JPL

Isotope Power Systems

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DEGRA – A Computer Model for Predicting Long Term Thermoelectric Generator Performance

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Presentation Outline

- Background
- RTG degradation mechanisms
- Status and Objectives

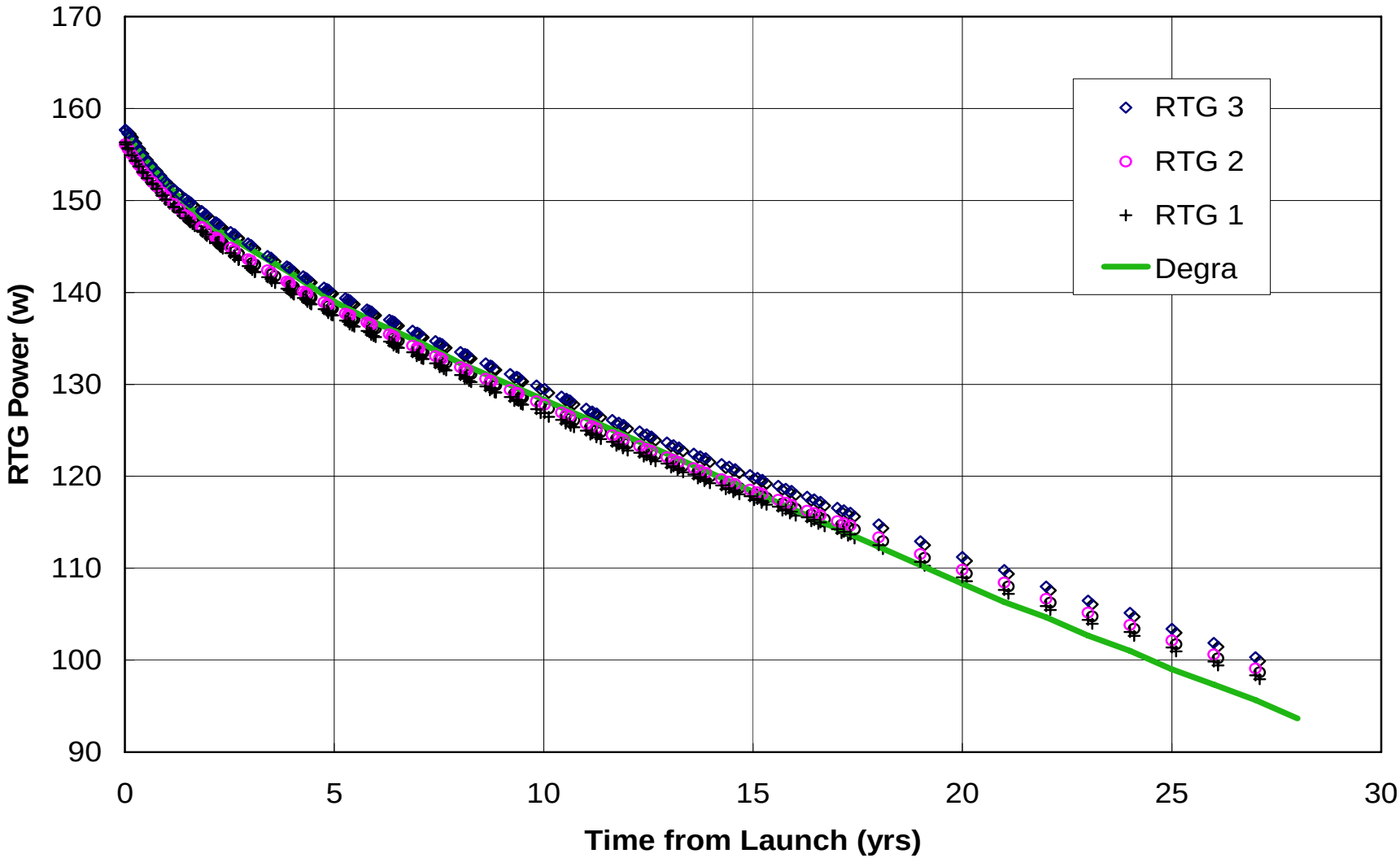
Purpose of Degra

- Computer code that calculates RTG performance & degradation for the following uses:
  - Mission operations to calculate power output as a function of time, output voltage and cold side temperature
  - Prediction of power output degradation as a function of lifetime
    - Degradation mechanisms include: isotope decay, material & interface properties changes and materials sublimation
  - RTG design trades and optimization

History of Degra

- Developed in the Mid 70's
  - Designed to model the Voyager RTG
- Model thermoelectric conversion physics
- Based on a simple one-dimensional model of heat transfer
- Input data base
  - Time-temperature thermoelectric (SiGe) materials properties (Seebeck, electrical and thermal resistivity) from coupon testing
  - Time-temperature dependant sublimation rates for coated and uncoated SiGe material
  - Thermal insulation degradation and shunt losses as a function of sublimation product deposition based on 4-couple module testing
- Results validated with Electrical Thermoelectric Generator test data and ultimately with Voyager, and Les 8 & 9 telemetry data
  - Degradation after 15 years slightly overestimated as a result of modeled sudden complete loss of sublimation suppression coating and data extrapolation
- Code was developed for batch input on a mainframe computer using Fortran IV

Voyager 1 Performance Comparison



Isotope Decay

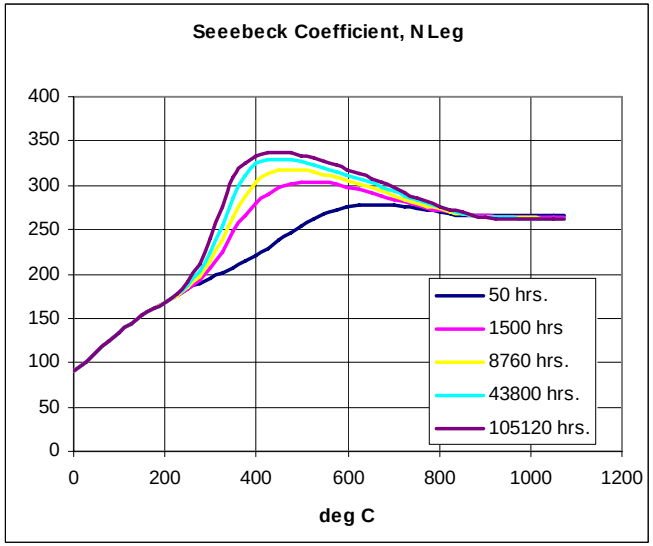
- As the particular isotope being used decays, the available thermal input power to the RTG diminishes.
    - The electrical output power is thus also reduced
- In addition as the isotope decays, because of the fixed couple geometry, the temperature differential across the thermoelectric material will decrease, reducing the conversion efficiency.
    - The electrical output power will be further reduced.
- Most RTG aplications use Plutonium Oxide as fuel for the RTG
    - Degra assumes the use of GPHS (General Purpose Heat Source) Modules with Pu_{238} with a half-life of 87.4 years.
- Other isotopes could be used with Degra

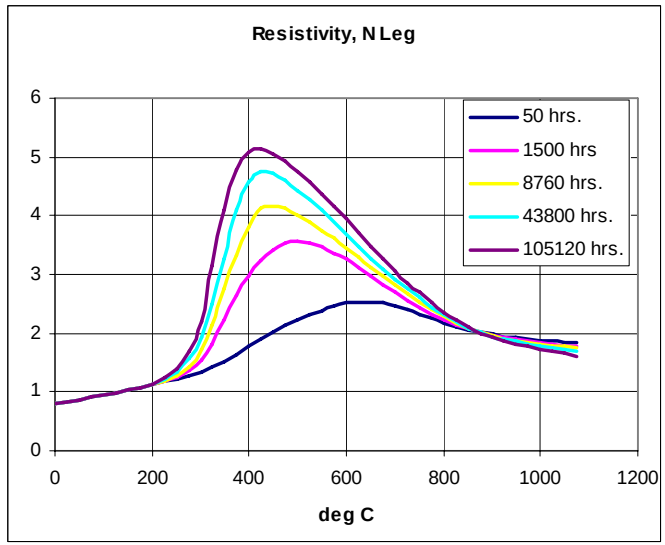
Thermoelectric Property Changes

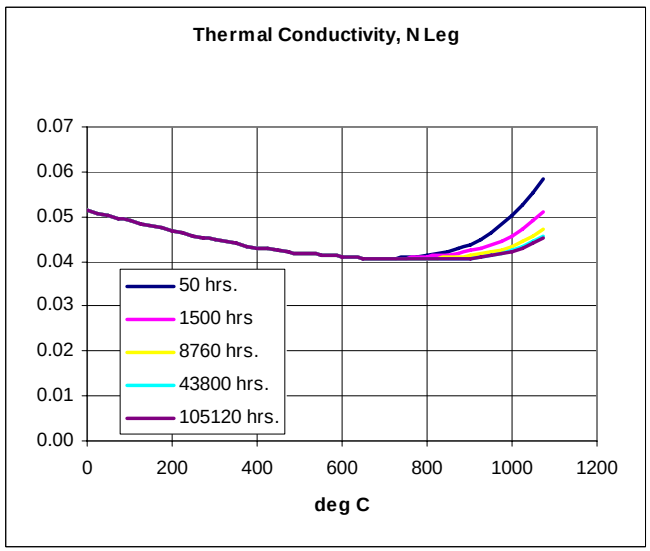
- Some of the thermoelectric properties may change as a function of operating time and operating temperatures
- In the case of the SiGe material, this change is due to dopant precipitation, which reduces the available current carriers
- Changes in thermal conductivity have also been observed, usually caused by a change in crystal structure at the higher operating temperatures
- Properties of the Lead-Telluride/TAGS system also change as a function of time, though at this time the extent of the change is still uncertain as is the cause for it
- As additional data on change rates becomes available, it will be incorporated into Degra

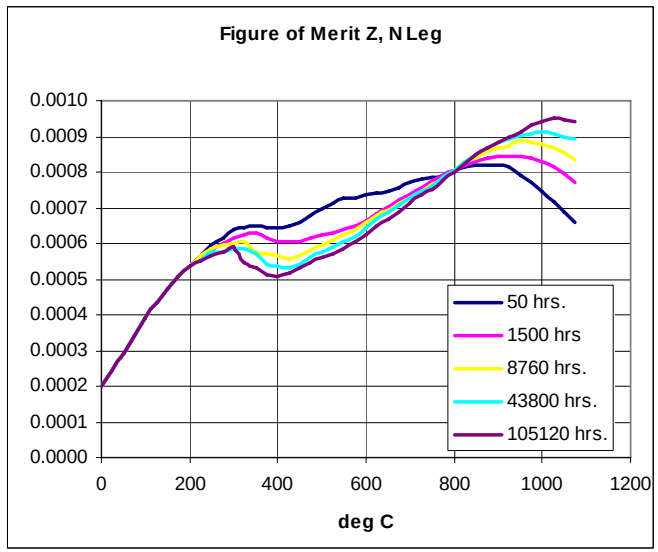
N leg SiGe Thermoelectric Property Data

Isotope Power Systems



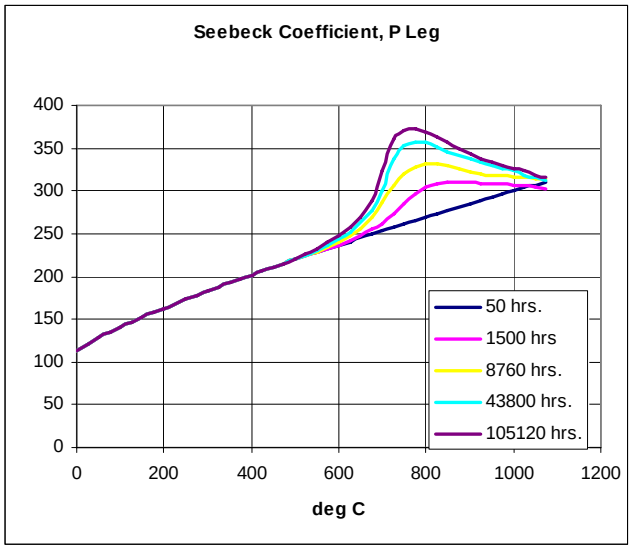


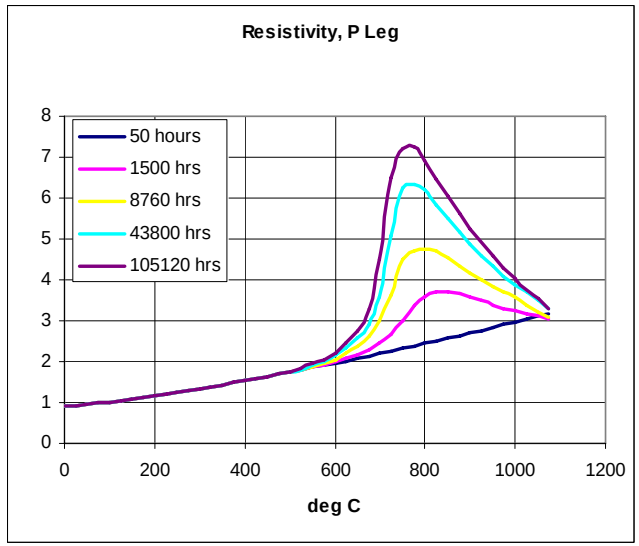


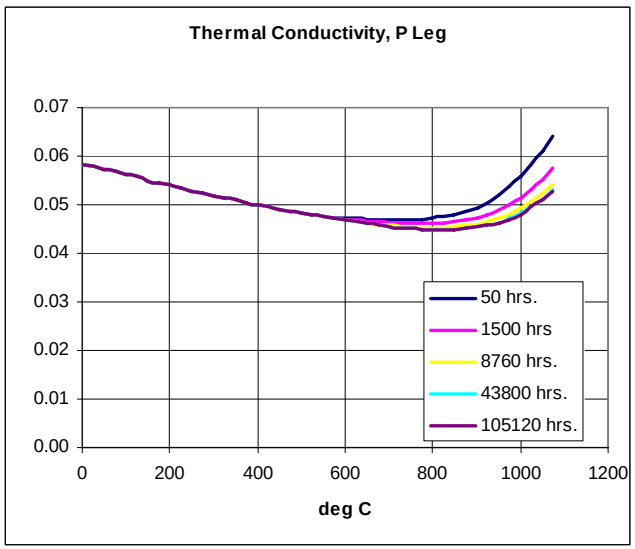


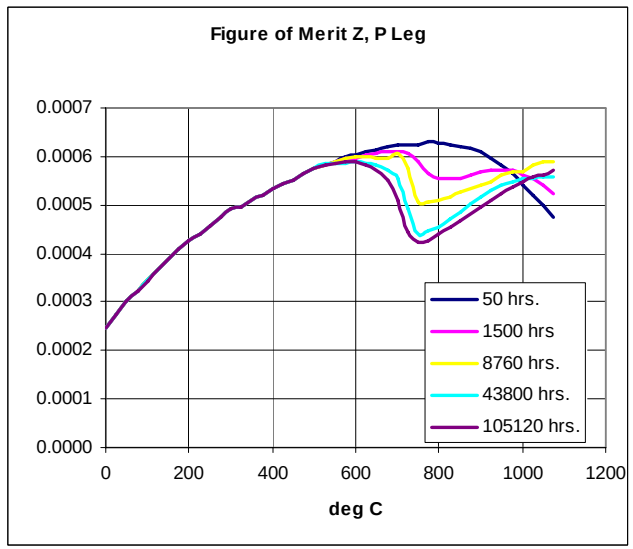
P leg SiGe Thermoelectric Property Data

Isotope Power Systems





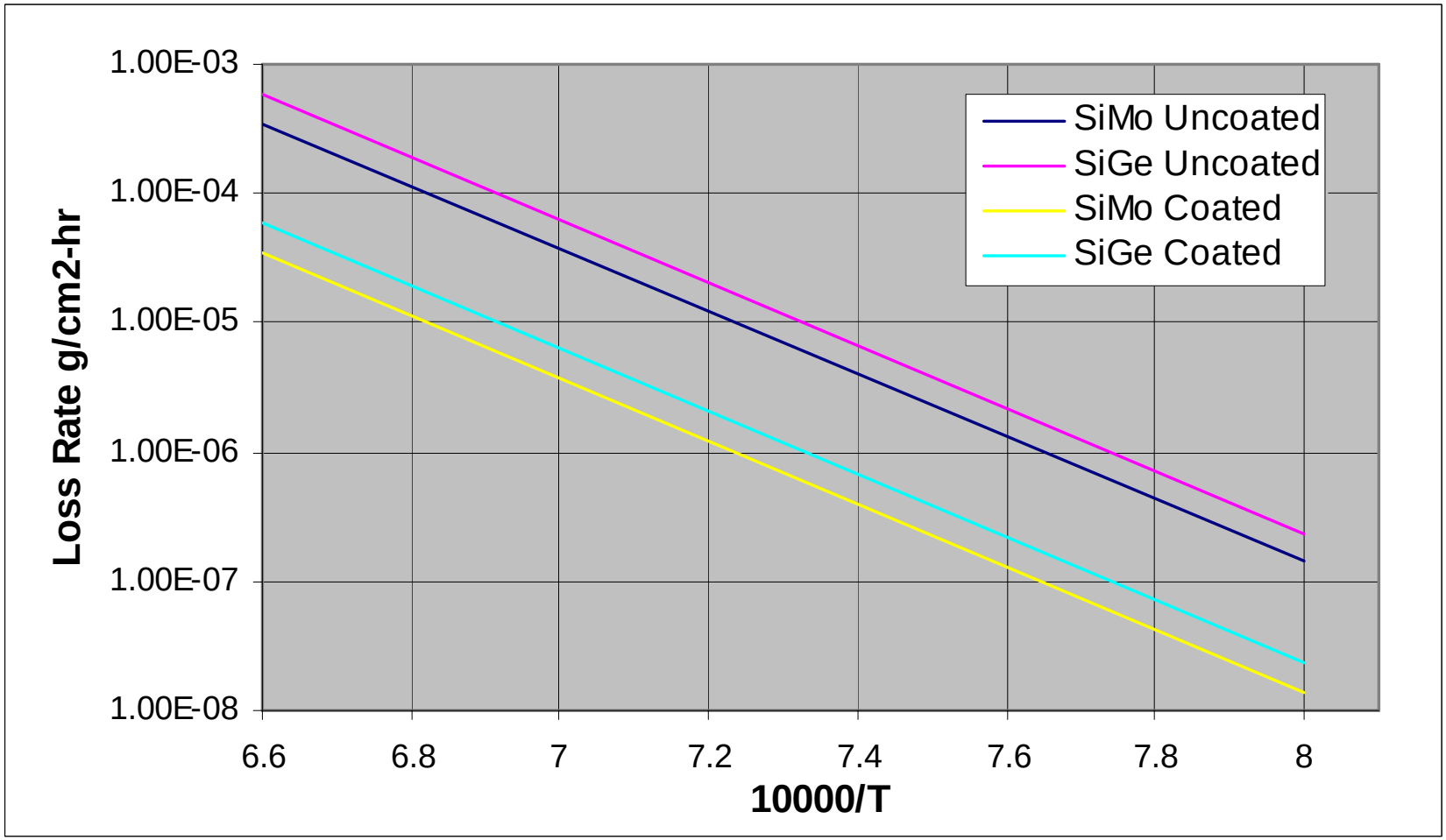




Sublimation

- Materials will be subliming at elevated temperatures. This phenomenon can reduce the electrical output power of the generator
- In the GPHS RTG, the sublimation of Silicon, subsequently reacting with the thermal insulation (SiO_2), was determined to be the primary cause for this degradation mechanism:
  - $Si(g) + SiO_2(s) \longrightarrow 2SiO(g)$
  - The source for the Si is from the SiMo Hot Shoe and the SiGe leg near the hot junction
- The SiO gas condenses at lower temperatures and in addition to effecting the thermal conductivity of the foil insulation, can provide an electrical path from the TE legs to the foil package, thus shunting some of the electrical current of the RTG

Sublimation Rates



Insulation Degradation

- The thermal insulation for many RTGs consist of multiple metal foil (Mo) layers interspaced with Astroquarz (SiO_2) cloth
  - The sublimed species (Si in the case of the GPHS-RTGs) will react with the Molybdenum, changing the effective emissivity
- The gaseous SiO permeates to the lower temperatures where it solidifies
  - The solid SiO bridges across the Astroquarz cloth separated foil layers, thus increases the thermal conductance of the foil package
- MinK or Microtherm insulation is used for other RTGs
  - Sublimed material can react or “clog” the MinK or Microtherm insulation and reduce the thermal resistance

- Degra accounts for such changes and thus increases the thermal losses, which in turn reduces the available electrical power

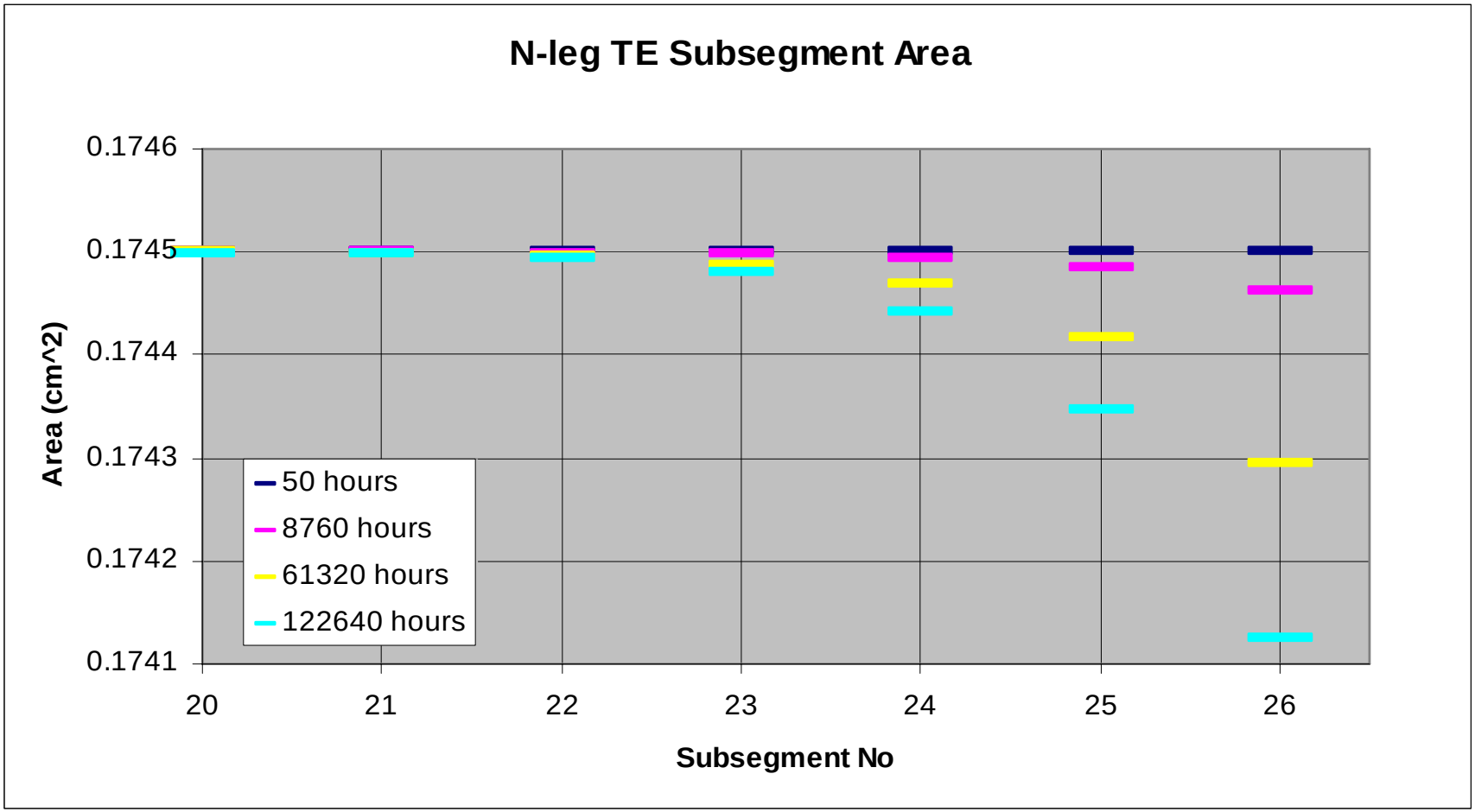
Shunt Resistance

- Sublimed material from the hot regions of the RTG, may deposit in the cooler regions near the cold strap.
- The SiO that solidifies in the GPHS RTG, is electrically conductive
- Its resistivity depends on the actual composition of the solidified SiO but can reach values near that of Silicon metal
- As the multi-foil package of the RTG is at a common potential throughout the generator, the SiO can short out portions of the thermoelectric string

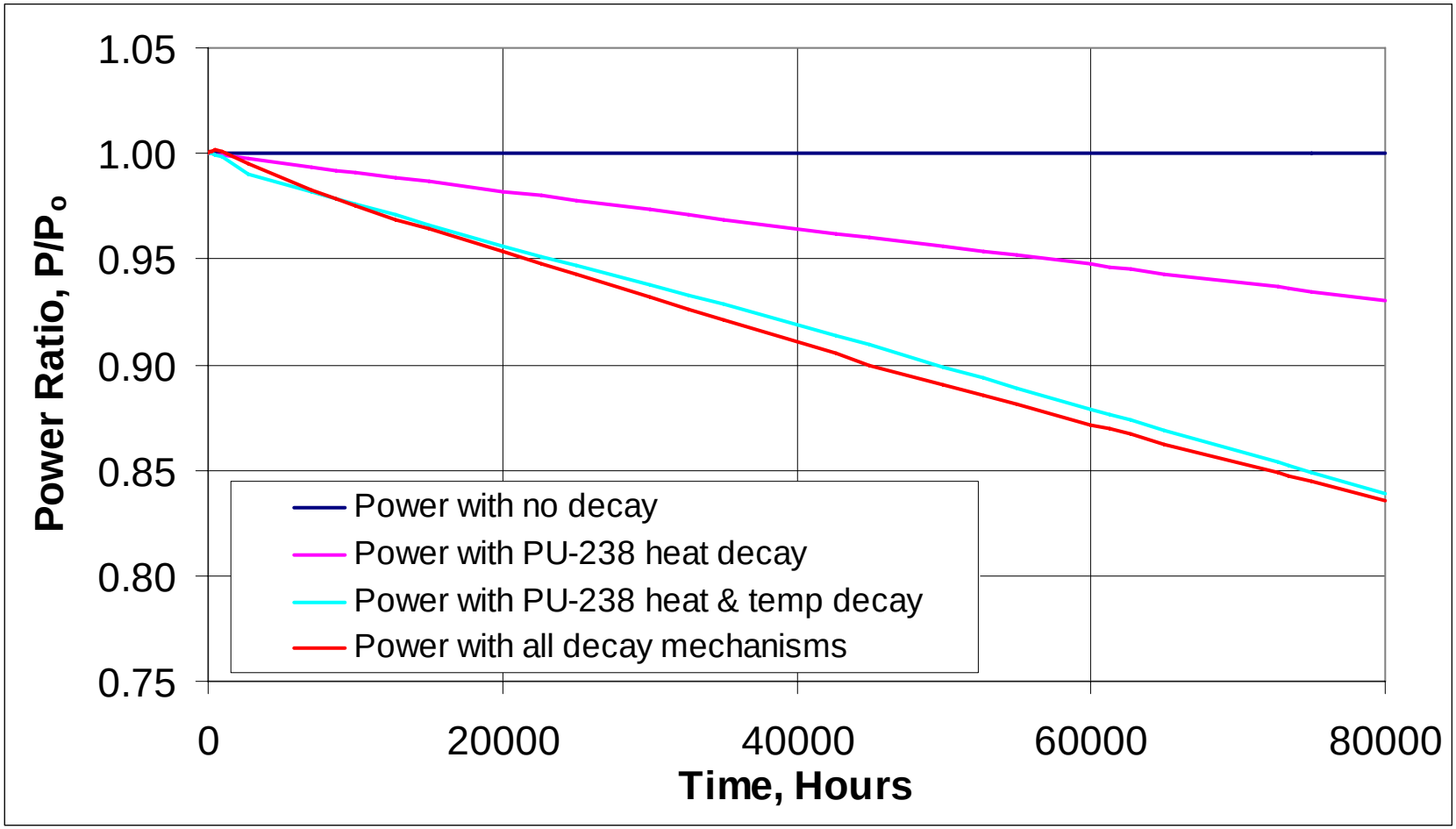
- Degra tracks the amount of sublimation products that are deposited and reduces the power output accordingly

Couple Area Degradation

- Degra also tracks the geometry changes associated with sublimation and accounts for them in both thermal and electrical calculations.



Combined Power Degradation Effects



Degra Version Comparison

Features and Cabilities	Initial Code	FY'04 Code	FY'05 Code	FY'06 Code
Data Input and Output				
Computer type	Main-Frame	PC	PC	PC/Mac/UNIX
Data Input	Fixed field data file	GUI & Fixed field files	GUI & flexible data files	GUI & flexible data files
Data Output	Text file	Text file	Excel with optional data	Excel with more data options
Graphical output		GUI graphs	GUI graphs	GUI graphs
User Support				
Users Guide		Document	Document	User's Guide
Online Help				Yes
Error Trapping & Warning			Limited Error Trapping	Yes
Analysis Capabilities				
Output Voltage	Fixed	Fixed	Variable	Variable
Heat Losses			Accounted	Automatically Adjusted
Variable Geometry			Adjustable	Enhanced Adjustability
Leg Segmentation			Yes	Yes
Mass Calculations			Yes	Enhanced
Sublimation losses	Fixed to SiGe	Fixed to SiGe	Fixed to SiGe	Adjustable
Resistive Losses	Fixed to SiGe	Fixed to SiGe	Fixed to SiGe	Adjustable
Themal Insulation Effectiveness	Fixed to SiGe	Fixed to SiGe	Fixed to SiGe	Adjustable
Time Steps	Manual	Manual	Manual	Automatically Adjusted
Radiator Temperature	Deep Space	Deep Space	Deep Space or Variable	Deep Space or Variable
Parametric Analysis	Manual	Manual	Manual	Excel Driven
Interface with MMPAT				Yes

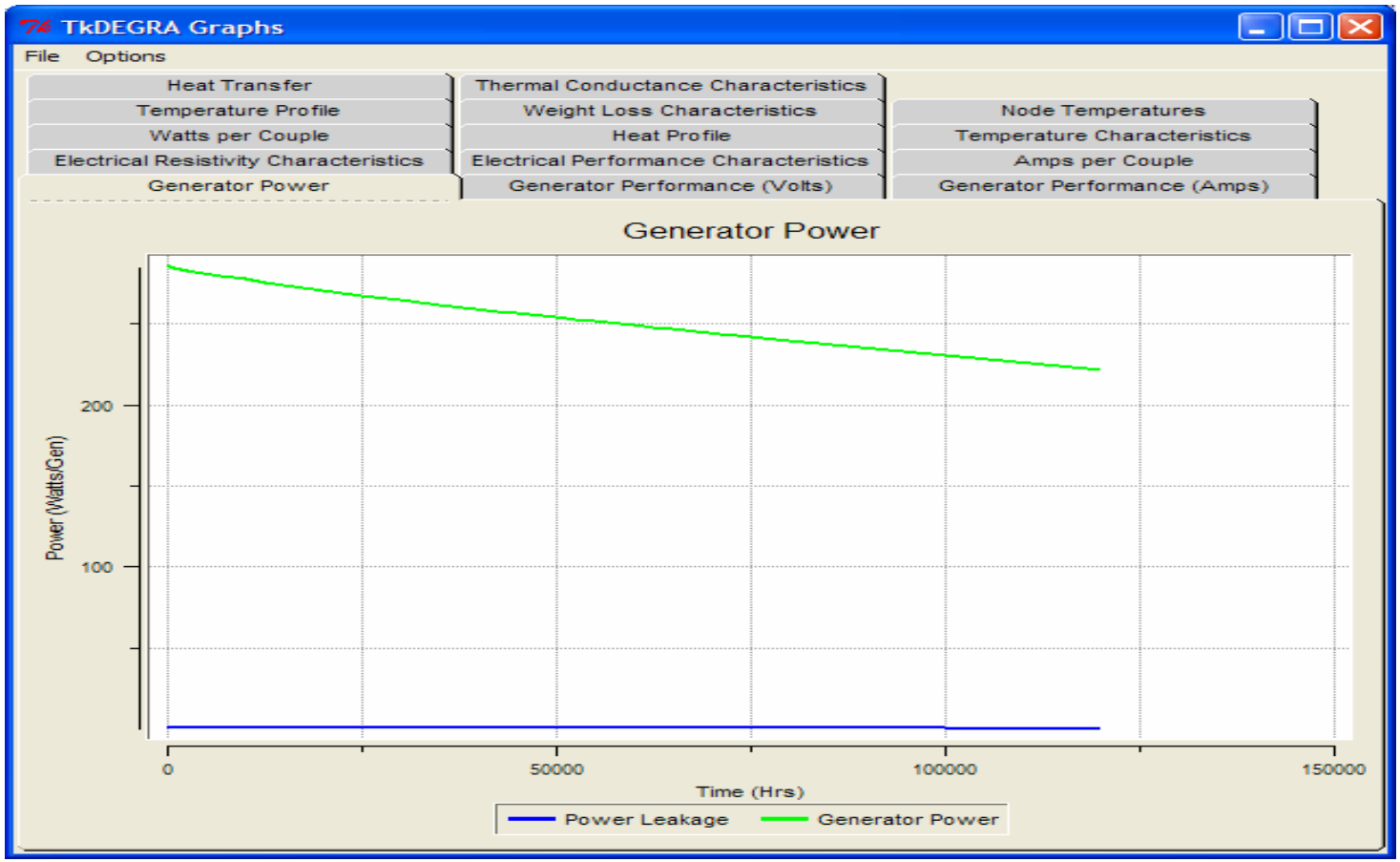
Results: Tabular Data

Microsoft Excel - GPHS-RTG_SiGe_baseline_timelessCond.txt

	B	M	N	O	P	Q	R	S	T	U
1	TIME	POWER	POWER	POWER	CURRENT	CURRENT	VOLTAGE	VOLTS	VOLTS	VOLTS
2	*	OUTPUT	OUTPUT	LEAKAGE	*	*	*	OPEN CIRCUIT	OPEN CIRCUIT	OPEN CIRCUIT
3	*	PER RTG	PER COUPLE	PER RTG	PER COUPLE	PER RTG	PER RTG	N-LEG	P-LEG	TOTAL
4	*	*	*	*	*	*	*	*	*	*
5	(HOURS)	(WATTS)	(WATTS)	(WATTS)	(AMPS)	(AMPS)	(VOLTS)	(VOLTS)	(VOLTS)	(VOLTS)
6	50	285.11	0.499167	0.413451	2.28653	9.14612	31.218	0.181027	0.169775	0.350802
7	51	284.863	0.498735	0.413441	2.28458	9.13831	31.2176	0.181058	0.169713	0.350771
8	52	284.879	0.498764	0.413442	2.28471	9.13883	31.2176	0.181149	0.169721	0.35087
9	53	284.903	0.498805	0.413443	2.2849	9.13959	31.2177	0.181241	0.169731	0.350972
10	54	284.923	0.49884	0.413443	2.28506	9.14022	31.2177	0.18133	0.169741	0.35107
11	55	284.928	0.498849	0.413444	2.28509	9.14037	31.2177	0.181413	0.169746	0.351159
12	56	284.86	0.498729	0.413441	2.28455	9.13821	31.2176	0.181478	0.169733	0.351211
13	57	284.978	0.498937	0.413446	2.28549	9.14196	31.2178	0.181586	0.16977	0.351356
14	58	284.984	0.498946	0.413446	2.28553	9.14213	31.2178	0.181666	0.169776	0.351442
15	59	285.015	0.499001	0.413447	2.28578	9.14312	31.2178	0.18175	0.16979	0.35154
16	60	285.022	0.499014	0.413447	2.28584	9.14336	31.2179	0.181828	0.169798	0.351625
17	100	285.499	0.499846	0.413465	2.2896	9.15841	31.2185	0.184238	0.170257	0.354495
18	110	285.559	0.499952	0.413468	2.29008	9.16032	31.2186	0.18468	0.170368	0.355048
19	120	285.609	0.50004	0.41347	2.29048	9.16191	31.2187	0.185083	0.170478	0.35556
20	130	285.646	0.500105	0.413471	2.29077	9.16308	31.2188	0.18545	0.170584	0.356034
21	140	285.521	0.499885	0.413466	2.28978	9.15911	31.2186	0.185752	0.170645	0.356397
22	150	285.545	0.499928	0.413467	2.28997	9.15989	31.2186	0.186067	0.170747	0.356813
23	160	285.726	0.500243	0.413474	2.2914	9.16558	31.2189	0.186399	0.170889	0.357288
24	170	285.742	0.500271	0.413475	2.29152	9.16609	31.2189	0.186674	0.170985	0.357659
25	180	285.586	0.499999	0.413469	2.29029	9.16116	31.2187	0.186891	0.171034	0.357925
26	190	285.593	0.500011	0.413469	2.29035	9.16138	31.2187	0.187134	0.171125	0.358259
27	200	285.599	0.500021	0.413469	2.29039	9.16157	31.2187	0.187365	0.171214	0.358578
28	500	285.331	0.499553	0.413459	2.28828	9.15311	31.2183	0.19136	0.173205	0.364565

Output compatible with Excel and allows user to select parameters

Results: Plots



Graphical output shows how parameters change with time and allows user to adjust scale and determine parameter values.

Conclusions

- Degra has been restored and updated to run on a PC with GUI for I/O
- Degra is being updated for Mars Science Lab (MSL) relative to their potential use of a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) which has been baselined for their mission.
- Degra is being updated for RTG design trades and optimization to facilitate the development of an advanced RTG