IMPROVEMENT IN GE DETECTOR COOLING

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ABSTRACT

High Purity Germanium (HPGe) detectors used by the International Monitoring System (IMS) radionuclide monitoring stations rely on Joule-Thomson (J-T) mechanical coolers to provide the low temperature necessary for operation. Cryocooler advances in recent years have resulted in commercial availability of Stirling and Pulse Tube mechanically cooled detector systems with improved reliability and enhanced HPGe detector performance. The Cryo-Cycle™ and Cryo-Pulse® 5 are two such commercial products being modified and evaluated for application in IMS Radionuclide Aerosol Sampler/Analyzer (RASA) systems.

An ultra-high vacuum (UHV) remote detector chamber and service body assembly has been designed and modeled for use on the Cryo-Pulse® 5. The cryostat assembly incorporates a low cross section metal end cap seal, UHV compatible hardware and joining techniques, permanent vacuum getter pumps, and low thermal loss UHV vibration isolation mounts between the enclosure and the internal cryogenic components. Most of the components have been fabricated. Assembly and testing are underway. Characterization of a UHV pumping station has been performed using residual gas analysis in preparation for evaluating the long-term vacuum reliability of cryostat components and assemblies. Nitrogen gas extractors have been researched for integration with the Cryo-Cycle™ hybrid cooler. Cryostat vacuum improvements on the Cryo-Cycle™ will be derived from the same sealing technologies used on the Cryo-Pulse® 5. Details of the investigations and progress are presented.

OBJECTIVES

The RASA Mark 4 and implementation of the Cryo-Pulse® 5 and Cryo-Cycle™ have been described previously by Yocum et al., (2008). The RASA was developed at the Pacific Northwest National Laboratory (PNNL) in the 1990s to meet Comprehensive Nuclear-Test-Ban Treaty (CTBT) requirements for aerosol radionuclide measurements, as described by Bowyer et al. (1997) and Miley et al. (1998). All of the aerosol samplers currently operating in the field rely on Joule-Thomson direct coolers. Performance of Joule-Thomson (J-T) coolers for this application has been problematic. The standard Cryo-Pulse®5 has been under evaluation and operating successfully in a prototype RASA system for over one year at Patrick AFB, Florida.

The goal of this project is to investigate improvements in HPGe detector cooling technology for use in the RASA Mark 4. Explorations in both direct pulse tube cooling and hybrid Stirling cooling are being conducted. CANBERRA Cryo-Pulse® 5 and the Cryo-Cycle™ standard products provide the starting point for this effort. UHV technology is being incorporated in the Cryo-Pulse®5 to improve long-term vacuum integrity and to eliminate the possibility of partial thermal cycles. This includes the use of metal vacuum seals, onboard vacuum pumps such as non-evaporable getter (NEG) pumps and ion pumps, and use of UHV compatible internal components.

A nitrogen gas generator is being integrated with the Cryo-Cycle™ cooler to maintain a seven-day cooling buffer in the event of a power outage. An uninterruptible power supply (UPS) will be used with both direct and hybrid coolers to provide redundant protection against partial thermal cycles and to keep the Cryo-Pulse® 5 at operating temperature in the event of short power outages.

Task 1

Task I is the design and testing of improvements to direct cooling with the Cryo-Pulse® 5. These comprise improvements in cryostat end cap sealing, incorporation of UHV technology in the detector cryostat construction, and investigation of vibration isolation/mitigation techniques.

Task 2

Task II is the integration of a nitrogen gas generator with the hybrid Cryo-Cycle™ cooler and evaluation for use in a RASA Mark 4 system. Operation with an uninterruptible power supply (UPS) will also be investigated.

RESEARCH ACCOMPLISHED

Both of the tasks have in common a detector chamber that must interface with the RASA assembly. The detector chamber designed is 4.0” in diameter and capable of containing an HPGe detector element of greater than 120% relative efficiency. The RASA incorporates a background radiation shield with a fixed 4.3” diameter penetration into which the detector chamber is inserted. To maximize the effectiveness of the shield, the design employs a remote detector chamber (RDC). This allows the shield penetration to be effectively closed by addition of a lead back-shield directly behind the RDC after the detector chamber is inserted (i.e. no-stream-path design). The RDC back-shield in close proximity to the detector element attenuates the ambient radiation background and increases the sensitivity of the detector as compared to designs incorporating long end caps to reach inside the RASA shield. The detector chamber, vacuum cryostat, ion pump, NEG pump, pinch-off tube and mechanical cooler for the UHV Cryo-Pulse® 5 are assembled using demountable metal seals. These in combination with welded UHV electrical feedthroughs and a metal pinch-seal comprise the UHV vacuum envelope. An outline drawing for the UHV Cryo-Pulse® 5 is shown in Figure 1.

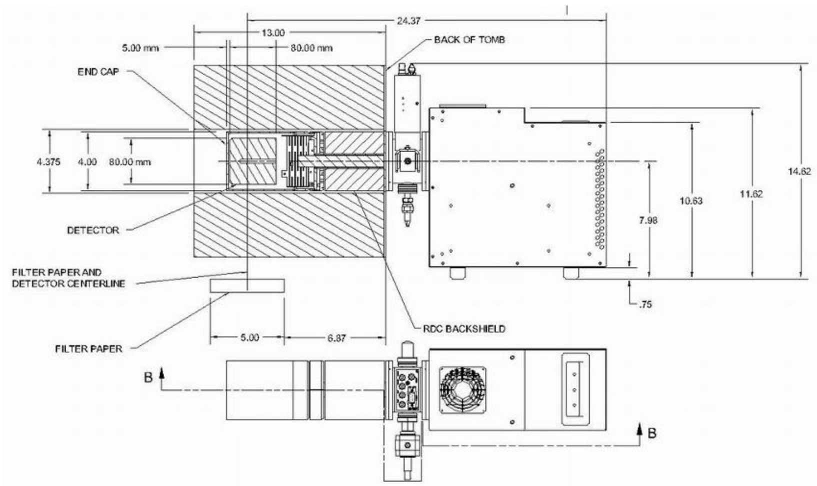


Figure 1. Outline drawing of the UHV Cryo-Pulse®5 inserted into the RASA cave.

End Cap Seal

The newly designed end cap incorporates a metal seal, is compatible with UHV, and has a slim profile to allow the maximum detector element diameter within the diameter of the end cap. The design was modeled using SolidWorks simulation software, COSMOS. It was optimized for parameters including deflection, preload, yield, flow, fatigue, and thermal response. The resultant seal assembly cross section (i.e., Detector Chamber Inner Radius minus Detector Chamber Outer radius) is 3.5 mm. This is accomplished using an indium seal flange design with a clamp fastener as shown conceptually in Figure 2. Extensive stress analyses were carried out on the end clamp fastener and indium seal to ensure the design would satisfy the vacuum integrity requirements.

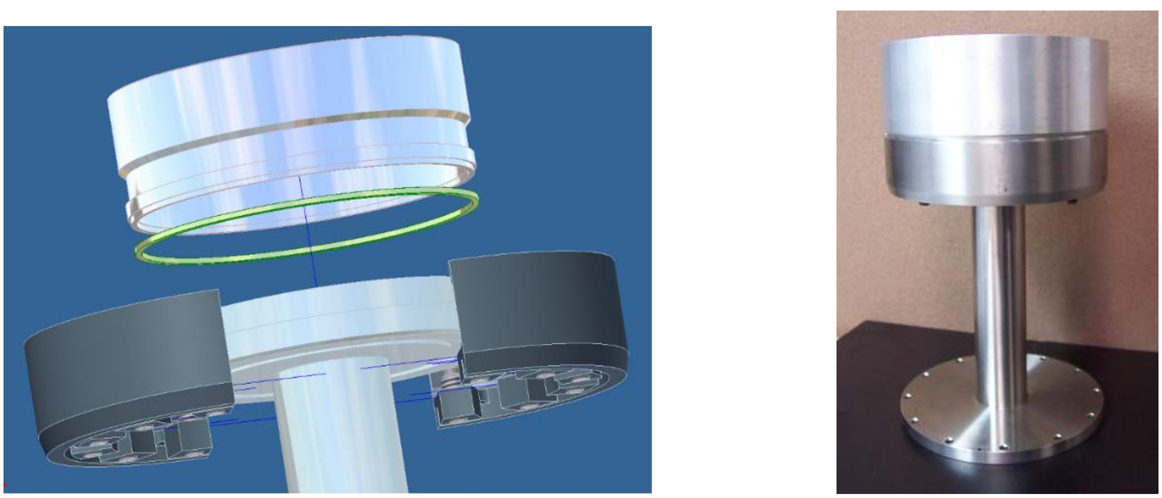


Figure 2. Concept drawing and fabricated RDC assembly, both with test end cap.

The assembly shown in Figure 2 was fabricated and tested for functionality. The test results were in good agreement with the modeling. The indium seal was assembled and tested multiple times for vacuum integrity and ease of assembly. The assembly was heated to 100°C and helium leak tested to $<10^{-9}$ atm. cc/sec. Seal leakage and permeability were tested using the helium bag test. While attached to the helium leak detector a plastic bag filled with helium was placed around the assembly. Helium was undetectable to a leak rate of $<10^{-9}$ atm. cc/sec. after 12 hours, which indicates there are no small leaks or areas with high permeability.

UHV Service Body

A flanged service body was designed and fabricated as shown conceptually in Figure 3. The service body connects the RDC assembly to the Cryo-Pulse® 5 vacuum housing and provides electrical feedthroughs to connect the preamplifier to the detector front-end. The service body flanges were designed to use Garlock's Helicoflex® delta seals. These seals are expensive and not reusable. Indium gasket material is used in the delta seal grooves during the prototype testing. UHV compatible feedthroughs from Solid Sealing Technology (SST) were welded to the side of the assembly. Mini-conflat flanges were welded on as shown to accommodate the ion pump, NEG pump, and pinch-off tube. The service body assembly was fabricated and tested for leak tightness in combination with the RDC assembly. In similar fashion to the RDC leak tests, the combined assembly was determined to be helium leak tight to $<10^{-9}$ atm. cc/sec. with low permeability.

Figure 3. Concept drawing and fabricated UHV service body.

A mock-up of the complete UHV Cryo-Pulse® 5 assembly is shown in Figure 4. The remaining parts of the vacuum enclosure to be fabricated are the vacuum housing inside the cabinet and the full-length aluminum end cap. The vacuum housing has been machined and is to be sent out for welding of the electrical feedthrough. The end cap is to be fabricated and welded.

Figure 4. Mock-up of the complete UHV Cryo-Pulse® 5 with test end cap.

Internal Supports

Materials and techniques to mechanically support the components inside the cryostat to provide an adequate cold path to the detector element were investigated. Axial and radial flexures were constructed from stainless steel for the mechanical supports. These components were modeled for thermal load and heat flux. The assembly was modeled to simulate stress and deflection under a 3G load as shown in Figure 5.

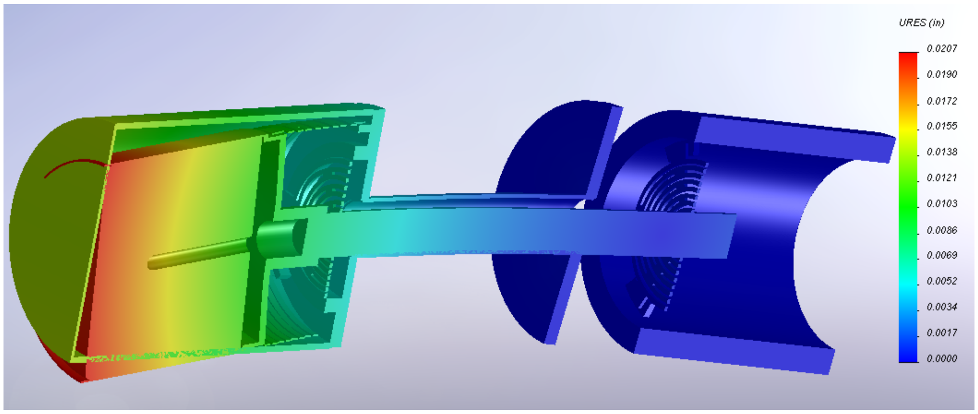


Figure 5. Deflection with a 2 kg detector mass under 3G load.

Modeling predicted a combined conductive heat load of < 0.75 watts for the three flexures required to support the detector and cold path components. Two of the flexures were tested and the heat loads predicted by modeling were confirmed. The third support will be tested after final assembly.

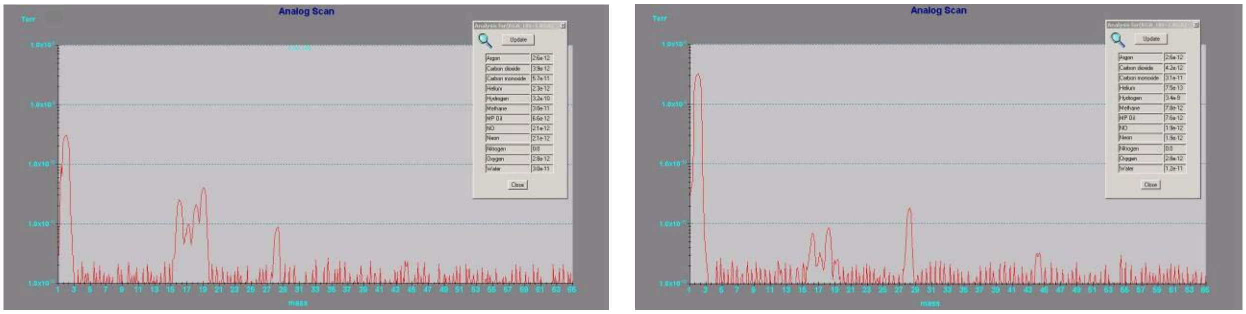
The vibration characteristics of the assembly in Figure 5 were simulated and the natural frequency and harmonics are listed in Table 1. The first harmonic is primarily axial direction.

TABLE 1. Vibration Characteristics of the Flexure System

Mode No.	Frequency (Rad/sec)	Frequency (Hz)	Period (Sec)
1	189.59	30.175	0.03314
2	305.34	48.596	0.020578
3	305.48	48.618	0.020568
4	865.78	137.79	0.007257
5	1019.7	162.29	0.006162

Residual Gas Analysis

The service body, RDC weldment, dummy end cap, ion pump, and pinch tube were assembled with all metal seals and tested for helium leak tightness on a UHV pumping station. The UHV pumping station is an all-metal seal, turbo-pumped system backed by an oil-free roughing pump. Base pressure of the system is in the low 10^{-10} torr range. Residual gas analysis (RGA) of the system after several days of mild baking before and after adding the cryostat assembly reveals that the major residual gas constituent is hydrogen as shown in Figure 6. Hydrogen is to be expected since it dissolves in stainless steel during manufacture and diffuses out slowly at low temperatures. Heating for hours or days at temperatures in excess of 400°C can accelerate the diffusion as discussed by O'Hanlon (1989). The assembly is limited to a maximum temperature below 150°C because of the low melting point of the end cap indium seal. The apparent preponderance of hydrogen is exacerbated by the fact that lighter gases are pumped less efficiently by the turbo-pump. Fortunately, the NEG pump has an extremely high capacity of up to 20-30 torr-liters/g for hydrogen as discussed by Ferris (2002). Residual hydrogen in the UHV Cryo-Pulse® 5 vacuum enclosure is not expected to present a problem.



Before **After**

Figure 6. RGA of the UHV system before and after adding the UHV cryostat assembly.

Other reactive gases such as O_2, CO, CO_2, N, and H_2O will be adequately pumped by the NEG pump in the final cryostat assembly. Methane and light hydrocarbons, as well as inert gases, are not pumped by the NEG pump. An ion pump is included on the cryostat to pump noble gases, CH_4, and light hydrocarbons.

Vibration Mitigation

Vibration decreases the signal-to-noise ratio and degrades the performance of HPGe detectors. Noise induced by mechanical vibration is referred to as a microphonic response (MR). When a surface at potential V vibrates with respect to another surface at ground potential the capacitance between the 2 surfaces is modulated by a $\Delta C(t)$, inducing a charge ΔQ in the circuit. If this ΔQ is coupled to the input of the preamplifier, either through the detector capacitance or directly onto the detector signal path, it is integrated in the preamplifier along with the signal charge and is amplified in proportion. The effect of MR on the signal can be mitigated electronically by the band pass of the amplifier, baseline restoration, and by many other signal conditioning techniques both digital and analog. Mechanical techniques for reducing MR are vibration damping, vibration isolation, structural design to shift frequencies and reduce resonance, stiffening, etc. All of these elements must be balanced in the design of the UHV Cryo-Pulse® 5 system.

The compressor is a source of vibration that frequently gives rise to MR on Stirling and J-T electrical coolers. In the case of the Cryo-Pulse® 5, the compressor is driven by dual piston linear motors. Techniques have been developed by the cooler manufacturer, Thales Cryogenics, to control the pistons independently in order to actively reduce the overall system vibration. The cooler system typically consists of a pulse tube cooler, DSP micro-controller based drive electronics, and an accelerometer. Normally the accelerometer is mounted directly on the compressor. The control loop is shown schematically in Figure 7.

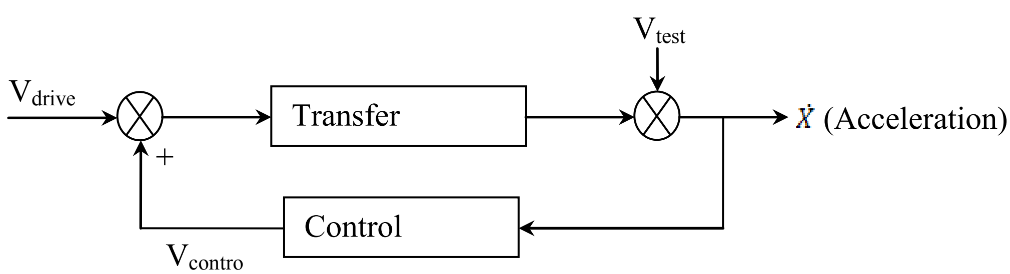


Figure 7. Schematic representation of the active noise cancellation control loop.

The linear compressor is driven by a sinusoidal drive voltage V_{drive}. The vibration control system uses a control algorithm that attempts to reduce the measured acceleration to zero by adjusting the drive parameters of one of the linear motors of the compressor. The transfer function G and the algorithm parameters are determined by measuring the initial uncontrolled acceleration and the acceleration after adding a known test voltage V_{test} to the drive voltage. This test voltage causes an imbalance and will change the vibration levels of the system. With the correct transfer function and algorithm parameters in place, the drive voltage of one of the linear motors is continuously corrected with a control voltage, V_{contro}. This control voltage consists of not only the drive frequency with the required amplitude, but also of several of the harmonics of this drive frequency. In this way the drive frequency and its first harmonics (up to the first 15–20 harmonics) of this drive frequency can be reduced quite effectively. The control algorithm uses the transfer function G of the entire dynamic system. This means not only the dynamics of the cooler will be included in the transfer function determination, but also in the dynamics of the entire mounting structure. Application of this technique to a standard Cryo-Pulse® 5, similar in configuration to the UHV unit being developed, reduced the amplitude of the primary vibration at 50 Hz by a factor of 10 on the external surface of the detector chamber. Further refinement and testing is required to optimize and determine the benefit of this type of active vibration cancellation to overall detector performance.

Investigate Commercial Solutions to Nitrogen Gas Extraction from Air

An advantage of the Cryo-Cycle™ system over conventional cryocoolers is its hybrid operation; that is, the actual cooling of the detector is accomplished with liquid nitrogen (LN), rather than direct electrical cooling. The Cryo-Cycle™ system stores up to 22 liters of LN in a Dewar. Maintaining the Dewar as a closed system and continually reliquifying the boil-off gas with a Stirling a cooler eliminate losses due to boil-off. Nitrogen can be lost to the system during a power outage or through small leaks. In a remote application such as the RASA, LN is not available to replace any losses. Pairing the Cryo-Cycle™ with a nitrogen gas extractor to automatically re-charge the nitrogen solves this problem. A CANBERRA 7186 LN level monitor can be used to control the operation of the nitrogen gas extractor.

The research team met with two vendors of nitrogen gas extraction systems. OnSite Gas Systems manufactures pressure swing adsorption (PSA) systems while Parker Hannifin makes both PSA and membrane separation systems. OnSite did not offer systems small enough for this application. Several other vendors were researched. A summary of the findings is shown in Tables 2 and 3 below.

Table 2. PSA systems.

	Bora	**Bora**	**LNS gas**	**Parker**	**Dionex**
Model	750	1250	N2-SIROCCO-3A	LCMS 12-1	MSQ10la
Type	PSA	PSA	PSA	PSA	PSA
Price	$9,542.00	$11,132.00	$18,125.00		
Size (WxHxD)	9"x14"x17"	9"x14"x17"	19"x 25" x 32.8"	14"x35"x26"	17"x25"x16”
Weight	45 lbs	50 lbs	253 lbs	198 lbs	104 lbs
Noise	<48dB	<48dB	<60dB		
Purity	99.999%	99.995%	99.999%	99.50%	
Output	0.750 LPM	1.25 LPM	3 LPM	12 LPM	10 LPM
Service interval	4000 hrs -filters 8000 hrs compressor	4000 hrs -filters 8000hrs compressor	4000 hrs filter 24000hrs trained service		
Power Requirements	110/230V 50/60 Hz 820 W	110/230V 50/60 Hz 820 W	110/230V 50/60 Hz	110/230V 50/60 Hz	220V 50/60Hz 1 kW

Table 3. Membrane systems.

	Dionex	Chrysalis-LC-MS-Nitrogen	Parker
Model	msq18la-068126	M4 with pure gas option	NitroFlow Lab
Price		$18,093.00	$14,000.00
Size (WxHxD)	17" x 35" x 16"	12" x 27" x 35"	36" x 28" x 12"
Weight	90 lbs	204 lbs	204 lbs
Noise	59 dB	58 dB	<58 dB
Purity	99.5%	96 - 99.9%	99.5%
Output	18 LPM	8 LPM	17 LPM
Type	Membrane	Membrane	Membrane
Power requirements	230V 50/60Hz	110/230V 50/60Hz	230V 50Hz 1400 W

Both PSA and membrane nitrogen generator systems were explored. PSA systems use charcoal and sometimes zeolite molecular sieves to adsorb and exhaust oxygen during the pressure swing cycle. In membrane systems the incoming air passes through tubes where oxygen and water vapor permeate through the walls of the tubes leaving the nitrogen in the flow stream. Membrane systems offer advantages such as simplicity, low maintenance, and small footprint when compared to PSA systems. However, membrane filters generally do not reach the nitrogen purity levels of PSA systems without additional filters that increase complexity and maintenance requirements. Purity is a critical issue because the boiling point of liquid oxygen (LOX) is higher than that of LN. Under certain circumstance (e.g., a large gas leak) oxygen in the gas stream can lead to preferential collection of LOX in the Cryo-Cycle™ Dewar. Inclusion of oxygen monitors on the output of nitrogen gas generators is a common feature.

Both PSA and membrane systems require compressed air to operate so an air compressor is required for the RASA application. Size, reliability, power consumption, noise, and mechanical maintenance are important considerations. These requirements and other maintenance requirements for the nitrogen generator filters and mechanical systems are mitigated by the expectation that the normal duty cycle of the system will be short. Except in the event of unexpected gas leaks in the Cryo-Cycle™, degradation of the cryostat vacuum, power outages, or initial filling of the Dewar the services of the nitrogen generator may not be required for months or years at a time. Based on the investigation, a BORA 1250 will be purchased. The time required to initially fill the Dewar is expected to be 20–25 days. The detector should be usable 3–5 days after the filling process is begun. These times will be more accurately determined when the unit is tested.

CONCLUSIONS AND RECOMMENDATIONS

A small cross section indium end cap seal has been designed and tested. This seal can be used to improve the long-term vacuum integrity of both Cryo-Pulse® 5 and Cryo-Cycle™ based products. Other components of the UHV Cryo-Pulse® 5 vacuum enclosure including the RDC assembly, service body, and support flexures have been fabricated, assembled, and tested. RGA tests indicate there are no leaks in the vacuum enclosure parts fabricated and the outgassing rates and permeability are low. The Cryo-Pulse® 5 vacuum housing and end cap are in process. The next step is to completely assemble the vacuum enclosure and analyze the vacuum by RGA as the internal components are added. Investigation of the long-term integrity, cooling performance, and detector performance will be carried out after the assembly is complete.

The Cryo-Cycle™ investigation will continue with the purchase of a nitrogen generator followed by system integration and testing. Tests will be performed to characterize the overall performance. An improved cryostat will be designed that makes use of the vacuum techniques developed for the UHV Cryo-Pulse® 5. These improvements include RDC with metal seal end cap, welded feedthroughs, and metal pinch seal.

ACKNOWLEDGEMENTS

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