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Technology Assessment of DOE's 55-We Stirling Technology Demonstrator Convertor (TDC)

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October 2000

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**TECHNOLOGY ASSESSMENT OF
DOE's 55-We STIRLING TECHNOLOGY DEMONSTRATOR CONVERTOR (TDC)**

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ABSTRACT

The Department of Energy (DOE), Germantown, MD and the NASA Glenn Research Center (GRC), Cleveland, OH are developing a Stirling Convertor for an advanced radioisotope power system as a potential power source for spacecraft on-board electric power for NASA deep space science missions. The Stirling Convertor is being evaluated as an alternative high efficiency power source to replace Radioisotope Thermoelectric Generators (RTGs). Stirling Technology Company (STC), Kennewick, WA, is developing the highly efficient, long life 55-We free-piston Stirling Convertor known as the Technology Demonstrator Convertor (TDC) under contract to DOE. GRC provides Stirling technology expertise under a Space Act Agreement with the DOE. Lockheed Martin Astronautics (LMA), Valley Forge, PA is the current power system integrator for the Advanced Radioisotope Power System (ARPS) Project for the DOE. JPL is responsible for the Outer Planets/Solar Probe Project for NASA.

HISTORY AND BACKGROUND

The Department of Energy (DOE), Germantown, MD and the NASA Glenn Research Center (GRC), Cleveland, OH are developing a Stirling Convertor for an advanced radioisotope power system as a potential power source for spacecraft on-board electric power for NASA deep space science missions. The Stirling Convertor is being evaluated as an alternative high efficiency power source to replace Radioisotope Thermoelectric Generators (RTG's). Stirling Technology Company (STC), Kennewick, WA, is developing the highly efficient, long life 55-We free-piston Stirling Convertor known as the Technology Demonstrator Convertor (TDC) under contract to DOE. GRC provides Stirling technology expertise under a

Space Act Agreement with the DOE. Lockheed Martin Astronautics (LMA), Valley Forge, PA is the current power system integrator for the Advanced Radioisotope Power System (ARPS) Project for the DOE. The Jet Propulsion Laboratory (JPL), Pasadena, CA is responsible for the Outer Planets/Solar Probe (OP/SP) Project for NASA.

On September 28, 1999, the DOE and NASA agreed to a three-month study to evaluate the technology readiness of DOE's 55-We TDC as an alternative power technology for NASA's future deep space science missions. This report provides a summary of the review conducted by the joint government/industry team and presents the team's conclusion that no technical showstoppers exist for the 55-We TDC. Further, the 55-We TDC is ready for the next step towards developing the Stirling technology into a radioisotope power system for a future NASA deep space science mission.

GOVERNMENT/INDUSTRY TECHNOLOGY
ASSESSMENT TEAM

The Department of Energy (DOE), the National Aeronautics and Space Administration (NASA) and the Jet Propulsion Laboratory (JPL) established a DOE-led team to assess the technology of the free-piston Stirling Convertor as an alternative to RTG's. The DOE joint government/industry technical assessment team included: NASA's Glenn Research Center (GRC), Cleveland, OH and the Jet Propulsion Laboratory (JPL), Pasadena, CA; Lockheed Martin Astronautics (LMA), Valley Forge, PA and Denver, CO; Orbital Sciences Corporation (OSC), Germantown, MD; Westinghouse, Pittsburgh, PA; Babcock & Wilcox (B&W), Mound, OH and Stirling Technology Company (STC), Kennewick, WA.

STIRLING TECHNOLOGY ASSESSMENT PROCESS

On October 7, 1999 the DOE government, industry team met to review the current capabilities of the Stirling Converter developed for DOE by STC. DOE wanted to determine if the existing Stirling technology was a viable option for a mission with a launch date of December 2004. DOE established the 55-We TDC, shown in Figure 1, as the baseline Stirling Converter for this assessment.

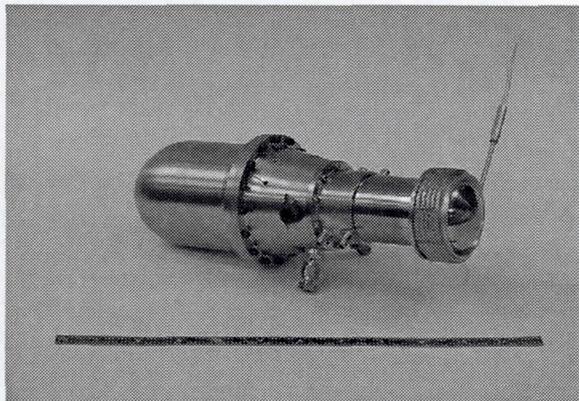


Figure 1. Photo of DOE's Stirling Converter
- 'the 55-We TDC'

LMA, at the NASA/DOE meeting of September 28, 1999, identified eight key areas for review. Included were the TDC's predicted and actual capabilities in the key areas shown in Table I.

The TDC's capabilities were also assessed against JPL's mission criteria for NASA's near-term [Europa Orbiter (EO) '03 and Pluto/Kuiper Express (PKE) '04] and long-term [Solar Probe-'07] missions along with the X2000 technology requirements. The Team proposed further testing and evaluation of the existing DOE 55-We TDC's to provide additional data for the technology assessment:

- 1) Dynamic Launch Load Capabilities,
- 2) EMI/EMC Characterization and
- 3) Performance Mapping.

Further, additional evaluation and analysis was proposed to better understand and define the following:

- 4) Radiation Survivability of the organics of the 55-We TDC design,
- 5) Controller Functionality & Survivability,

- 6) FMECA and Life & Reliability Analysis of the 55-We TDC designs; and
- 7) Fault Tolerance of the Power System to meet ARPS power requirement.

Data from these key technical areas would provide a better understanding of the status of the technology and help determine the availability of the 55-We TDC design for a future Stirling Radioisotope Power System (SRPS) to meet the needs of NASA's future deep space missions.

55-We TDC TEST AND EVALUATION

Launch Environments Vibration Testing at GRC by GRC and STC

GRC and STC personnel conducted tests on a single 55-We TDC (S/N 001) the week of November 29, 1999.^{1, 2} The TDC is shown in Figure 2 at GRC's Structural Dynamics Laboratory. The purpose was to characterize the TDC and determine if it could meet the criteria established by JPL for launch environments. The single 55-We TDC was operated at full-stroke and full power conditions during the vibration testing. The 55-We TDC was tested in two orientations with the moving components (displacer and piston) parallel to and then perpendicular to the vibration axis. These tests had a peak vibration level of $0.2g^2/Hz$ from 50-250 Hz and test duration of 3 minutes in each axis, which is equivalent to the JPL qualification requirement. No changes in the 55-We TDC performance were found after the completion of each test point. The random vibration levels were chosen to simulate the maximum anticipated launch vibration conditions. The TDC successfully passed workmanship (6.8 Grms), flight acceptance (8.7 Grms), and qualification (12.3 Grms) of random vibration testing levels over a frequency range of 20 to 2000 Hz. Representatives from the DOE, JPL, LMA, OSC, B&W, and Teledyne Brown witnessed the tests at GRC.

EMI/EMC Characterization of a pair of 55-We TDC's at GRC by LMA, JPL and GRC

GRC, LMA and JPL personnel conducted tests on a pair of 55-We TDC's (S/N 001 and 002), shown in Figure 3, the week of December 6, 1999 at GRC's EMI/EMC Laboratory.³ The purpose was to characterize the radiated electromagnetic fields in order to determine whether the 55-We TDC's are electromagnetically compatible with X2000

Table I. Stirling Technology Assessment of the 55-We TDC as of Sept. 28, 1999

No.	Attribute	Current Data/Key Issues	Assessment Rating
1	Efficiency	Data needed with cold end rejection temp at 120 C	G
2	Lifetime	Several organics will not survive rad environment Permanent magnet radiation survivability unknown	Y
3	Dynamic Capability	No test data available	Y
4	Vibration	Two synced TDC's provide adequate damping	G
5	Magnetic and EMI	No test data available	Y
6	Model Validation	Data needed under steady state & transient conditions	Y
7	Controller Functionality	Design needed to evaluate controller	Y
8	Controller Survivability	Rad environment exceeds ratings for parts	Y

Assessment ratings: G) No technology issues, Y) Technology issues identified with solutions defined or identified and R) Technology unavailable and solutions are unknown.

requirements. The main concern is that the X2000 radiated emissions requirements are up to 100 dB more stringent than the corresponding MIL-STD-461 requirements (current X2000 specification is -30 dBpT/(Hz @ 1m). Currently, of the three missions considered (EO, PKE and Solar Probe), only the Solar Probe mission is planned to have the plasma experiments that would drive the tight EMC requirements. It should be noted that the TDC's tested were not optimized for Electromagnetic Compatibility.

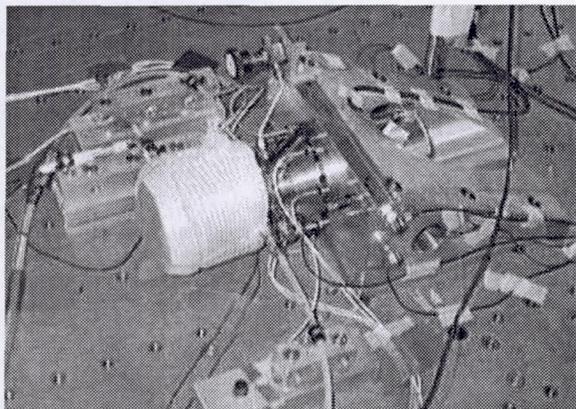


Figure 2. Photo of 55-We TDC at GRC's Structural Dynamics Laboratory

(EMC), as there was no attempt to minimize loop area, clock the TDC's relative to one another, or provide any shielding in the TDC design.

The tests performed at GRC included:

- RE01 AC Magnetic Emissions, 50 Hz - 150 kHz, 13.3 cm loop antenna, 4 antenna positions - 12.5cm, 25cm, 50cm, 1m
- RE04 AC Magnetics, 50 Hz - 150 kHz, larger loop antenna, at 3 antenna positions - 25cm, 50cm, 1m

- Search coil measurements, 25cm and 1m (3 axis measurement)
- RE02 Electric Field Emissions, 50 Hz - 150 kHz and 14 kHz - 1 GHz at 1 meter
- CE01 (conducted current emissions measurement) test, measured at engine/alternator interface for information only; JPL spec not applicable at this interface
- Characterized controller voltage and current waveforms
- Magnetic Field Emissions test using partial mumetal shields over ends of alternators

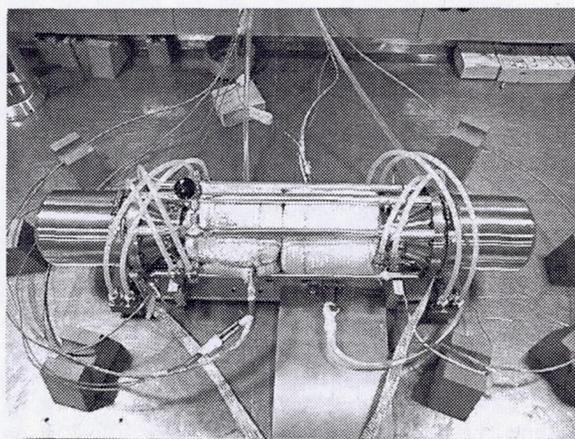


Figure 3. Photo of a Pair of 55-We TDC's at GRC's EMI/EMC Laboratory

Based on the test data, the non-optimized 55-We TDC's would meet the missions EMC requirements for the EO and PKE missions, but would exceed the Solar Probe magnetic field requirements by up to about 100 dB at the 80 Hz fundamental operating frequency. The

electric field emissions exceeded the Solar Probe electric field requirements by about 60 dB, but further testing showed that these emissions were primarily being radiated by the interconnecting cable, and were reduced by 30 dB with minimal effort. Harmonic content is largely a function of the current waveform, which is expected to be quite sinusoidal in a flight unit, thus making the harmonics insignificant

In order to use a 55-We TDC on a science mission with plasma experiment (i.e., the Solar Probe mission), it is recommended that care be taken to ensure that all current loops are minimized. Large improvements in magnetic field emissions performance would be expected just by controlling wiring layout and providing counter-loops to offset any generated fields. In addition to current loop control, it is also anticipated that magnetic shielding will be required to meet the science objectives of this type of mission.

During the EMI/EMC characterization at GRC, the 55-We TDC was operated for 35 hours. This operation provided 10^7 cycles on the flexures in the TDC S/N 001, which is an accepted criterion used to verify long life. Performance was monitored during this period and no degradation of performance was observed. At the conclusion of the EMI/EMC testing, both TDC's were returned to STC, Kennewick, WA for subsequent disassembly and inspection. On January 4, 2000, representatives from GRC, LMA and STC witnessed the disassembly and inspection of the 55-We TDC S/N 001. It is the consensus of the inspection team that no apparent damage or change in the physical condition resulted from the vibration testing at GRC.

Performance Testing of the 55-We TDC by STC

STC conducted additional tests on the 55-We TDC's (S/N 003 and 004) at their facilities in Kennewick, WA.⁴ The purpose of the additional testing was to characterize the 55-We TDC at 650°C heater head and 120°C heat rejection temperatures. Initial performance of the TDC was demonstrated for a unit optimized for an 80°C heat rejection temperature. The units were subsequently optimized and tested at a 120°C heat rejection temperature. These rejection temperature levels cover the range believed to be optimum from an overall system standpoint. System mass and power output trade off as rejection temperature varies, with power output improving for lower rejection temperatures. Reference performance measurements were made for the condition representing thermal input available from a GPHS nine years after fabrication,

with a calculated vacuum foil insulation thermal loss of 6%.

The predicted and measured performance of the 55-We TDC are shown in Figure 4. At an 80°C heat rejection temperature, power output was 62 watts with a TDC efficiency of 29.1%. With the rejection temperature increased to 120°C, the TDC efficiency was 26.4%, which results in 56.2 watts of electric power. When a TDC is optimized for a specific rejection heat temperature, it can operate over a range of rejection temperatures encountered during a range of mission profile conditions. Specific performance characterization of the TDC is currently being conducted for a range of conditions that may be encountered during a typical mission.

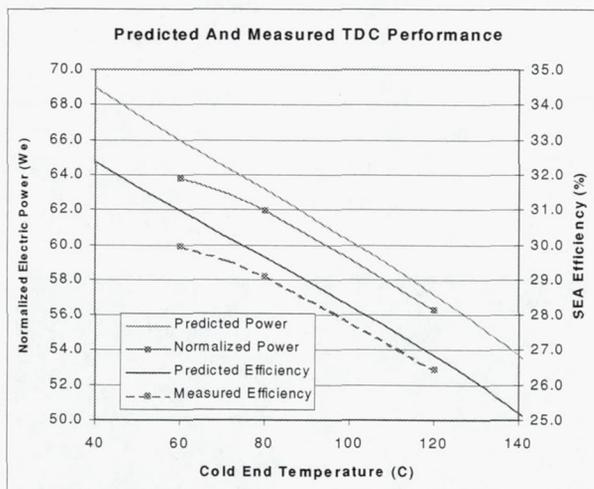


Figure 4. Predicted and Measured Performance of the 55-We TDC

ADDITIONAL 55-We TDC STUDIES

Controller Assessment by LMA

An ARPS with Stirling Convertors (engine/alternator) for power conversion requires a more active and complex control approach than the thermoelectric conversion used in past radioisotope thermoelectric generators. Specifically the 55-We TDC output power is at 80 Hz, 70 Vac. This output must be converted to 28 Vdc and filtered to be compatible with the spacecraft power bus. In addition, the controller must regulate the Convertor output to protect the 55-We TDC and ensure optimum power production. The mass and power processing efficiency of the controller affect the overall performance of a Stirling ARPS.

In the past, the specific requirements for the Stirling controller have not been well defined. A requirement

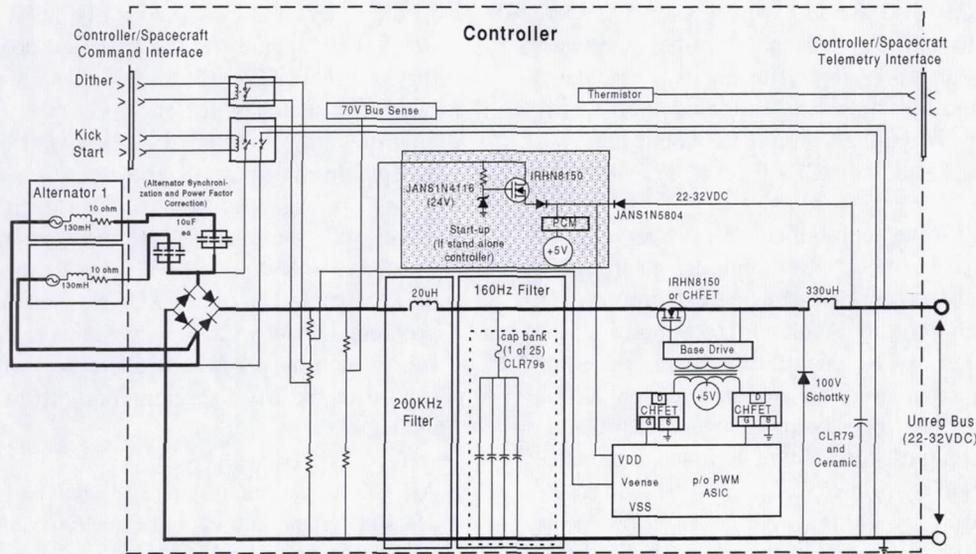


Figure 5. Stirling Controller Schematic

of particular concern for the Europa Mission is the severe radiation environment, which can significantly affect the performance and the mass of spacecraft electronics. The issues at question are: 1) Is it feasible to implement a controller design given the requirements and the environment? and 2) Have reasonable estimates of controller mass and power processing performance been used in evaluating the Stirling ARPS?

The approach to this assessment has been twofold: 1) Establish and document the requirements and interfaces for the controller, and 2) Develop a controller design to meet those requirements at a sufficient level of detail to enable the assessment of performance, estimate the mass, and to evaluate the radiation tolerance.

Lockheed Martin and DOE utilized experience from previous RTG programs, Stirling engine expertise from NASA/GRC and STC, along with JPL and Lockheed Martin knowledge of the outer planets mission and spacecraft requirements to define the controller interfaces and the basic functional requirements.³ The key requirements include the following:

- Compatible with Battery-Dominated Spacecraft Power Bus Interface
- Process and Control the Output of Two "Paired" Convertors

- Provide "Dither" Control to Enable Reduced Stroke Operation During Launch and Acceleration (If required)
- Provide Convertor Restart Capability (If required)
- Provide Generator Telemetry to Spacecraft & EGSE Interface
- Accept Commands from Spacecraft or EGSE
- Operate Continuously When Connected to Generator
- Provide "Make-Before-Break" Capability

These requirements were then expanded into a preliminary Controller Performance Specification that was based on the existing design and environmental requirements for the X2000 spacecraft power system electronics.

These requirements were then used to develop a circuit design and packaging approach for the Stirling Controller. The detailed requirements and design work was performed by Lockheed Martin Commercial Space Systems (who is also under contract to JPL for the technology development of the X2000 power systems electronics). The circuit design utilizes proven power conversion and regulation concepts.

Electronic components utilized are either existing rad-hard parts or currently under development for X2000. The SABER circuit simulation tool was used to verify circuit operation and performance. The

design was developed using a single-string approach with the fault-tolerance approach described in a following section. Mass and volume estimates were developed based on existing similar hardware designs. Power processing efficiency was calculated at 90.3%; Controller mass was estimated to be 3.3 kg. If redundancy is required within the controller, it is estimated that an additional 1 kg would be required.

The basic controller requirements have been defined and are well understood. The circuit design shown in Figure 5 can be accomplished using existing, proven power conversion and regulation techniques. The rad-hard design can be implemented using the same "set" of components that are required for the X2000 power system electronics being developed for use on the OP/SP missions - there are no unique components required for the Stirling Controller. Finally, the controller efficiency and mass are consistent with the estimates used in the system comparison studies.

Organic Materials Ionizing Radiation Survivability Study by GRC et al

The mission to Europa imposes a very severe ionizing radiation environment to the 55-We TDC. The radiation from the isotope power source is insignificant when compared to radiation from the environment for 30 days in the Europa orbit. The alternator magnets and organic materials were initially believed to be inadequate to meet these

requirements. The magnets meet the Europa requirements. The data from literature along with LMA analysis shows practically no degradation of the NbFeB magnets at the expected dose. However, the 55-We TDC's built to date contain some organic materials, which will not survive the harsh Europa environment. A detailed assessment has shown that acceptable substitute materials exist for the organics.⁵ An effort was made to choose substitute materials close to the same family and function as the original. These were evaluated by STC and were assessed to be acceptable for future TDC's. Should unexpected problems arise with the substitutes, and a second substitution must be made, there is a sufficient list of candidate radiation tolerant organic materials from which to choose.

All of the organic materials are sealed inside the pressure vessel and cannot escape to contaminate the rest of the spacecraft. Therefore, outgassing should not be a problem. The pressure of the helium inside the vessel should also act to inhibit outgassing from the organic materials. Since the coldest part of the Converter is the pressure vessel wall, any outgassed organic material would deposit there, and will not affect the function of the Converter.

NASA Glenn through consultation with members of the JPL staff, Lockheed Martin, GE-Schenectady, STC, and commercial material vendors has carried

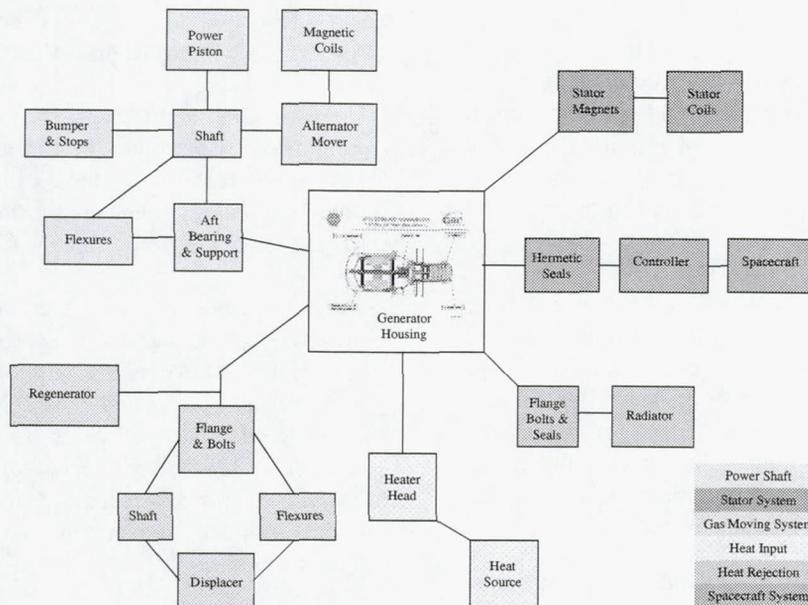


Figure 6. Reliability Block Diagram of the Stirling Converter

out this evaluation. Additional coordination with the JPL Europa spacecraft materials engineers is expected as the decision to consider using Stirling for an RPS is finalized. Further confirmation of functional suitability of the new materials will come in the following months as 55-We TDC (S/N 005 and 006) will be built with these new materials. These TDC's are scheduled for delivery and testing at NASA GRC in mid-2000.

FMECA and Life/Reliability Study by GRC

The Office of Safety and Assurance Technologies (OSAT) was tasked to do an independent reliability assessment of the 55-We TDC that was proposed as a possible power source for upcoming deep space missions.⁶ The assessment included two tasks. First, develop a Failure Modes Effects and Criticality Analysis (FMECA) for the 55-We TDC. The analysis was to address only the Stirling Converter itself, which included the heater head, alternator, displacer, pistons, rods, flexures, hermetic closures, and the pressure vessel. It did not include the subsystems outside of the vessel. This excluded the radiator, controller, structural interface, GPHS blocks and housing from the study. The reliability block diagram of the Stirling Converter is shown in Figure 6.

The second task was the development of a life and reliability model using the available component test data. The purpose of this task was to determine if the TDC was capable of completing a 14-year mission.

The first step in creating the FMECA was to develop a list of assumptions. The major assumption was the definition of a critical failure. The following is taken from the list of assumptions.

A critical failure is defined as a failure that prevents the 55-We TDC from producing power at or near its full capacity. A failure that shuts the TDC down but allows a restart is not a critical failure. A failure that diminishes the electrical output of the TDC is not a critical failure. (An area open for discussion is what level of reduced electrical power should be considered the threshold for a critical failure.) The criticality categorization of a failure mode shall be made on the basis of the worst-case potential failure effect regardless of the probability of occurrence.

The first portion of the FMECA was completed by late November. This was comprised of the component level Failure Mode and Effects Analysis (FMEA) which was based on STC's drawing package (2013-1) and parts lists of the 55-We TDC (S/N 001 and 002). The FMEA consisted of all phases of the TDC operational life from

fuel loading to completion of mission. This data was sent out to various team leads for review. While the component FMEA was being reviewed, a top level FMEA was generated. The purpose of this analysis was to determine if there were any failures in external systems that would cause a critical failure in the TDC.

From the component FMEA, a Critical Item List (CIL) was generated. The CIL consisted of all failures deemed critical that were exposed in the FMEA. Entries in the CIL were given a qualitative assessment of the feasibility of the failure (ranked 1-3).

The Life and Reliability study was done on components in the CIL. Test data, materials data, and component design data was researched. Recommendations for reaching a 14-year life were listed for each component. The assessment of the 55-We TDC indicates that all design issues are well understood and within the capabilities of the current best design practices.

STIRLING RADIOISOTOPE POWER SYSTEM (SRPS) CONCEPTS

Fault Tolerance Study of 55-We TDC's for an ARPS by LMA

A study of Stirling generator concepts was initiated at the request of the DOE to investigate system options that offer some degree of fault tolerance.³ The study was in response to the observation that the baseline concept (shown in Figure 7) of two Convertors per generator with two generators per spacecraft failed to meet the proposed JPL single failure power loss requirement of not more than ~ 13% of generator output power. Thermal analyses showed that the loss of one Converter would result in excessive temperatures that are expected to lead directly to the failure of the second engine as well, unless provisions are made to remove the excess thermal energy from the heat source.

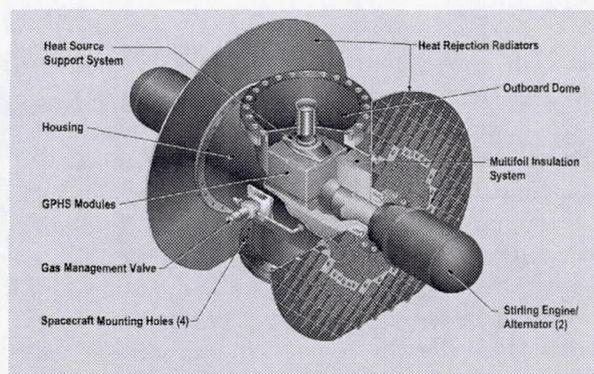


Figure 7. LMA's Stirling Generator Concept
- Courtesy of DOE

STIRLING RADIOISOTOPE POWER SYSTEM
USING A PAIR OF 55-We TDC's

Among the alternate concepts considered, two have the potential of meeting the JPL requirement:

1. Provide three generators per spacecraft for the baseline design; such that upon failure of one generator the two survivors meet mission power requirements.
2. Provide four 55-We TDC's in each of the two generators, such that failure of one convertor allows mission power requirements to be met by the remaining operating convertors.

It is concluded that generator concepts can be identified that meet JPL single fault power requirements. However, a mass penalty is associated with these fault tolerant concepts that is at least 26 kg when compared to the baseline concept. Additional work is needed to further evaluate generator concepts and determine failure rates.

Table II. Characteristics of Fault Tolerance Concepts

	Concept 1 (Baseline)	Concept 2
Number of GPHS Modules per	2/6	3/6
Convertor Efficiency	27.9	23.4 to 25.0
EO EOM Spacecraft Power, We	318	268 to 288
EO EOM Spacecraft Power with One Failure	212	280 to 290
Mass of Generators (Kg)	78	99.8

CONCLUSIONS

The DOE joint industry/government team concluded that no technical showstoppers exist for the 55-We TDC. Current testing has shown the existing Stirling Convertor design to be reliable and robust. Additional work is required in the following areas: 1) Fault tolerance (minimum power requirement), 2) Stirling model validation, 3) Detailed cost and schedule, 4) Meeting JPL's technology readiness criteria, and 5) Thermal shunt design if required. Data from the launch environments vibration testing indicates that the dither control and restart capability may not be required, therefore further simplifying the controller design,

weight and cost. In conclusion, the 55-We TDC is ready for the next step towards developing the Stirling technology into a radioisotope power system for a future NASA deep space science mission.

All the data was presented to DOE/NASA at a management meeting in Germantown, MD on December 16, 1999. In attendance were representatives from DOE, NASA GRC, JPL, LMA, STC, OSC and Teledyne-Brown. Current efforts are directed in developing formal documentation for the data as a final report to DOE and NASA. The assessment of the 55-We TDC is shown in Table II. The findings of this assessment were presented by the DOE led government/industry team to NASA Headquarters, Office of Space Science and JPL on January 27, 2000. As a result, NASA has identified the Stirling generator as the advanced power system for potential missions such as Europa Orbiter ('06) and Solar Probe ('07).

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13. ABSTRACT (<i>Maximum 200 words</i>) The Department of Energy (DOE), Germantown, Maryland and the NASA Glenn Research Center (GRC), Cleveland, Ohio are developing a Stirling Convertor for an advanced radioisotope power system as a potential power source for spacecraft on-board electric power for NASA deep space science missions. The Stirling Convertor is being evaluated as an alternative high efficiency power source to replace Radioisotope Thermoelectric Generators (RTGs). Stirling Technology Company (STC), Kennewick, Washington, is developing the highly efficient, long life 55-We free-piston Stirling Convertor known as the Technology Demonstrator Convertor (TDC) under contract to DOE. GRC provides Stirling technology expertise under a Space Act Agreement with the DOE. Lockheed Martin Astronautics (LMA), Valley Forge, Pennsylvania is the current power system integrator for the Advanced Radioisotope Power System (ARPS) Project for the DOE. JPL is responsible for the Outer Planets/Solar Probe Project for NASA.				
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