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Design and Build of Reactor Simulator for Fission Surface Power Technology Demonstrator Unit

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Abstract. The Nuclear Systems Team at NASA Marshall Space Flight Center (MSFC) focuses on technology development for state of the art capability in non-nuclear testing of nuclear system and Space Nuclear Power for fission reactor systems for lunar and Mars surface power generation as well as radioisotope power systems for both spacecraft and surface applications. Currently being designed and developed is a reactor simulator (RxSim) for incorporation into the Technology Demonstrator Unit (TDU) for the Fission Surface Power System (FSPS) Program, which is supported by multiple national laboratories and NASA centers. The ultimate purpose of the RxSim is to provide heated NaK to a pair of Stirling engines in the TDU. The RxSim includes many different systems, components, and instrumentation that have been developed at MSFC while working with pumped NaK systems and in partnership with the national laboratories and NASA centers. The main components of the RxSim are a core, a pump, a heat exchanger (to mimic the thermal load of the Stirling engines), and a flow meter for tests at MSFC. When tested at NASA Glenn Research Center (GRC) the heat exchanger will be replaced with a Stirling power conversion engine. Additional components include storage reservoirs, expansion volumes, overflow catch tanks, safety and support hardware, instrumentation (temperature, pressure, flow) for data collection, and power supplies. This paper will discuss the design and current build status of the RxSim for delivery to GRC in early 2012.

Keywords: Reactor, Reactor Simulator, Fission Surface Power, Core Simulator, LM Pump, TDU, FSPS

INTRODUCTION

NASA and the DOE have partnered to investigate an affordable UO_2 fueled fast spectrum, pumped liquid-metal cooled reactor with Stirling based power conversion[1] for use on the moon. The Nuclear Systems Team at Marshall Space Flight Center (MSFC) focuses on technology development for state of the art capability in non-nuclear testing of nuclear system and Space Nuclear Power for fission reactor systems for lunar and mars surface power generation as well as radioisotope power systems for both spacecraft and surface applications. Currently being designed and developed at MSFC as part of the Fission Surface Power System (FSPS) Program is a reactor simulator (RxSim) for incorporation into the Technology Demonstrator Unit (TDU), which is supported by multiple national laboratories and NASA centers. A FSPS can provide a long life with abundant power in space environments. This document is meant to provide a brief overview of the RxSim mechanical design.

The TDU brings together all the components necessary for a FSPS for test which include radiator panels, Stirling power converters, core, pump, volume accumulator, as well as data acquisition and control systems. The responsibility for delivery of the components is divided between the national laboratories and NASA centers. The RxSim was originally designed to be a stand-alone system based on a two loop design that contained a core, a pump, a liquid-to-liquid heat exchanger that transferred the heat to a second loop that contained a pump, and a pair of Stirling engines. Separation would have been made at the intermediate side of the heat exchanger allowing for the RxSim to be 'plug and play' when installed into the TDU. However, in August of 2010 budget shortfalls required the TDU design to change to a single loop design by removing the heat exchanger and intermediate loop components, thus reducing the system to one loop. This single loop will need to be disassembled and re-assembled when delivered to GRC in March 2012. FIGURE 1 shows a rendering of the 2-Loop TDU design layout installed in Tank 6 at GRC, a 25 foot diameter by 68 foot long vacuum chamber; the 1-Loop design is similar in scale. A positive benefit to this change is greater design flexibility and less coordination required between MSFC and GRC on integration issues.

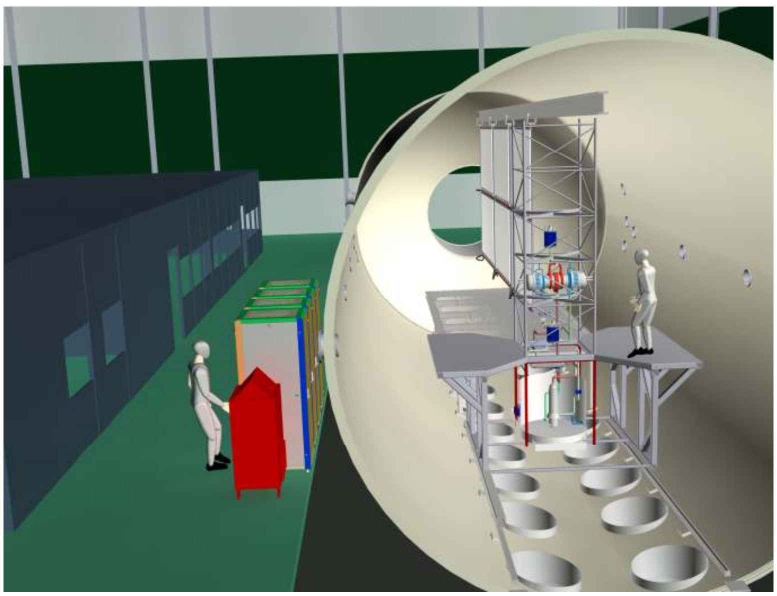

FIGURE 1. TDU Conceptual Layout.

REACTOR SIMULATOR

The RxSim is an amalgam of mechanical components, the data acquisition system, and the control software used to monitor and control all operations of the RxSim. By building and testing the RxSim prior to delivery at GRC most of the bugs can be worked out, eliminating this burden from integration into the TDU and allowing the system to be characterized and the control codes adjusted to perform as needed. The mechanical configurations is discussed in the following sections.

Component Layout

The component layout for the RxSim considers many factors. First, the RxSim must fit within the test chamber. At MSFC this test chamber is a 3.05 m (10 ft) diameter by 6.10 m (20 ft) long vacuum chamber. FIGURE 2 shows a transparent view of the vacuum chamber. Component relative positions are considered to facilitate gravity draining of NaK; if pockets of NaK are left in the test article this can present a problem during operation, fill, and drain. This configuration is not prototypic of an actual FSP reactor system with respect to component placement. With the component positions determined, support structures and spill containment are designed. A great deal of coordination and planning between GRC and MSFC for the structural integration is needed to ensure quality integration and a final product that will be perform as planned. A Department of Energy (DOE) facility, Oak Ridge National Laboratory, leads the data acquisition and control integration effort, providing the continuity of systems and information between GRC and MSFC.

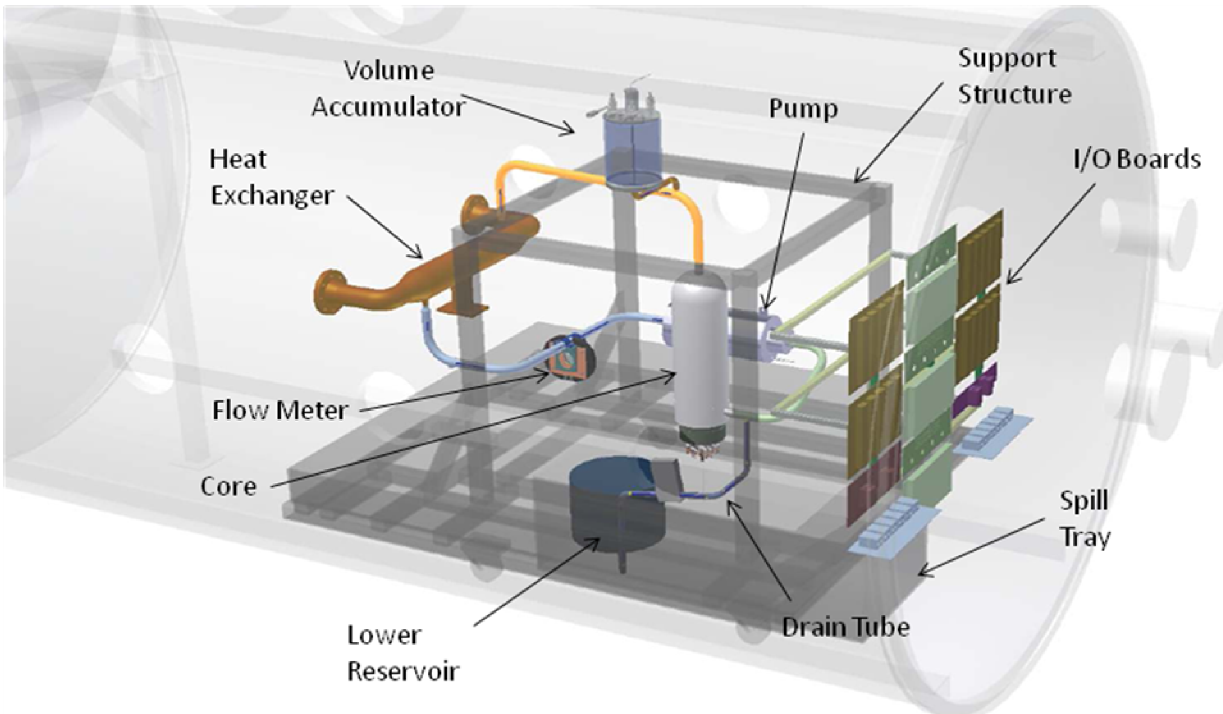

FIGURE 2. Component Identification on the Redesigned RxSim Single Loop Design.

Core

The test core was designed by MSFC based upon the FSPS nuclear core designed by Los Alamos National Laboratory.[2] The nuclear design of the core is a 37 pin UO_2 fueled fast spectrum, pumped liquid-metal NaK cooled reactor with Stirling based power conversion. The physical geometry of the RxSim core was taken from the nuclear design, preserving the critical elements such as pin spacing and size. Some core design requirements and the as-built capability are presented in TABLE 1.

TABLE 1. Core requirements and as-built capability.

Parameter	Requirement	As-Built	Units
Nominal/Transient Power	55/90	55/+100	kWe
Pins	37	36 (Center pin for TC's)	
Control Zones	12	12	Individually controlled
Outlet/Peak outlet	875/925	875/925	K
Tin/Tout Delta	50	200	K
Maximum Press Drop at 1.75kg/s flow	14	<2	kPa
Thermocouples	30	22 internal, 10 external	Type K thermocouples

The nuclear design uses 37 pins; however, to allow for symmetric zones (3 pins per zone), with the center pin is left empty and used for temperature measurements. Past experience with simulating cores of this approximate size and power level have shown that the center pin power is reduced significantly or turned off completely to balance temperature distribution; thus, no heating from the center pin is an acceptable practice. The zones of the core are arranged in radial rings. When controlling zone power to balance the temperature distribution across the core, experience has shown that this type of arrangement offers the highest degree of control and fidelity short of individual pin control.

Core Thermal Simulators

The purpose of the core is to mimic the heat produced from a fission reaction. In this case, to achieve 90 kW thermal power each simulator must have the ability to produce a minimum of 2.5kW thermal power. These types of heaters are not available commercially and are custom designed in-house. The heaters that were custom designed and tested for use in the RxSim core use graphite as the heating element. FIGURE 3 shows the simulators in a cross section view and in the clad. Each zone in the core contains 3 simulators and each zone is matched to one power supply. The power supplies are DC power supplies capable of producing 15 kW of power in a perfectly matched system. Here, based upon the carefully selected material and geometry of the simulator, each zone will be capable of producing over 8 kW of power. Significant engineering and test has gone into all aspects of these simulators including the electrical connection scheme, graphite shape, mechanical connections, etc. This simulator design has the capability of having a thermocouple inserted in the center of the graphite to monitor centerline temperature.

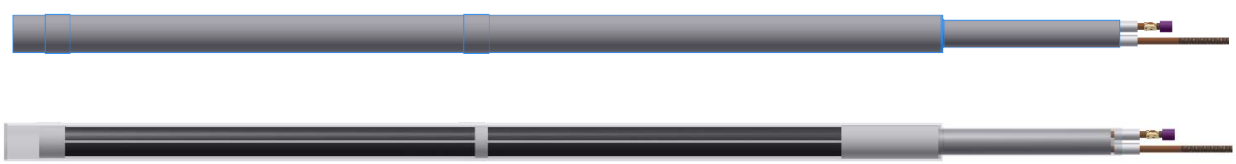

FIGURE 3. RxSim Core Thermal Simulator.

Core

Like the simulators, a significant amount of engineering and testing has gone into the core design. Documentation of the core design will be produced for a future NASA Technical Paper. The NaK inlet end of the core is where the electrical feedthroughs penetrate into the core, see FIGURE 4. For each zone there are two power feeds, so there are 24 power feeds that enter into the helium plenum, see FIGURE 5. One feedthrough connects to three simulators in series with the jumpering completed in the helium plenum. The simulator clads are welded to an endplate that provides the NaK-to-helium boundary. Helium is used to provide a conducting medium to transfer the heat generated from the graphite to the internal wall of the clad where it then conducts through the clad into the NaK. On the exit side of the core, 17 thermo-wells are used at carefully chosen heights and positions to reconstruct a temperature profile of the core (see FIGURE 4 and FIGURE 5). Simple flexible alumina insulation is used to mimic the insulative properties of the reflector material that would normally be present in the core. Follow-on engineering and design will address the integration of the reflector and drums.

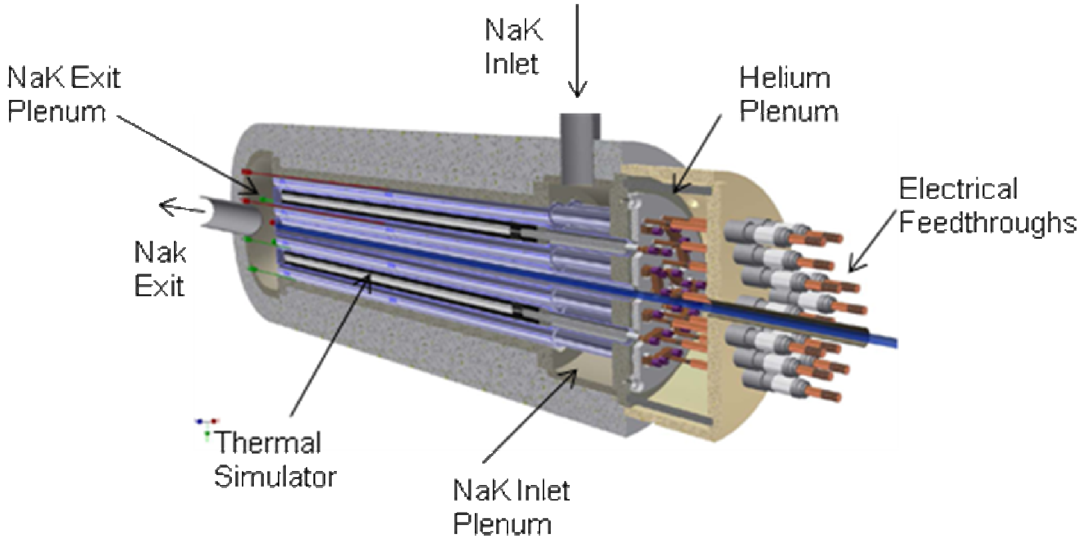

FIGURE 4. Cross Sectional Rendering of the TDU Core.

FIGURE 5. Core Exit End and Electrical Side as Built, No Insulation Shown.

Pump

The pump for the RxSim is an Annular Linear Induction Pump (ALIP) designed by Idaho National Laboratory. It has no moving parts and can operate high temperature, see FIGURE 6. The pump is capable of producing 1.75 kg/s of NaK flow and 14 kPa of pressure at 875 K. The pump is positioned after the heat exchanger (which simulates the use of heat by a Stirling), which keeps the pump operational temperature as low as possible. Details of the pump are discussed in other papers.[3]

FIGURE 6. Cross Sectional Rendering of the ALIP.

Flow Meter

To quantify the NaK flow in the RxSim, a flow meter was custom designed for this application. MSFC has designed many flow meters for high temperature, in-vacuum operation for liquid metal flow measurement. The flow meter is a DC flow meter; as the NaK moves through a magnetic field, a current can be produced in a wire. This current signal is measured and compared to a calibrated value to determine the flow rate. In the current design a clamp is used to secure the flow meter to the flow tube. The clamp material is the same as the tube, 316L stainless steel, to allow for equal thermal expansion. An option in the design exists to use a second clamp that would be set slightly loose to allow for differential thermal expansion between the tube and the flow meter. The clamp connects to a copper plate via a low surface area connection to inhibit thermal conduction from the pipe to the copper plate. The copper plate then couples to iron yokes that are used to transfer the magnetic field from the magnets to the straddle location around the tube. This arrangement keeps the magnets away from the hot NaK tubing and thus below their curie temperature. If the magnet heats undesirably, the copper support plates can be outfitted with water-cooled tubes to keep the magnetic temperature low. FIGURE 7 shows the flow meter and a model of the magnetic field lines of force. Previous designs have employed rare earth magnets for their high field strength and thus high signal strength; however, the design here uses a lower magnetic field strength but higher curie temperature Alnico magnetic material. By using Alnico an attempt is made to forgo water cooling of the flow meter and reduce complexity in the TDU. Past experience has shown that a using water cooling to keep the rare earth magnets below their curie temperature has the side benefit of producing an extremely stable signal at the expense of system complexity.

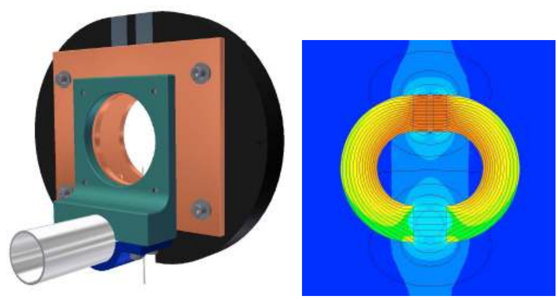

FIGURE 7. EM Flow Meter Design for TDU and Magnetic Field Model.

Reservoirs

To manage the NaK before, during, and after test several types of reservoirs are required: a volume accumulator, a lower reservoir, and overflow tanks.

Volume Accumulator

Oak Ridge National Laboratory has designed the volume accumulator for the system.[4] FIGURE 8 shows a rendering of the volume accumulator. NaK expands approximately 15% when heated from room temperature the operating temperature of the RxSim. To accommodate this expansion, a reservoir is used that is sized based on the volume of NaK in the system; this reservoir is called the volume accumulator (VA). The VA is also used as the argon gas system interface point. Argon is used to pressurize the RxSim. The RxSim must have a base pressure of greater than 14 kPa (2 psi) to overcome surface tension and gravitational forces but less than the maximum operational pressure (275 kPa) minus maximum pump developed pressure (35 kPa); here, that would equal about 240 kPa. For the RxSim the lowest possible pressure for operation is desired. Thus, the system will be charged to about 100 kPa. On the VA are several level measurement devices and a pressure transducer. As part of a typical VA design splash guards and anti-swirl features are present to retard rapid movement of NaK such as typically occurs with an expanding gas bubble.

Lower Reservoir

The lower reservoir (LR), shown in FIGURE 2, is a volume that can hold all the NaK in the RxSim when hot. It is used when transferring the NaK for the first time into the system. Once the LR is filled, the RxSim is loaded using argon cover gas to push the NaK up into the RxSim. The isolation valve is closed to trap the NaK at a predetermined level. Level sensors in the LR provide an indication of how the transfer process is proceeding and level sensors in the VA indicate when the system is full.[5]

Overflow Catch Tanks

Experience has taught that all penetrations to and from the system must utilize some form of overflow tank or reservoir to contain the NaK in the event of an unanticipated event. This event can be caused by a rapidly expanding gas bubble, system out-gassing generating gas volumes, or operator error. Each of these events can lead to NaK escaping the RxSim. To manage this condition, the RxSim utilizes overflow tanks. These tanks are simple volumes that have an indicator to signal the presence of NaK.

FIGURE 8. Volume Accumulator.

Tubing

Tubing for the system is all stainless steel 316L, seamless, 3.8 cm (1.5 in) OD by .17 cm (.065 in) thick wall with a bright finish. The bright finish ensures a smooth surface with minimal pitting or scaling on the inside. Joining to components and to other tubes is accomplished using a butt-weld. To minimize the use of fittings and pressure drops large radii are used. The only two fittings required are tees that lead to the VA and the LR.

Support Structure

The support structure for the RxSim has several purposes. It must support the RxSim when the spill tray is resting on rails during test at MSFC, it must support a hanging load when installed in the TDU, and it must support the components. To accomplish this, a 7.6 cm (3 in) stainless box beam was used to create the support backbone of the spill tray and to create the 1.22 m (48 in) square truss section. This square truss section was selected to be similar in dimensions to the truss structure on the TDU and it will serve as support for the RxSim/TDU components. FIGURE 1 and FIGURE 2 illustrate these points. FIGURE 9 shows the current status of the support structure/spill tray. Once final installation of the components is complete, the spill tray edges and the truss gussets will be welded in place.

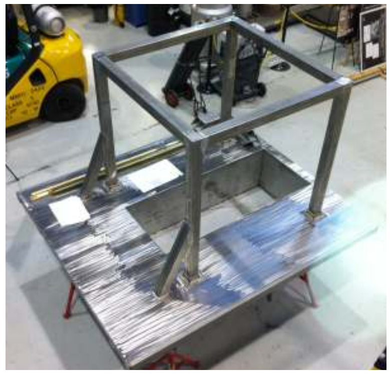

FIGURE 9. Support Structure and Spill Tray.

Gas Systems

There are three gas systems on the RxSim: an argon, a helium, and a nitrogen system. Integral to these gas systems is a vacuum system which is used as necessary to remove the gasses and establish a vacuum. The vacuum system is also used to bleed down pressure if necessary. During the filling and draining operations, the use of vacuum as well as pressure is needed to ensure a good fill with no trapped gas bubble in the system. Typically, when a system is run for the first time, water is driven out of the metal as the steel in the system is heated. This water reacts with the NaK bringing oxygen into solution, contaminating the NaK, and releasing H_2 where it can collect in dead-headed sections of the RxSim, such as pressure transducer sense lines. For this reason, after a new system is heated for the first time, it is drained of NaK and evacuated to remove this gas. Once refilled with NaK the system generally does not experience this issue again.

Argon System

The argon system controls pressure in the LR and the RxSim independently via the isolation valve. The argon gas system is used when filling and draining the RxSim as pressure differentials are used to move the NaK around the system. Once the RxSim is ready for operation, the argon is used to establish a minimum pressure to overcome the surface tension in narrow spaces in the loop, such as in the core or heat exchanger, and to overcome gravitational forces that may inhibit filling of vertical tubes, such as those use to connect pressure transducers.

Helium System

The helium system is used to charge the core with 13.3 - 26.6 kPa (100-200 Torr) of Helium. This is accomplished by first evacuating the electrical section, or helium plenum, of the core then charging it to the specified pressure, see FIGURE 4. Over long duration runs, some out-gassing of the heater elements can occur, raising the pressure in the helium plenum. When this occurs, the helium plenum is evacuated and refilled with helium. As the graphite heaters age from use this effect tapers off significantly.

Nitrogen System

The nitrogen system is used to control the in-vacuum pneumatic valves and to control the actuating solenoids. It is advantageous to use bottle gas versus facility-provided nitrogen, as loss of building power could prevent cycling of the RxSim isolation valve. Both the ALIP and the Stirling engine have strict temperature delta restrictions and experience has shown that some loss of building power scenarios may require the ability to cycle the isolation valve to protect the equipment. The amount of valve cycling during testing is usually very minimal so bottle gas provides sufficient volume.

FIGURE 10. Gas System Racks.

Power System

To supply power to the core, one 15 kW DC power supply capable of 100 A at 150 V is used per zone, requiring a total of 12 power supplies. FIGURE 11 shows the power supply racks. Each rack contains four power supplies. Additional components are added for remote control and high fidelity measurement of current and voltage.

FIGURE 11. Power Distribution Racks.

Cold Trap

A cold trap will be installed on the system in an advantageous position. A cold trap is used to remove impurities or oxides from the system. As NaK is heated, oxygen, which is present from many sources, goes into solution. Once in solution, oxygen acts to facilitate mass transport of the stainless steel walls in a manner that is dependent upon overall loop temperature, delta temperatures, flow velocity, oxygen levels, materials, etc. This mass transport works to corrode the hotter areas and deposit these products in cooler areas. A cold trap works by creating a thermo-trap or well to trap the oxides, keeping them out of the main loop and inhibit the mass transport or corrosion. The final position of the cold trap will be determined after the build is nearly complete.[6]

In addition to a cold trap a plugging meter is commonly employed.[6] A plugging meter works on the same principle as a cold trap but provides the ability to quantify the amount of oxygen or oxygen in solution. A plugging meter will be used on the RxSim. Results of the data collected during RxSim operation will determine if this meter will needed on the TDU.[7]

CONCLUSION

The RxSim continues to be designed and built. Most of the major components have been briefly discussed here. Data acquisition and control was not addressed in this paper but is a significant part of the build effort. More detailed discussion of all aspects of the RxSim will be published in NASA Technical Publications in the near future.

ACKNOWLEDGMENTS

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