0 in.) by 17 cm (6.6 in.) by 29 cm (11.4 in.), the mass will be 7.7 kg (17 lb), and the required electric power will be 312 W at 120 VAC. These predictions are based on scoping analyses, with physical features and performance characteristics scaled from other programs. The following paragraphs describe the primary components in our conceptual design.

Table 2. Critical parameters for conceptual design

Parameter	Value
Compressor Mass Flow Rate	0.80 g/s (40 slpm)
Inlet Temperature	293 K
Outlet Temperature	300 K
Inlet Pressure	101 kPa
Outlet Pressure	608 kPa
Compressor 1 Pressure Ratio	2.60
Compressor 2 Pressure Ratio	2.31
Compressor 1 Aerodynamic Efficiency	65%
Compressor 2 Aerodynamic Efficiency	60%
Compressor 1 and 2 Impeller Diameter	12.7 mm (0.500 in.)
Compressor 1 and 2 Rotational Speed	10,000 rev/s
Total Aerodynamic Power	231 W
Motor, Drag, and Electronic Losses	58 W
Blower Power	23 W
Total Electric Power at 120 VAC	**312 W**

Table 3. Mass estimates

Component	Mass
Compressor 1	2.5 kg
Compressor 2	2.5 kg
Power and Control Electronics	0.8 kg
Enclosure and Support Features	0.7 kg
Heat Exchangers	0.5 kg
Inlet Filter	0.3 kg
Air Blower	0.2 kg
Tubing and Ducting	0.2 kg
Total	**7.7 kg (17 lb)**

Compressors. The two compressors will use our existing 160 W design pictured in Figure 3 and detailed in Figure 4. We have fabricated several versions of this compressor, and we have tested three of them operating in series. Although we plan to rely heavily on the existing design, we will also consider changes to reduce mass and improve efficiency. Our current conceptual design assumes both impeller diameters will be 12.7 mm (0.500 in.) and both machines will operate at 10,000 rev/s. We do not plan to change these values at this time because they have well-established heritage. The primary challenge will be to develop advanced aerodynamic features for the specified operating conditions. Prior designs were developed to compress lighter gases (i.e., helium and neon) with lower pressure ratios in closed-loop systems.

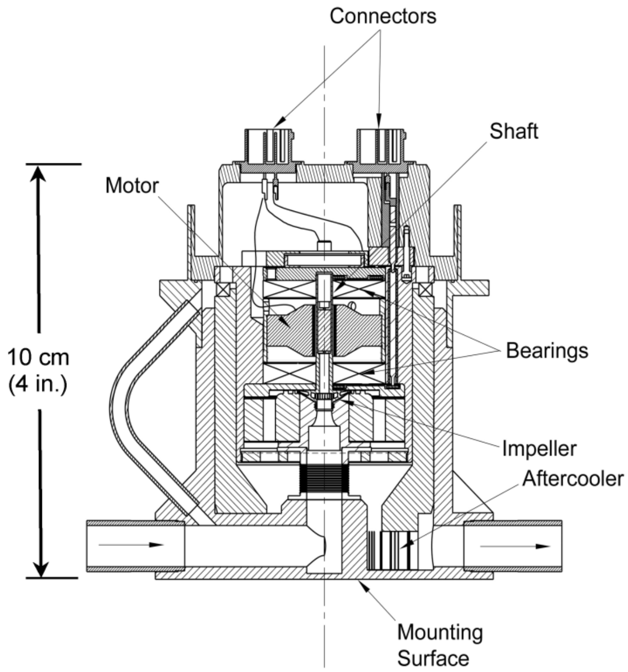

Figure 4. Existing design for 160 W centrifugal compressor.

The two compressor assemblies will be identical to each other, except their impellers and diffusers will have different aerodynamic features. Each rotor will include a two-pole rare-earth permanent magnet inside its hollow shaft. A three-phase wire-wound motor stator will create an alternating magnetic field that will cause the rotor to spin. During operation, gas bearings and clearance seals will prevent the rotor from contacting stationary components, which eliminates wear and the need for lubrication. The rotor and bearings will also include a hard coating to prevent wear from momentary contact that occurs during startup and shutdown. The journal bearings and thrust bearings will use self-acting hydrodynamic designs. Each compressor assembly will include thermally conductive features to transfer fluid drag and motor losses from the compressor housing to an integral heat exchanger, described below.

Heat Exchangers. Each compressor includes an integral heat exchanger in our design. These exchangers transfer heat from the compressor assemblies, compressor discharge flow streams, and electronics to a coolant flow stream. Our current design assumes the coolant stream is air supplied by a small blower. If liquid coolant is available from an external source, it could be used instead of air to reduce the size of the heat exchangers, eliminate the blower, and reduce power consumption. We plan to use brazed, plate-fin, counter-flow heat exchangers with stainless steel plates and copper fins. We have assumed a very simple configuration to minimize development effort and production costs. Specifically, our design has only one flow channel in each direction, which simplifies flow distribution and eliminates the need for complex headers.

Inlet Filter. We plan to include a filter at the inlet of our compressor system to prevent particulate contamination from entering. Although we may be able to use a commercially available filter for this application, we have also developed the capabilities to fabricate custom filters because commercial versions do not have the best balance of characteristics for some applications. Our custom filters are all-metal assemblies that use commercially available woven stainless steel filter media. We have mature axial and radial designs available that achieve 9 μm and 1 μm ratings. We developed these designs specifically to provide low mass, low volume, and low pressure losses, without introducing condensable gases into the system.

Electronics. Our system will include power and control electronics. The power electronics will consist of two small board-mounted AC-to-DC converters and a three-phase inverter. The converters will use standard 120 V, 50-60 Hz, AC electricity to produce DC power for the blower and inverter. The blower will consume less than 30 W at 24 VDC, and the inverter will require less than 300 W at approximately 48 VDC. The inverter will create high-frequency three-phase power to drive both compressors simultaneously. We plan to use a commercially available military-grade inverter that we have used extensively for other programs. Our control electronics will use a military-grade microcontroller to start and stop the compressors and blower as directed by the radioxenon monitoring system and an internal hardware safety system. The safety system will monitor the compressor housing temperatures and the two DC currents continuously. It will compare the measured values to specified limits, notify the user when warning limits are exceeded, and disable the system when shutdown limits are violated. The controller will also log faults so shutdown causes can be determined.

Air Blower. A small blower will provide a steady flow of air to remove heat from the compressor assemblies, compressor discharge flows, and electronics. Our current design includes a commercial blower that provides approximately 7.0 g/s (12 scfm) of air with a pressure rise of 620 Pa (2.5 inches H_2O). The blower can achieve these conditions at about 60% of its rated power, which provides ample margin to increase cooling if necessary. These blowers are very inexpensive, and they have an L10 life of 40,000 hours. We have used them for several other Creare programs, and we are happy with their performance. If periodic down time for blower replacement is unacceptable, our design can be configured to include a set of two redundant blowers so that replacement can occur without disabling the system. This change would have a minor impact on system weight because the blower mass is only 190 g. We also plan to install a coarse, wire-mesh, filter screen at the blower inlet to prevent ingestion of large debris that could disable the blower.

Anticipated Benefits

The successful completion of this program will provide the NNSA and others with a more reliable network of approximately 80 ARSA systems that will detect nuclear detonations around the world (RDNS, 2010). This result will enhance global safety and security. The particular focus of our project is to develop an advanced, oil-free, centrifugal compressor system to replace prior piston compressors, which have been unreliable. The advanced compressors will also have uses in other government and commercial applications, most notably as compressors in turbo-Brayton cryocoolers. NASA applications include future astronomical observatories utilizing infrared, far infrared, submillimeter, and X-ray detectors. DOD applications include space-based surveillance and missile defense, and high-bandwidth superconducting communication devices. Commercial applications include cooling for communication satellites, superconducting circuits in wireless base stations, and cryogenic computers. The specific technical benefits of our technology are described in more detail below.

High Reliability and Long Maintenance-Free Lifetimes. Creare turbomachines have been designed for space applications, where long-life (>10 years) and maintenance-free are inherent requirements. The only moving parts in the compressors are miniature rotors. The rotors are supported by gas bearings, and there is no mechanical contact between the bearings and rotor during operation. Mechanical contact does occur briefly during startup and coastdown, when surface speeds are low. Low friction coatings are applied to both the shaft and bearings to eliminate wear during these events. Several tests have been performed on turbo-Brayton components to demonstrate their reliability and endurance. In addition, the materials, parts, and processes in Creare turbomachines have been selected and developed for usage in long-life, zero-maintenance, cryogenic systems. Here, volatile contamination would freeze at the cold end of the system and impact performance. Therefore, we have developed methods to virtually eliminate volatile and particulate contamination from our turbomachines. The result is high reliability and long maintenance-free lifetimes, as shown in Table 1.

Compact Size and Low Mass. Turbomachines, in general, have extremely high power density due to their high operating speeds. In addition, Creare turbomachines are designed to satisfy stringent aerospace requirements for mass, size, and efficiency. Materials are selected with an optimal combination of low mass and high strength, and non-essential parts and materials are eliminated. The high efficiency of our turbomachines also reduces the size, mass, and power level of the drive electronics and heat exchangers.

Vibration-Free Operation. Our compressor system will produce no detectable vibration during normal operation. The miniature turbomachine rotors have a mass less than 3 grams, they are precisely balanced, and they are supported by non-contact gas bearings. The rotors have diameters of just over 1 cm and rotate in an axisymmetric manner at speeds of several thousand revolutions per second. The net result is that exported vibrations are extremely small and occur at high frequencies where the predicted mechanical displacement caused by vibrations is on the order of nanometers. This feature will eliminate vibration-induced failures.

Orientation Insensitivity. The performance of our compressors is not sensitive to orientation. Buoyancy effects are small due to the relatively low density and high velocity of the process gas. Mechanical effects are also small during normal operation since the gravitational forces on the rotors are orders of magnitude less than the hydrodynamic forces of the bearings. The only time mechanical effects are important is during starting and stopping when rotor speeds are extremely low (<50 rev/s) and bearing forces are commensurate with gravitational forces. During a prior program, we completed multiple start-stop cycle tests with a compressor and turboalternator for different orientations at ambient and cryogenic temperatures. These tests are summarized in Table 1.

Project Goals

The primary goal of our Phase I project is to design an oil-free compressor system for radionxenon monitoring. Initial projections indicate our system will be extremely compact, lightweight, and efficient. We are now performing detailed design, analyses, trade studies, fabrication trials, testing, and evaluations to refine these estimates and reduce their uncertainty. Phase I will conclude with a Preliminary Design Review that provides detailed assessments of volume, mass, power requirements, technical risks, and production costs for evaluation by NNSA personnel. We expect this review to demonstrate our approach is feasible and its benefits are significant for radioxenon monitoring. We are currently working to complete the following specific objectives.

1. Optimize conceptual design. We are conducting analyses to specify top-level design details that optimize trade-offs between size, mass, power requirements, manufacturing costs, development effort, and technical risk. The resulting configuration, operating conditions, and performance targets will be inputs for subsequent design work.

2. Develop preliminary design. We are developing a preliminary design for each component and the overall assembly. The design details will define each component, specify how the components integrate with each other, identify critical dimensions, and show the assembly layout.

3. Determine size and mass. We are determining the size and mass of each component and the overall assembly using CAD solid models.

4. Fabricate prototypical compressor components. We plan to fabricate a prototypical compressor impeller and diffuser to demonstrate that the aerodynamic features specified by our design can be produced.

5. Measure aerodynamic performance. We plan to conduct a series of tests with an existing brassboard turbomachine to measure the aerodynamic efficiency of our prototypical compressor components. We will use the test results to calibrate our performance models and guide subsequent detailed design activities.

6. Quantify power requirement. We plan to combine our aerodynamic performance measurements with detailed analyses to determine the power required to operate our compressor system.

7. Assess technical risks. We are assessing the technical risks associated with our design. These assessments will help NNSA personnel judge the feasibility of our approach.

8. Estimate production costs. We are estimating the cost to manufacture our compressor system in relevant production quantities. The resulting information will help NNSA representatives and others evaluate cost effectiveness.

RESEARCH ACCOMPLISHED

There are no significant accomplishments to report at this time because work on this project had just begun when this paper was submitted. We plan to submit a follow-up paper that documents our accomplishments for the 2012 MRR meeting.

CONCLUSIONS AND RECOMMENDATIONS

Creare has developed miniature, gas-bearing, centrifugal compressor technology that can improve existing radioxenon monitoring systems. Most notably, hydrodynamic gas bearings and clearance seals eliminate wear, which enables reliable, maintenance-free, long-life operation. In addition, particulate and condensable contamination from these devices is negligible because they were developed initially for long-life cryogenic refrigerators, which are extremely sensitive to contamination. The compressor system we are developing for the NNSA includes two centrifugal compressors with integral heat exchangers, an inlet filter, power and control electronics, and a small air blower. The overall dimensions will be approximately 13 cm (5.0 in.) by 17 cm (6.6 in.) by 29 cm (11.4 in.), the mass will be about 7.7 kg (17 lbs), and the total electric power consumption will be approximately 312 W. The primary challenge is to optimize this design for the specific requirements of a radioxenon monitoring system.

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REFERENCES

Bowyer, T .W., K. H. Abel, W. K. Hensley, C. W. Hubbard, A. D. McKinnon, M. E. Panisko, R. W. Perkins, P. L. Reeder, R. C. Thompson, and R. A. Warner (1996). Automatic radioxenon analyzer for CTBT monitoring, prepared for the U.S. Department of Energy under Contract DE-AC06-76RLO 1830.

Breedlove, J. J., M. V. Zagarola, G. F. Nellis, J. A. Gibbon, F. X. Dolan, and W. L. Swift (2001). Life and reliability characteristics of turbo-Brayton coolers, *Cryocoolers 11*, edited by R.G. Ross, Jr., Kluwer Academic/Plenum Publishers, New York, NY, 489–498.

Dolan, F. X., W. L. Swift, Lt. B. J. Tomlinson, A. Gilbert, and J. Bruning (1997). A single stage reverse Brayton cryocooler: performance and endurance tests on the engineering mode, *Cryocoolers 9*, Plenum Press, New York, 465–474.

Miley, H. S., S. M. Bowyer, C. W. Hubbard, A. D. McKinnon, R. W. Perkins, R. C. Thomspon, R. C., and R. A. Warner (1998). A description of the DoE radionuclide aerosol sampler/analyzer for the comprehensive nuclear-test-ban treaty, *J. Radioanalytical and Nuclear Chem.*, 235: 1-2, 83-87.

Perkins, R. W., and L. A. Casey (1996). Radioxenons: their role in monitoring a comprehensive test ban treaty, DoE/RL-96-51, prepared for the U.S. Department of Energy by the Pacific Northwest National Laboratory, Richland, WA.

RDNS (2010). Radiation Detection and Nuclear Sciences, <http://rdnsgroup.pnl.gov/deployments.stm>.

Rynes, J. C., D. Penn, and P. Donohoe (2004). Research and development of radioxenon monitoring systems," *26th Seismic Research Review – Trends in Nuclear Explosion Monitoring*, LA-UR-04-5801, Vol. 2, pp. 588–597.

Swift, W. L., F. X. Dolan, and M. V. Zagarola (2008). The NICMOS cooling system – 5 years of successful on-orbit operation, *Transactions of the Cryogenic Engineering Conference – CEC*, 52: 799–806.

Zagarola, M. V., J. Breedlove, C. S. Kirkconnell, J. T. Russo, and T. Chiang (2008). Demonstration of a two-stage turbo-Brayton cryocooler for space applications, *International Cryocooler Conference 15*.