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RADIOISOTOPE POWER GENERATION WITH THERMOACOUSTIC POWER SYSTEM (TAPS) TECHNOLOGY

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Nirvana Energy Systems (NES) has pioneered and is commercializing an innovative ThermoAcoustic Power System (TAPS) based on technology developed by NASA and Xerox Palo Alto Research Center (PARC). The novel TAPS technology has no hot moving parts and incorporates well proven, reliable linear actuators in an engine based on the Stirling cycle. NES has designed, optimized, built and tested all sub-systems for reliability, ease of manufacturing and cost reduction over free-piston Stirling engines. The convertor is insensitive to radioisotope heat degradation, capable of 10+ years continuous operation, inexpensive to manufacture using well-established methods, and yields greater than 25% thermal to electrical efficiency all while being designed for a specific power greater than 30 W_e/kg. The NES Thermoacoustic Radioisotope Generator (TRG) represents the ultimate in remote power devices and is the next step toward reliable dynamic power conversion for space.

I. SYSTEM PERFORMANCE

The Thermoacoustic Radioisotope Generator (TRG) has been designed utilizing Nirvana Energy Systems (NES) ThermoAcoustic Power System (TAPS) technology and is being constructed under the NASA Small Business Innovative Research (SBIR) program.

I.A. Performance Objectives

The TRG system has been designed to produce >250 W_e of usable electrical power using 5 General Purpose Heat Sources (GPHS) with a system efficiency of >20%. Furthermore, in order to meet the needs of the Radioisotope Power Systems (RPS) program, the system is designed with a life of greater than 10 years and a specific power greater than 4 W_e/kg.

I.B. System Architecture Overview

In contrast to standard Alpha Stirling engines [Mason][1], rather than using mechanically coupled pistons at either end, the TAPS unit uses electromechanical convertors. This approach is essentially a speaker at one end and a microphone at the other. The "speaker" is used to produce a pressure wave at the "motor" side and the "microphone" is used to receive an amplified wave at the "alternator" side. A pair of opposing motors and alternators may be used at either end to cancel vibrations, depending on system requirements. The phasing and amplitude of the two ends is controlled electronically by the power electronics, which can vary the resistive and capacitive loads in order to achieve the appropriate ratio of real and reactive power necessary to pair the mechanical components to the acoustic engine. Electrical power from the alternator is used to power the motor and keep the cycle going, essentially forming a "feedback" circuit. Figure 1 shows the architecture of the TRG system with the GPHS units affixed.

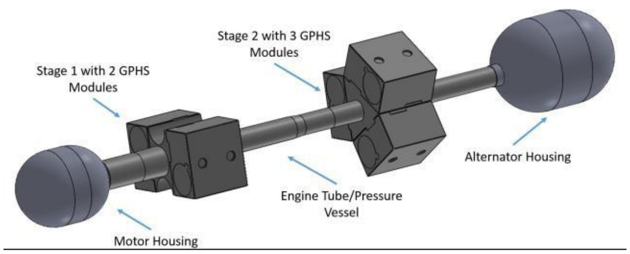

Fig. 1. Thermoacoustic Radioisotope Generator (TRG) System Developed for NASA.

A further distinction from standard Alpha Stirling engines, TAPS technology utilizes thermoacoustic interactions to decrease the amount of power needed to drive the compression side. Adding a second set of components required to convert heat energy into acoustic power through the use of the Stirling cycle provides additional amplification of acoustic power. The components, a cold heat exchanger, hot heat exchanger, and a regenerator in-between are, hereafter, referred to as a "Stage" in the TAPS system. The TAPS device uses two Stirling stages, which are each able to convert heat energy into acoustic energy by roughly the equivalent of the temperature ratio across them, effectively "amplifying" the pressure oscillation within the engine. For example, 1123 K hot end and 323 K cold end theoretically yields an amplification of 3.47 per stage. Achieving this theoretical gain gets more difficult with more stages, so a three-stage engine is not necessarily better than a two-stage system.

TAPS can also be viewed as a traveling wave toroidal thermoacoustic engine in which the inertance and compliance volumes have been replaced with their electrical equivalents, avoiding the "Gedeon" streaming inherent with pneumatically linking the hot and cold end of those engines. With this control methodology, the device is able to shift pressure/velocity phasing within the regenerators and effectively "de-tune" the engine to shift the power to thermal ratio. So, the device can almost instantaneously adjust power output to accommodate available radioisotope heat energy, or electronic demand.

Moreover, the TAPS device is roughly linear, avoiding the complex 3D geometry within annular Free Piston Stirling (FPS) devices. This allows excellent correspondence between prediction and experiment. NES has seen <5% difference between prediction and test data with its prototypes. Additionally, 100 W_e, 1 kW_e units and beyond have been produced, demonstrating that the units are easily able to be scaled based on design.

II.C. Materials Considerations

Materials investigations related to application in space power systems have a long history. Only a few years ago, it was much easier to list the projects and programs that spent incredible time and resources to develop power possibilities for space. From a NASA perspective, however, two programs are foundational for how material science has evolved and matured to meet specialized requirements over a range of complexities. The Space Reactor Prototype, SP-100, project in the late 20th century and the Advanced Stirling Radioisotope Generator (ASRG) project in the early 21st century. SP-100 had a higher power goal, which led to the consideration of higher temperature capable materials while ASRG targeted a lower power which allowed for slightly lower temperature capable materials. While the goals of these two projects were different, significant materials screening and evaluations were performed to facilitate materials choices for a range of systems going forward.

The thermoacoustic Stirling engine being designed contains a pressure vessel, hot acceptor heat exchanger, cold rejector heat exchanger and a regenerator. To meet performance and efficiency criteria for the space power system, hot-end temperatures of 850 °C will be experienced. The paper entitled, "Evaluation of Candidate Materials for a High-Temperature Stirling Convertor Heater Head" [Bowman][2] acknowledges that the upper temperature limit of superalloys for heater head application is 850 °C. The heritage and capability of Ni- base superalloys has been significantly, if not thoroughly, investigated in the literature. The strength mechanisms, environmental protection, physical properties, and much more have been investigated such that alloy development strategies are well understood and the reasons behind material responses are largely known. At temperatures higher than 850 °C creep strength becomes an issue and other unknowns such as microstructural evolution that directly affects mechanical response. Since anticipated lifetimes are over 10 years, it has been concluded that nickel-base superalloys will not have the durability necessary for next generation power system definition.

[Bowman][2] also discusses the candidacy of refractory metal alloys and ceramic materials for pressure vessel application in Stirling-type space power systems. Compelling cases can be made for some ceramic materials for pressure vessel candidacy; however, since the heritage of such application is lean, ceramic materials were determined to be of higher risk and were not considered for the TRG.

Like [Bowman][2], [Ritzert][3] considered the potential for Ni-base superalloys, refractory metal alloys and ceramic materials for a space power mission, specifically for a Venus lander. Per aforementioned reasons, Ni-base superalloys and ceramic materials were not candidates for the thermoacoustic power system. Refractory metal alloys, however, were explored. While [Ritzert][3] do not comprehensively discuss refractory metal alloys, they do give enough of a high-level view for a deeper investigation into the literature for a subset of those alloys. The goals of [Ritzert][3] were similar to those of SP-100 – higher temperature application at a moderate stress level.

Refractory metal alloys absolutely have their drawbacks. Some of them are very heavy. All of them have poor oxidation properties. Thermal conductivity and thermal expansion can be issues depending on what end of the spectrum the application requires. Some of them have a high ductile-to-brittle transition temperature (DBTT), which can mean brittle properties at lower temperatures. Some can have low recrystallization temperatures which means that an alloy can lose its high temperature, high strength properties if the material happens to recrystallize (i.e., loses the strain stored in the "worked" structure). But the right refractory alloy can be the best solution possible.

Refractory metal definition is not universally agreed upon in the materials community, but this author uses the definition of the godfather of refractory metals, [Buckman][4]. That definition is that the melting temperature must be over 2000 °C, it must have a body-centered cubic (BCC) structure, and must be able to form a carbide. That leaves molybdenum (Mo), niobium (Nb), tantalum (Ta) and tungsten (W). Alloys based on W and Ta could be very excellent candidates for pressure vessel application, but since their densities are so high (16.4 g/cc and 19.8 g/cc, respectively), "specific" properties suffer. So, while Ta and W can remain candidates, first order vetting of materials for pressure vessel application will be the Mo- and Nb-based alloys.

II.C.1 Materials Selection

A Nb alloy was chosen as the pressure vessel material for the TRG. Several Nb alloys have been considered in the past and are excellent. The only commercially available Nb alloy today is C-103 (Table 1). Nb alloys, refractory alloys indeed, have only a modestly higher temperature application for pressure vessels in power systems than Ni-base superalloys – but the delta is enough. In fact, a Nb-base alloy (Nb-1Zr) was chosen in SP-100 as the alloy of choice for the pressure vessel. Niobium alloys are not the strongest of the refractory alloys, but they are sufficiently so based on 1 percent creep strain Larson-Miller prediction of 20-year life at 850 °C and 11 ksi (Figure 2). C-103 has a modest thermal conductivity (Figure 3), which is perfect for pressure vessel application as it is undesirable if heat is conducted through the metal away from the hot zone towards the cold heat exchanger. Also, since the thermal expansion coefficient will be consistent with mating components (e.g., heat exchangers also made of C-103), stresses and metallurgical compatibility become extremely favorable. This optimized interfacial interaction is a benefit as the heat needs to get into the thermoacoustic system that resides inside of the pressure vessel and metallurgical interface issues add a layer of complexity. C-103 has a DBTT that is below what a spacecraft will encounter so no brittle failure issues should exist in the pressure vessel. Lastly, its density is relatively low (8.85 g/cc), especially compared to other types refractory metal alloys.

TABLE II. Chemistries of C-103[5].

Alloy	Composition
C-103	Nb-10Hf-(0.7-1.3)Ti-0.5Ta-0.5W

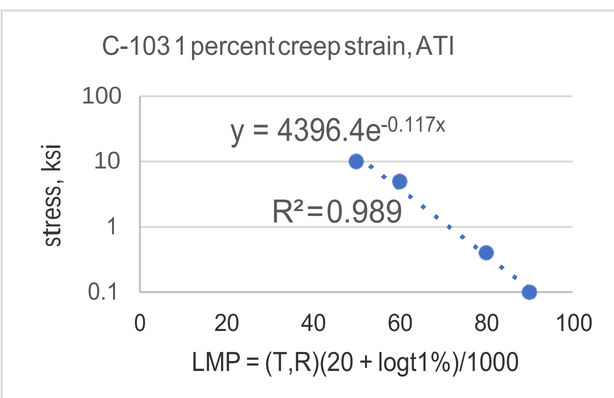

Fig 2. C-103 1 Percent Creep Strain[5].

Heat must efficiently get into the thermoacoustic system from the general-purpose heat source (GPHS) modules. If it was preferred and needed to select an alloy that maximizes thermal conductivity, then a refractory metal with higher thermal conductivity (e.g., Mo-TZM) could be selected. Instead, due to short conduction paths, it is of more interest to make the power system to have a high probability of success for fabrication. This goal encourages the consideration of making thermoacoustic components from the same alloy material (i.e., C-103) While the C-103 alloy has a more modest thermal conductivity (Figure 3), COMSOL and Sage® modeling indicate that all power and efficiency goals are still met [Bruder][6].

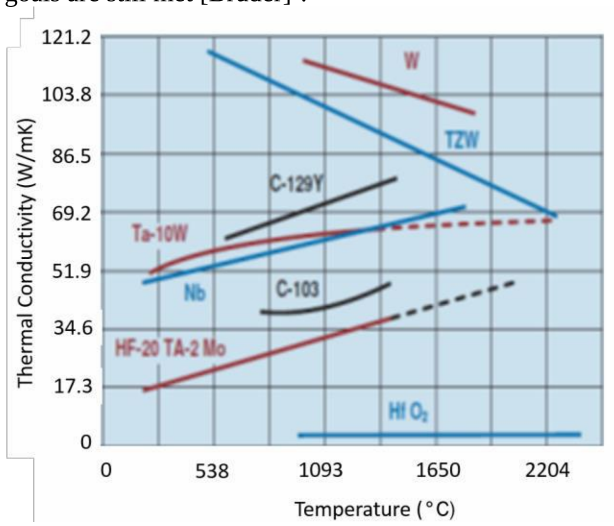

Fig 3. Thermal conductivity of several refractory alloys[3].

II.C.2 Refractory Coating

One limitation often noted for the use of refractory metals and their alloys is that they oxidize at higher temperatures, for some alloys even as low as 200 °C. The refractory metals such as Mo, W, Ta and Nb do not naturally form thin, protective oxides, but rather they oxidize rapidly via formation of non-protective oxides. This poses less of a threat during a space mission as the environment is a vacuum, but for any ground testing the refractory alloys are susceptible to oxidation degradation. Therefore, for the portion of time that the refractory alloys will see oxygen at high temperature, a coating will be necessary.

Coating of refractory metals and alloys has a long heritage. While deposition coatings like platinum or palladium are thought to be effective, any "open" in the coating (e.g., crack) would allow the refractory metal to be oxidized while leaving a precious metal shell behind. Diffusion coatings have been more historically protective and relied upon.

Aluminizing the surface of a refractory material allows an aluminide with the base material to form. Such an aluminide on the surface provides a reservoir of aluminum available to form aluminum oxide (i.e., alumina) on the surface at high temperature in an oxidizing environment. The alumina layer is a protective oxide – it protects the base material from catastrophic oxidation. However, the aluminide that forms on the surface is a product of aluminum diffusing outward from the aluminum case that was added and oxygen diffuses inward to react with the aluminum. When the aluminum case becomes depleted, no more is available to form more protective oxide should spallation or other damage to the initial alumina layer take place.

The most relied upon protection of refractory alloys is the formation of a silicide on the surface. Processes are defined such that silicon (Si) diffuses into the base metal and forms either a single layer or several layers of silicide with the base metal as a constituent. These silicide layer(s) promote the formation of a protective silicon dioxide (i.e., silica) layer that protects the base metal from the environment. If a crack in a silicide layer should occur, the silica reforms to "heal" the fissure with a protective layer. The silicide layer(s) formed are thought to provide a good reservoir of silicon for continued silica formation; however, calculations and/or experiments should be made for confirmation. Several types of this silicide coating are commercially available and have heritage – R512E (Si-20Cr-20Fe), SIBOR, Mo-Si-B.

II. MEETING THE PERFORMANCE OBJECTIVES

TRG has been designed to meet the SBIR program criteria through extensive modeling. The device internal thermoacoustics are modeled utilizing the 1-D Navier Stokes equation solver, Sage® while system stresses are modeled using the Multiphysics solver COMSOL.

II.A. Performance Overview

Figure 4 shows the predicted power transmission throughout the TRG system. From left to right (1) electrical power is utilized to drive the linear motor, (2) losses are accounted for in generating the acoustic wave in the system and transmitting it to the first regenerator, (3) the first regenerator gain, (4) transmission losses between stages, (5) the second regenerator gain, (6) transmission losses and conversion of the acoustic wave into mechanical energy, (7) electrical output of the linear alternator.

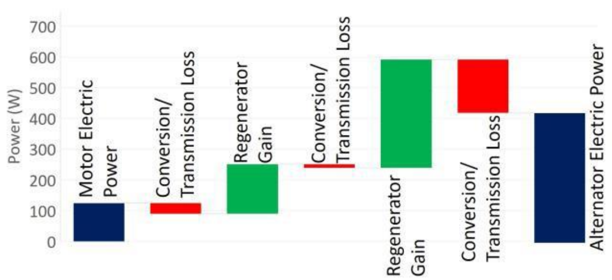

Fig 4. TRG Acoustic Power Accounting

The net output power described through this process is an output power in excess of 250 W_e and an efficiency of >20% for the generator system. NES is able to use test data from commercial power device to estimate the electrical conversion efficiencies within the power electronics, and these numbers are included within the net reported efficiency.

III. CONCLUSIONS

Through the efforts of the Phase I and Phase II SBIR programs, NES has designed the TRG system to meet or exceed all NASA RPS requirements. Table 2 summarizes the system criteria and adherence of the design.

TABLE II. TRG Project Criteria.

Requirement	Criteria	Criteria Met?
Design Life	10+ years	Exceeded
Electrical Power	100 - 500 W_e	Met
Thermal Input	Integer GPHS	Met
Specific Power	>4 W_e/kg	Exceeded
System Efficiency	20%	Exceeded

The TRG system has been designed to exceed life requirements by meeting creep criteria of pressure vessel components such that 1 percent strain is not exceeded after 20 years of service life. A specific mass optimization was performed which showed a unit with a >250 W_e output using 5 GPHS modules would be optimum. A preliminary estimate including packaging and insulation shows the system at 9.81 W_e/kg. Finally, system efficiency is shown to be in excess of the required 20% thermal-to-electrical conversion, including power electronics conversion losses.

ACKNOWLEDGMENTS

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