RQA: 847

From: Reliability Engineering

Date: September 21, 1965

Subject: Failure Mode Analysis of
TE Module

For: WANL-TM 1002

ASTRONUCLEAR LABORATORY

TO: Mr. J. Kenney

cc: F. R. Lorenz
A. Selz
D. V. Foster

F. W. Henning
N. A. Pollack
J. O. Hutchinson

Regina, Tex.

MASTER

A failure mode analysis for the thermoelectric module is being submitted with this letter.

The attached study is intended to serve as a guide for future design modifications. It may also be used as a guide for test planning and failure analysis where appropriate.

In general the study covers both testing and actual application, including failure modes induced in either environment.

No attempt has been made to assess the relative probability or severity of the various failure modes nor were the suggested remedies fully investigated as to feasibility or possible side effects. These latter efforts should prove more fruitful when alternative designs are considered.

G. L. Wagner, Supervisor
Reliability Engineering

FO/dj

Attachment

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September 22, 1965

COMPACT THERMOELECTRIC CONVERTER PROGRAM
INTERNAL TECHNICAL MEMORANDUM

SUBJECT: Failure Mode Analysis of the TE Module
Reference Drawing 909E680

SHOP ORDER NO.: TC 2110

ISSUED DATE: September 22, 1965

AUTHOR: F. Ottenheimer/G. L. Wagner

SUMMARY: A detailed Failure Mode Analysis of the Thermoelectric Module, based on the drawing referenced, has been performed and is presented in the following pages. This effort is to be used as guidance in test planning and future design modifications. Recommendations for means of minimizing or eliminating failure modes are given with each detail review.

INFORMATION CATEGORY

UNCLASSIFIED

F. W. Henning 9/22/65
Authorized Classifier Date

PART NAME Electrical Insulation Parts

PAGE 1

PART NUMBER _____

ENGINE _____

PLANNING PART NO. _____

SKETCH:

MATERIAL BN, Mica

FUNCTION:

NO. PER ENGINE:

Insulate various parts of generator operating at different potentials.

MODES OF FAILURE:

Deterioration of insulation, partial or local shorting of generator during operation or sintering.

POSSIBLE CAUSE OF FAILURE:

Sublimation of washer material near inner conductor rings and redeposition in crevices or absorption in insulating parts.

RESULTS OF FAILURE:

Degradation of module by loss of insulation resistance.

REQUIRED TO PREVENT FAILURE:

Design to maintain compression. Prevent voids (gas passages) per pp. 3, 4.
Impervious protective coating on washers, if feasible.

PART NAME Electrical Insulation Parts

PAGE 2

PART NUMBER _____

ENGINE _____

PLANNING PART NO. _____

NAME _____ DATE _____

SKETCH:

MATERIAL: BN, Alsimag, Mica

FUNCTION:

NO. PER ENGINE:

Insulate various parts of generator operating at different potentials.

MODES OF FAILURE:

POSSIBLE CAUSE OF FAILURE:

Deterioration of insulation, partial shorting of generator.

Hygroscopic absorption during shutdown, and especially during cooldown when air (moist) is drawn in by contraction of parts, lowering of vapor pressure.

RESULTS OF FAILURE:

Lowering of efficiency immediately following startup; should correct itself as air and moisture are driven out at high temperature. See oxidation, p. 6; contamination, p. 7.

REQUIRED TO PREVENT FAILURE:

Proper design and operation of test facility required to avoid accidental shutdowns. Store module in dry air or inert gas during prolonged shutdown.

PART NAME Insulating Ring

PAGE 3

PART NUMBER _____

ENGINE _____

PLANNING PART NO. _____

NAME _____ DATE _____

SKETCH:

MATERIAL: Mica

See Page 1

FUNCTION:

NO. PER ENGINE:

Provide electrical insulation between axially adjacent washers and between conductor rings.

MODES OF FAILURE:

Local shorting between adjacent inner conductor rings at normal operation.

POSSIBLE CAUSE OF FAILURE:

Shearing of insulating rings by thermal expansion of inner conductor rings relative to other internals.

RESULTS OF FAILURE:

Degradation of Module. See also pp. 1 and 5.

REQUIRED TO PREVENT FAILURE:

Shorten length (axial dimension) of inner conductor rings. Avoid thermal cycling associated with accidental shutdowns and restarts.

PART NAME Inner insulating sleeve

PAGE 4

PART NUMBER _____

ENGINE _____

PLANNING PART NO. _____

NAME _____

DATE _____

SKETCH:

MATERIAL: BN

See also Page 2.

Saw Cuts in Inner Conductor Ring

FUNCTION:

NO. PER ENGINE:

Electrical insulation and heat conduction between inner clad and inner conductor rings.

MODES OF FAILURE:

Poor heat transfer across inner insulating sleeve.

POSSIBLE CAUSE OF FAILURE:

Low contact pressure between inner insulating sleeve and adjacent metallic members. (Conductor rings tend to grow away from clads.) Aggravated if local voids are formed due to differential axial expansion of sleeve and metal parts.

RESULTS OF FAILURE:

Lower module efficiency. Note: Efficiency is more sensitive to heat transfer across inner sleeve than across outer sleeve. See also pp. 1 and 5.

REQUIRED TO PREVENT FAILURE:

Eliminate redundancy of conductor rings as stress members by segmenting them into quadrants. Assembly is facilitated if saw cuts are made (see sketch) rather than discrete segments. Avoid thermal shock associated with accidental shutdown. Place spray BN on outside of inner clad. This produces fused interface, prevents formation of crevice or voids during operation.

PART NAME <u>Washers</u>		PAGE <u>5</u>
PART NUMBER _____		ENGINE _____
PLANNING PART NO. _____	NAME _____	DATE _____
<u>SKETCH:</u> <div style="text-align: center; padding-top: 50px;">See Page 4</div>		<u>MATERIAL:</u> <u>PbTe</u>
<u>FUNCTION:</u> Produce power by thermoelectric effect.		<u>NO. PER ENGINE:</u> _____
<u>MODES OF FAILURE:</u> Extrusion of material through insulating sleeve, or through or around insulating rings, resulting in local short.	<u>POSSIBLE CAUSE OF FAILURE:</u> Pressure induced by thermal stress between conducting rings and washers. Perforation of insulating sleeve or insulating rings per pp. 3, 4.	
<u>RESULTS OF FAILURE:</u> Degradation by shorting, mass transfer.		
<u>REQUIRED TO PREVENT FAILURE:</u> Design to prevent damage of insulating parts per pp. 3, 4.		

PART NAME Washers

PAGE 6

PART NUMBER _____

ENGINE _____

PLANNING PART NO. _____

NAME _____ DATE _____

SKETCH:

MATERIAL: PbTe

See Page 2

FUNCTION:

NO. PER ENGINE: _____

Produce power by thermoelectric effect.

MODES OF FAILURE:

Resistance buildup at conducting surfaces.

POSSIBLE CAUSE OF FAILURE:

Oxidation of surfaces by air absorbed during shutdown. See Page 2.

RESULTS OF FAILURE:

Degradation of module by increased contact resistance and material contamination.

REQUIRED TO PREVENT FAILURE:

Proper design and operation of test facility required to avoid accidental shutdowns. Store module in inert gas during prolonged shutdown. Consider feasibility of providing impervious non-oxidizing coating on washers.

PART NAME Washers

PAGE 7

PART NUMBER _____

ENGINE _____

PLANNING PART NO. _____

NAME _____

DATE _____

SKETCH:

MATERIAL: PbTe

See Page 2

FUNCTION:

NO. PER ENGINE:

Produce power by thermoelectric effect.

MODES OF FAILURE:

Lowering of Seebeck coefficient

POSSIBLE CAUSE OF FAILURE:

Material contamination by other materials in proximity (insulation, conductor rings, cladding) or by impurities contained in the latter or introduced during shutdown.

RESULTS OF FAILURE:

Continuous degradation of module.

REQUIRED TO PREVENT FAILURE:

Thorough material study; careful choice, inspection, handling of parts. Protective coating of washers if feasible. See also pp. 2 and 6.

PART NAME <u>Washers</u>		PAGE <u>8</u>
PART NUMBER _____		ENGINE _____
PLANNING PART NO. _____	NAME _____	DATE _____
<u>SKETCH:</u> <div style="text-align: center; margin-top: 50px;">See Page 2</div>		<u>MATERIAL:</u> <u>PbTe</u>
<u>FUNCTION:</u> Produce power by thermoelectric effect		<u>NO. PER ENGINE:</u> _____
<u>MODES OF FAILURE:</u> High internal resistance or open circuit in module.	<u>POSSIBLE CAUSE OF FAILURE:</u> Sublimation of end washer and leakage through seal around conductor pins.	
<u>RESULTS OF FAILURE:</u> Gradual degradation, loss of module.		
<u>REQUIRED TO PREVENT FAILURE:</u> Protective coating on end washers, if feasible. Inspection of seal after operation for signs of loosening due to thermal movement of pins and retaining rings. Prevention of thermal movement by avoidance of accidental shutdowns. Addition of Hermetic seal around conductor pins (Joy Type).		

PART NAME <u>Heat transfer medium</u>		PAGE <u>9</u>
PART NUMBER _____		ENGINE _____
PLANNING PART NO. _____	NAME _____	DATE _____
<u>SKETCH:</u> <div style="text-align: center; padding-top: 50px;">See Page 2</div>		<u>MATERIAL:</u> NaK
<u>FUNCTION:</u> Maintain hot junction temperature via inner clad.		<u>NO. PER ENGINE:</u>
<u>MODES OF FAILURE:</u> Poor heat transfer at inner clad (or heater sheath). Steep thermal gradient across film.	<u>POSSIBLE CAUSE OF FAILURE:</u> NaK fails to wet surface because of initial dirt deposit or oxide buildup during operation.	
<u>RESULTS OF FAILURE:</u> Initial or gradual lowering of efficiency, i.e., reduced power for a given apparent temperature difference across module.		
<u>REQUIRED TO PREVENT FAILURE:</u> High standard of cleanliness applied to NaK and all surfaces in contact with NaK.		

PART NAME Module

PAGE 10

PART NUMBER _____

ENGINE _____

PLANNING PART NO. _____

NAME _____

DATE _____

SKETCH:

MATERIAL:

See Page 2

FUNCTION:

NO. PER ENGINE:

Thermoelectric power generator.

MODES OF FAILURE:

Loss of power due to loss of washer material.

POSSIBLE CAUSE OF FAILURE:

Failure of assembly weld or cracking of outer clad, with resultant escape of sublimated PbTe.

RESULTS OF FAILURE:

Gradual to rapid degradation.

REQUIRED TO PREVENT FAILURE: Minimize thrusts and moments from connecting piping.

Tight quality control during fabrication and assembly. Strict enforcement of cleanliness requirements to prevent corrosion of stainless steel. Check fatigue strength of stainless steel - to - Inconel weld, minimize thermal cycling due to accidental shutdowns.

PART NAME <u>Module</u>		PAGE <u>11</u>
PART NUMBER _____		ENGINE _____
PLANNING PART NO. _____	NAME _____	DATE _____
<u>SKETCH:</u>		<u>MATERIAL:</u>
<p>See Page 2</p>		
<u>FUNCTION:</u>		<u>NO. PER ENGINE:</u>
<p>Thermoelectric power generator.</p>		
<u>MODES OF FAILURE:</u> <p>Entry of NaK, shorting out of generator</p>	<u>POSSIBLE CAUSE OF FAILURE:</u> <p>Failure of assembly weld. Cracking of inner clad during test, inner or outer clad during operation.</p>	
<u>RESULTS OF FAILURE:</u> <p>Dramatic termination of power generation.</p>		
<u>REQUIRED TO PREVENT FAILURE:</u> <p>See Page 10.</p>		

PART NAME <u>Various Interfaces</u>		PAGE <u>12</u>
PART NUMBER _____		ENGINE _____
PLANNING PART NO. _____	NAME _____	DATE _____
<u>SKETCH:</u> <div style="text-align: center; margin-top: 20px;">See Page 2</div>		<u>MATERIAL:</u>
<u>FUNCTION:</u> Conduct heat and electricity.		<u>NO. PER ENGINE:</u>
<u>MODES OF FAILURE:</u> Heat transfer deteriorates, temperature differential rises.	<u>POSSIBLE CAUSE OF FAILURE:</u> Mechanical relaxation of inner clad reduces contact pressures.	
<u>RESULTS OF FAILURE:</u> Degradation of module output.		
<u>REQUIRED TO PREVENT FAILURE:</u> Proper design, heat treatment of inner clad to prevent creep at circumferential stress corresponding to minimum contact pressure. Careful control of heat source and heat sink to prevent creep of inner clad.		

PART NAME <u>Various Interfaces</u>		PAGE <u>13</u>
PART NUMBER _____		ENGINE _____
PLANNING PART NO. _____	NAME _____	DATE _____
<u>SKETCH:</u>		<u>MATERIAL:</u> _____
<u>FUNCTION:</u> Conduct heat and electricity.		<u>NO. PER ENGINE:</u> _____
<u>MODES OF FAILURE:</u> Heat transfer deteriorates, temperature differential rises.	<u>POSSIBLE CAUSE OF FAILURE:</u> Decreased displaced volume due to a combination of collapse (external pressure), buckling (axial compression), and bending (moment from external piping) of inner clad. Restraint by inner conductor rings and viscosity of PbTe will slow action down, not eliminate it (Fe, PbTe in plastic range). May straighten out on cooling.	
<u>RESULTS OF FAILURE:</u> Degradation of module output.		
<u>REQUIRED TO PREVENT FAILURE:</u> Proper design of module and flexible arrangement of external converter piping or NaK loop. Note: This mode of failure is quite unlikely with present configuration unless external piping is too stiff.		

PART NAME <u>Various Interfaces</u>		PAGE <u>14</u>
PART NUMBER _____		ENGINE _____
PLANNING PART NO. _____	NAME _____	DATE _____
<u>SKETCH:</u> <div style="text-align: center; margin-top: 20px;"><u>See Page 1</u></div>		<u>MATERIAL:</u>
<u>FUNCTION:</u> Conduct heat and electricity		<u>NO. PER ENGINE:</u>
<u>MODES OF FAILURE:</u> Heat transfer deteriorates, contact resistance rises.	<u>POSSIBLE CAUSE OF FAILURE:</u> Further densification of washer material or insulating sleeves during operation. Can be detected by autopsy procedures.	
<u>RESULTS OF FAILURE:</u> Degradation of module output.		
<u>REQUIRED TO PREVENT FAILURE:</u> Revise swaging and/or sintering procedure for greater initial compaction. Minimize effects of conductor rings per Page. 4.		

PART NAME <u>Various Interfaces</u>		PAGE <u>15</u>
PART NUMBER _____		ENGINE _____
PLANNING PART NO. _____	NAME _____	DATE _____
<u>SKETCH:</u> <div style="text-align: center; margin-top: 50px;"><u>See Page 2</u></div>		<u>MATERIAL:</u>
<u>FUNCTION:</u> Conduct heat and electricity		<u>NO. PER ENGINE:</u>
<u>MODES OF FAILURE:</u> Heat transfer deteriorates, contact resistance rises.	<u>POSSIBLE CAUSE OF FAILURE:</u> Axial movement of internals towards ends due to lack of stiffness of retaining rings or redensification of Alsimag parts. Can be detected by radiography during operation.	
<u>RESULTS OF FAILURE:</u> Degradation of module output.		
<u>REQUIRED TO PREVENT FAILURE:</u> Redesign end parts.		