CHART 0

OBSERVATIONS ON THE SP-100 PROGRAM

CHART 1

SP-100 THERMOELECTRIC CONVERTER

I AM CONFIDENT THAT LARGE SPACE POWER SYSTEMS CAN WORK AND ARE AN INEVITABLE PART OF LARGE-SCALE UTILIZATION OF SPACE

I AM CONCERNED THAT THE SP-100 PROGRAM, AS CURRENTLY CONFIGURED, WILL NOT BE AN EFFECTIVE TOOL TO REALIZE THAT GOAL

I WILL TRY TO TELL YOU WHY I FEEL THIS WAY

- INTRODUCTION
- BACKGROUND
- SP-100 TECHNICAL ISSUES
    - BULK MATERIALS ISSUES
    - JOINING ISSUES
- SUMMARY
- APPENDIX: EXECUTIVE SUMMARY

	FLIGHT RTG's	SP-100	SCALE FACTOR
HEAT SOURCE:	Plutonium-238	Fast Reactor	
CONVERSION DEVICE:	UNICOUPLES	MULTICOUPLES	
THERMAL POWER:	4.4 KW	6,800 kW	1500
ELECTRICAL POWER:	0.3 kW	300 kW	1000
EFFICIENCY	6.8 %	4.4 %	0.65
DELIVERED VOLTAGE:	28 V	200 V	7
WEIGHT:	56 kg	10,000 kg	178
SPECIFIC POWER:	5.4 W/kg	30 W/kg	5.5
SIZE:	1.1 meters	12 meters	11

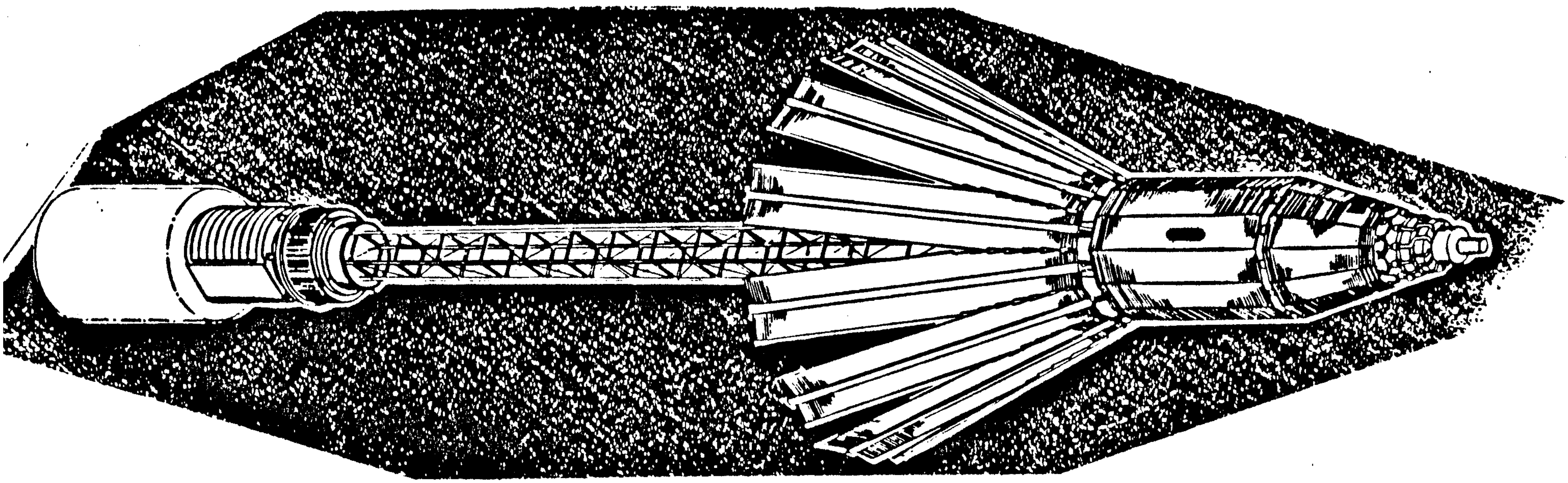

CHART #3

RTG SUCCESS STORY

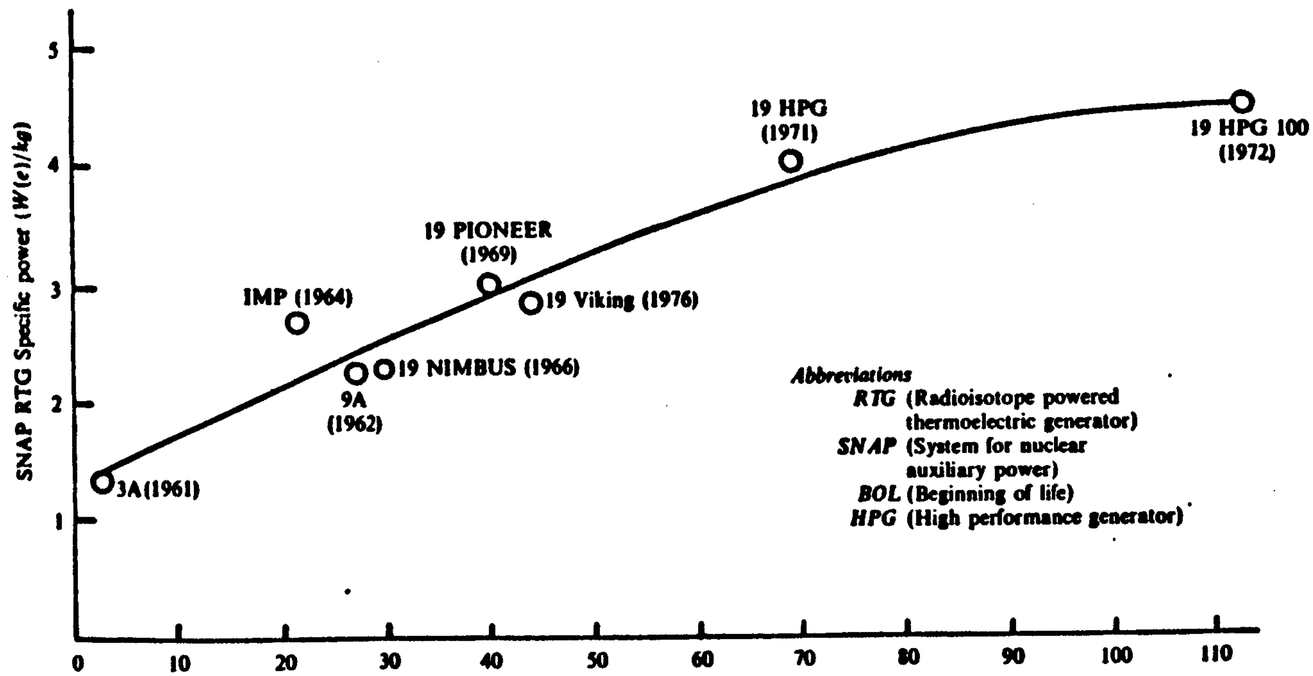

Figure 8.3 Growth history of plutonium-238. (After Dick, reference 4.)

RTG SUCCESSES HAVE GIVEN THERMOELECTRICS A REPUTATION FOR RELIABILITY

SP-100 SPECIFIC POWER NEEDS (30 W/kg) REQUIRE A REACTOR

SNAP-10A IS THE ONLY PREVIOUS REACTOR FLOWN BY THE US (1965)
PRODUCED ABOUT 500 W OF ELECTRICAL OUTPUT

CHART #4

CUSTOMER SATISFACTION

DOE HAS RESPONSIBILITY FOR U.S. NUCLEAR CAPABILITIES
NASA-JPL HAS RESPONSIBILITY FOR U.S. SPACE CAPABILITIES

THERMOELECTRICS ARE NEITHER "SPACE" NOR "NUCLEAR"
- BOTH SEEM TO SEEK OWNERSHIP OF THERMOELECTRIC TECHNOLOGY

THERMOELECTRIC TECHNOLOGY IS CENTRAL TO BOTH FAMILIES OF PROGRAMS

1. SP-100 FAMILY - GERRY STAPFER (NASA-JPL)
   - GROUND ENGINEERING SYSTEM
     - GE - PRIME
     - TECO, WESTINGHOUSE - SUBCONTRACTORS
     - GENERAL ATOMICS, RASOR - PLANNED SUBCONTRACTORS
   - COMPLIANT PAD TECHNOLOGY CONTRACT
     - GE - PRIME
     - TECO - SUBCONTRACTOR
   - SiGe/GaP DEVELOPMENT CONTRACT
     - TECO - PRIME
     - GE - SUBCONTRACTOR

2. RTG FAMILY - JIM LOMBARDO (DOE-GERMANTOWN)
   - GENERAL PURPOSE HEAT SOURCE (GPHS) - GALLILEO FLIGHT PROGRAM
   - MODULAR RADIOISOTOPE THERMOELECTRIC GENERATOR (MOD-RTG)
   - IMPROVED THERMOELECTRIC MATERIALS (ITM)

3. DIPS - JIM LOMBARDO (DOE-GERMANTOWN)
   - PROPOSAL EFFORTS

PERFORMANCE ON RTG PROGRAMS IMPACT SP-100, AND VICE-VERSA
- SP-100 NEEDS CLOSE-PACKED DEVICES RTG'S ONLY WANT THEM
- PERFORMANCE IMPROVEMENTS ENHANCE RTG's, WHICH ALREADY WORK
- SP-100 NEEDS PERFORMANCE IMRPOVEMENTS TO REMAIN COMPETITIVE

COMBINED PERFORMANCE ON SP-100 AND RTG's COULD IMPACT WINNING DIPS
- IF GE HAS TROUBLE JUGGLING SP-100 AND RTG's,
  - THEN HOW CAN GE ABSORB DIPS?

CHART #5

OTHER BACKGROUND

COMPETITION WITH ALTERNATE CONVERSION SYSTEMS
- THERMOELECTRICS ARE <u>EXPECTED</u> TO WORK BASED ON HISTORY
  - AND HAVE BEEN SOLD AS RELIABLE
  - CURRENT DESIGN CONCEPTS ARE MORE AGGRESSIVE AND RISKY
- THERMIONICS, STIRLING ETC, REQUIRE MORE DEVELOPMENT
  - OFFERED GREATER GROWTH POTENTIAL
- TO COUNTER COMPETITION, SP-100 HAS TAKEN AN AGGRESSIVE APPROACH

CATASTROPHIC FAILURE HAS STRUCK BEFORE
- IN EARLY 1970's SiGe/UNICOUPLE TECHNOLOGY SHUT DOWN AT RCA
- SELENIDES PROGRAM WAS INITIATED AT 3M BASED UPON NEW MATERIALS
- PROGRAM CANCELLED WHEN GES FAILED DUE TO INTRINSIC WEAKNESSES
- 3M NO LONGER WORKS ON THERMOELECTRICS
- "SELENIDE" HAS BECOME A SYNONYM FOR FAILURE
- (LANTHANUM SULFIDE, ONCE THE PRIME CANDIDATE FOR SP-100, IS PRACTICALLY IDENTICAL TO THE SELENIDES)

SPECIALIZED TECHNOLOGY
- NOT THAT MANY EXPERTS EXIST
- WIDE VARIETY OF SUBTLE AND COMPLEX PROBLEMS

HAS NO IDENTIFIED MISSION
CURRENT PERFORMANCE GOALS ARE ALMOST CERTAINLY UNREASONABLE
LOWER GOALS DECREASES TECHNICAL RISK, INCREASES POLITICAL RISK

CHART #6

SP-100 KEY TECHNICAL ISSUES

- OUTSIDE CONVERTER SUBSYSTEM
    - FUEL ELEMENT LIFE
    - COMPATIBILITY OF FUEL, LINER AND CLADDING
    - LITHIUM THAW
    - TEM PUMP PERFORMANCE
        - REQUIRES A THERMOELECTRIC CELL WHICH IS IN SOME WAYS MORE DEMANDING THAN THE CONVERTER CELLS SINCE THE COMPLIANT PADS ARE IN THE ELECTRICAL PATH
    - DEPLOYABLE RADIATOR
    - HEAT PIPE TRANSIENT
    - CONVERTER PRODUCTION HIGH VOLUME/LOW COST
    - SAFETY SAFETY SAFETY

CHART 6A

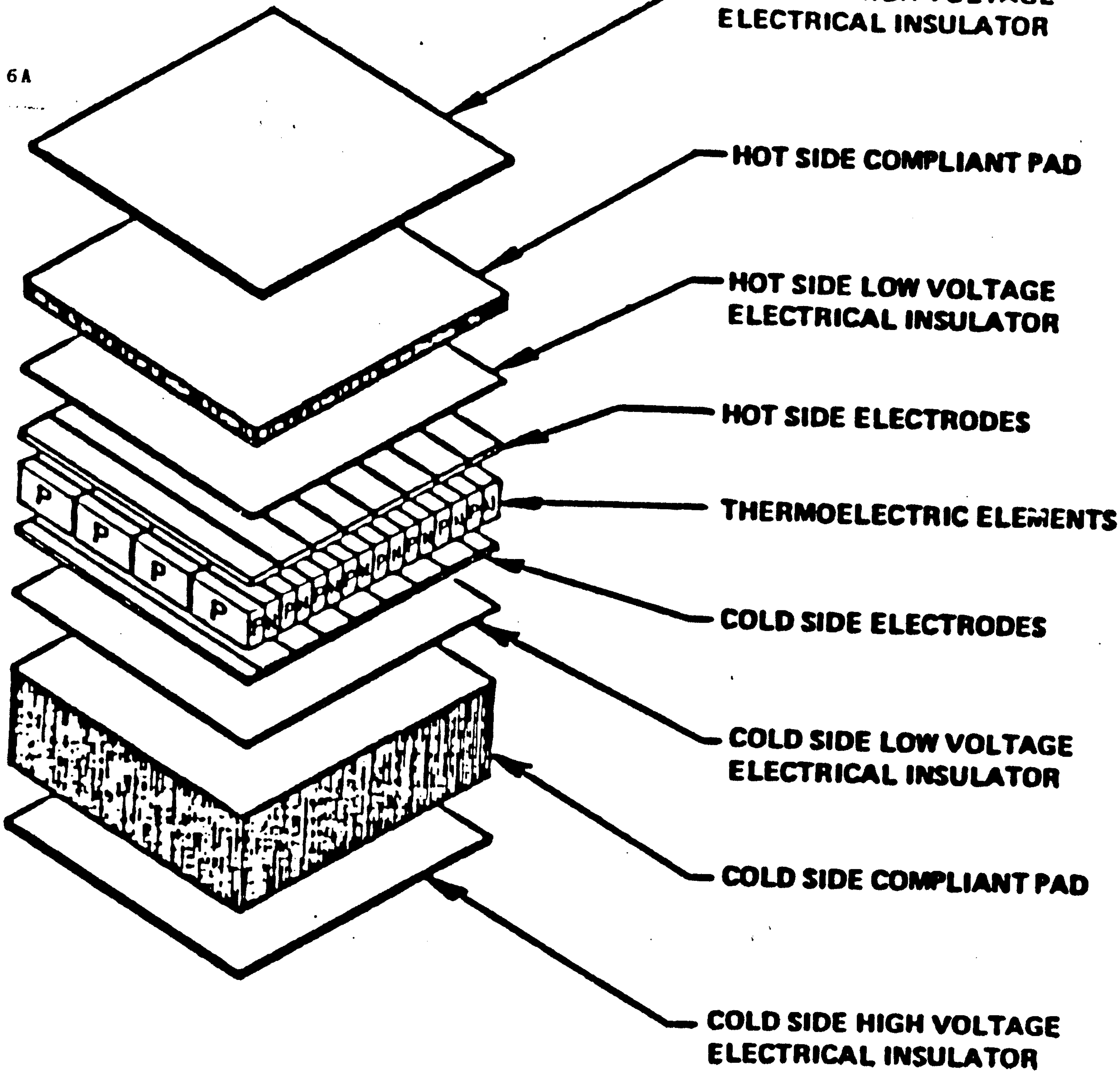
HOT SIDE HIGH VOLTAGE ELECTRICAL INSULATOR
HOT SIDE COMPLIANT PAD
HOT SIDE LOW VOLTAGE ELECTRICAL INSULATOR
HOT SIDE ELECTRODES
THERMOELECTRIC ELEMENTS
COLD SIDE ELECTRODES
COLD SIDE LOW VOLTAGE ELECTRICAL INSULATOR
COLD SIDE COMPLIANT PAD
COLD SIDE HIGH VOLTAGE ELECTRICAL INSULATOR
P
P
P
P

CHART 6B

THERMOELECTRIC CELL TECHNICAL ISSUES

1 JOINING OF PRIMARY HEAT LOOP TO HOT SIDE ELECTRICAL INSULATOR
2 HOT SIDE HIGH VOLTAGE INSULATOR
3 JOINING OF INSULATOR TO COMPLIANT PAD
4 HOT SIDE COMPLIANT PAD
5 JOINING OF COMPLIANT PAD TO LOW VOLTAGE INSULATOR, HOT SIDE
6 HOT SIDE LOW VOLTAGE ELECTRICAL INSULATOR
7 JOINING OF LOW VOLTAGE INSULATOR TO ELECTRODE, HOT SIDE
8 HOT SIDE ELECTRODE MATERIAL
9 CONTACT RESISTANCE/JOINING OF ELECTRODE TO T/E MATERIALS, HOT SIDE
10 THERMOELECTRIC MATERIALS: SiGe, SiGe/GaP OR OTHER
11 GLASSING
12 CONTACT RESISTANCE/JOINING OF ELECTRODE TO T/E MATERIALS, COLD SIDE
13 COLD SIDE ELECTRODE MATERIAL
14 CELL TO CELL ELECTRICAL STRAP
15 JOINING OF ELECTRODE TO LOW VOLTAGE INSULATOR, COLD SIDE
16 COLD SIDE LOW VOLTAGE INSULATOR
17 JOINING OF LOW VOLTAGE INSULATOR TO COMPLIANT PAD, COLD SIDE
18 COMPLIANT PAD, COLD SIDE
19 JOINING OF COMPLIANT PAD TO INSULATOR, COLD SIDE
20 COLD SIDE HIGH VOLTAGE ELECTRICAL INSULATOR
21 JOINING OF COLD SIDE ELECTRICAL INSULATOR TO HEAT REJECTION SYSTEM

CHART #7

ISSUE #1: JOINING OF PRIMARY HEAT LOOP TO HOT SIDE ELECTRICAL INSULATOR

FUNCTION: COMPLETE THE HEAT PATH TO THE MODULE

REQUIREMENTS:

- HIGH THERMAL CONDUCTIVITY
- NOT TOO HOT TO DAMAGE MATERIALS OR PREVIOUSLY MADE BONDS
- HOT ENOUGH TO BE STABLE FOR YEARS AT OPERATION TEMPERATURE
- SUFFICIENT MECHANICAL STRENGTH
- CHEMICAL COMPATIBILITY WITH INSULATOR AND Nb1Zr

IMPACT:

- CONDUCTIVELY COUPLED CONCEPT FAILS WITHOUT FUNCTIONAL JOINT

STATUS:

- CONCERN ABOUT USING NOBLE-METAL BRAZES
- EXPECT TO REQUIRE METALIZED INSULATOR
- MAY REQUIRE "GRADED SEAL"
- HIGH CONFIDENCE APPROACH NOT YET DEMONSTRATED

CHART #8

ISSUE #2: HOT SIDE HIGH VOLTAGE INSULATOR STABILITY

FUNCTION: ELECTRICALLY ISOLATE EACH CELL FROM COMMON STRUCTURAL ELEMENTS

REQUIREMENTS:

- THERMAL EXPANSION MATCH
- HIGH THERMAL CONDUCTIVITY (K) TO MINIMIZE TEMPERATURE DROP
- HIGH ELECTRICAL RESISTIVITY (R) TO MINIMIZE ELECTRICAL POWER LOSS
  - FIGURE OF MERIT = R*K, GOAL OF 2,000,000 V^2/K
- CHEMICAL COMPATIBILITY (THERMODYNAMIC)
- STABILITY IN HIGH ELECTRIC FIELD (4000 V/cm)
- JOINABLE TO PRIMARY HEAT LOOP AND COMPLIANT PAD

IMPACT:

- CONDUCTIVELY COUPLED CONCEPT FAILS WITHOUT FUNCTIONAL INSULATOR
- SYSTEM PERFORMANCE IS DIRECTLY RELATED TO INSULATOR F.O.M.

STATUS:

- Al_2O_3 IS PRIMARY CANDIDATE, BeO AND AlN BEING CONSIDERED
- LITERATURE INDICATES CHEMICAL INCOMPATIBILITY IN Li-Nb1Zr-Al_2O_3
- MODELS INDICATE UNMODIFIED Al_2O_3 WILL BREAKDOWN FROM IONIC
  MIGRATION. DATA IS SCARCE.
- 9 MONTH, $700,000 PROGRAM AT GENERAL ATOMICS: FEW USEFUL RESULTS
- ACCEPTABLE INSULATOR HAS NOT BEEN DEMONSTRATED

CHART #9

ISSUE #3: JOINING OF INSULATOR TO COMPLIANT PAD

FUNCTION: COMPLETE THE HEAT PATH TO THE MODULE

REQUIREMENTS:

- HIGH THERMAL CONDUCTIVITY
- NOT TOO HOT TO DAMAGE MATERIALS OR PREVIOUSLY MADE BONDS
- HOT ENOUGH TO BE STABLE FOR YEARS AT OPERATION TEMPERATURE
- SUFFICIENT MECHANICAL STRENGTH
- MUST BE EFFECTED WITHOUT CRUSHING COMPLIANT PAD

IMPACT:

- CONDUCTIVELY COUPLED CONCEPT FAILS WITHOUT FUNCTIONAL JOINT

STATUS:

- EXPECT TO REQUIRE METALIZED INSULATOR
- MAY REQUIRE "GRADED SEAL"
- HIGH CONFIDENCE APPROACH NOT YET DEMONSTRATED

CHART #10

ISSUE #4: HOT SIDE COMPLIANT PAD

FUNCTION: ACCOMMODATE THERMAL EXPANSION DIFFERENCE BETWEEN MODULE AND HOT SIDE INSULATOR/PRIMARY HEAT LOOP (Nb1Zr)

REQUIREMENTS:

- MINIMIZE STRESSES ON THERMOELECTRIC MODULE
- MECHANICAL INTEGRITY
- HIGH THERMAL CONDUCTIVITY
- TRANSMITS SMALL FORCES INTO THERMOELECTRIC MODULE
- INTERNAL CHEMICAL COMPATIBILITY
- JOINABLE TO HIGH AND LOW VOLTAGE INSULATORS

IMPACT:

- CONDUCTIVELY COUPLED CONCEPT FAILS WITHOUT FUNCTIONAL PAD
- SYSTEM PERFORMANCE IS STRONGLY DRIVEN BY PAD PERFORMANCE

STATUS:

- INITIAL DEVELOPMENT UNDER IRD RESULTED IN TEST MODULE
  - POOR THERMAL PERFORMANCE
  - MANY FIBERS BROKEN
- ACCEPTABLE PAD HAS NOT BEEN DEMONSTRATED

CHART 11

ISSUE #5: JOINING OF COMPLIANT PAD TO LOW VOLTAGE INSULATOR, HOT SIDE

FUNCTION: COMPLETE THE HEAT PATH TO THE MODULE

REQUIREMENTS:

- HIGH THERMAL CONDUCTIVITY
- NOT TOO HOT TO DAMAGE MATERIALS OR PREVIOUSLY MADE BONDS
- HOT ENOUGH TO BE STABLE FOR YEARS AT OPERATION TEMPERATURE
- SUFFICIENT MECHANICAL STRENGTH
- MUST BE EFFECTED WITHOUT CRUSHING COMPLIANT PAD

IMPACT:

- CONDUCTIVELY COUPLED CONCEPT FAILS WITHOUT FUNCTIONAL JOINT

STATUS:

- EXPECT TO REQUIRE METALLIZATION OF LOW VOLTAGE INSULATOR
- HIGH CONFIDENCE APPROACH NOT YET DEMONSTRATED

CHART 12

ISSUE #6 HOT SIDE LOW VOLTAGE ELECTRICAL INSULATOR

FUNCTION: ELECTRICALLY ISOLATE A MODULE FROM COMPLIANT PAD

REQUIREMENTS:

- THERMAL EXPANSION MATCH
- HIGH THERMAL CONDUCTIVITY (K) TO MINIMIZE TEMPERATURE DROP
- HIGH ELECTRICAL RESISTIVITY (R) TO MINIMIZE ELECTRICAL POWER LO
  - FIGURE OF MERIT = R*K, 300 V^2/K IS PROBABLY ACCEPTABLE
- CHEMICAL COMPATIBILITY (THERMODYNAMIC)
- STABILITY IN MODERATE ELECTRIC FIELD (200 V/cm)
- JOINABLE TO COMPLIANT PAD AND ELECTRODES

IMPACT:

- MODULES LOSE POWER IF GLASS FAILS

STATUS:

- EE2/EE9 GLASS IDENTIFIED
- IDENTICAL GLASS USED FOR MODULE GLASSING

CHART 13

ISSUE #7: JOINING OF LOW VOLTAGE INSULATOR TO ELECTRODE, HOT SIDE

FUNCTION: COMPLETE THE HEAT PATH TO THE MODULE

REQUIREMENTS:

- HIGH THERMAL CONDUCTIVITY
- NOT TOO HOT TO DAMAGE MATERIALS OR PREVIOUSLY MADE BONDS
- HOT ENOUGH TO BE STABLE FOR YEARS AT OPERATION TEMPERATURE
- SUFFICIENT MECHANICAL STRENGTH
- MUST BE EFFECTED WITHOUT CRUSHING COMPLIANT PAD

IMPACT:

- LOSS OF HEAT FLUX IF JOINT FAILS

STATUS:

- APPLICATION TECHNOLOGY EXISTS FOR SiMo AND GRAPHITE
- CONCERN ABOUT REDUCTION OF OXIDES BY GRAPHITE

CHART 14

ISSUE #8: HOT SIDE ELECTRODE MATERIAL

FUNCTION: COMPLETE THE ELECTRICAL CIRCUIT BETWEEN LEGS

REQUIREMENTS:

- THERMAL EXPANSION MATCH TO SiGe
- HIGH THERMAL CONDUCTIVITY
- LOW ELECTRICAL RESISTIVITY
- CHEMICAL COMPATIBILITY
- JOINABLE TO SiGe WITH LOW SPECIFIC CONTACT RESISTANCE
- JOINABLE TO LOW VOLTAGE INSULATOR

IMPACT:

- LESS POWER OUTPUT

STATUS

- ELECTRODE PERFORMANCE IS MORE IMPORTANT TO SP-100 THAN RTG's
  - SHORTER LEGS MAKE ELECTRODES A LARGER FRACTION OF TOTAL LOSS
- EXISTING SiMo TECHNOLOGY CAN BE READILY ADAPTED TO SP-100
  - PERFORMANCE PENALTY CONSIDERED LARGE
- GRAPHITE IDENTIFIED AS ALTERNATIVE, SUPERIOR k THAN SiMo
- EXPERIENCE WITH GRAPHITE INDICATED FAILURES DUE TO SiC FORMATION
- CONCERN ABOUT REACTION OF GRAPHITE WITH GLASS

CHART 15

ISSUE #9: JOINING OF ELECTRODE TO T/E MATERIALS, HOT SIDE

FUNCTION: COMPLETE THE ELECTRICAL PATH TO THE THERMOELECTRICS

REQUIREMENTS:

- LOW ELECTRICAL CONTACT RESISTANCE
- HIGH THERMAL CONDUCTIVITY
- NOT TOO HOT TO DAMAGE MATERIALS (EG. GLASS, SiGe)
- HOT ENOUGH TO BE STABLE FOR YEARS AT OPERATION TEMPERATURE
- SUFFICIENT MECHANICAL STRENGTH

IMPACT:

- LESS POWER OUTPUT

STATUS:

- CONTACT RESISTANCE IS MORE IMPORTANT TO SP-100 THAN RTG's
    - SHORTER LEGS MAKE ELECTRODES A LARGER FRACTION OF TOTAL LOSS
- EXISTING SiMo TECHNOLOGY CAN BE ADAPTED TO SP-100
    - PERFORMANCE PENALTY NOT WELL KNOWN
- EXISTING TEST METHODS ARE INADEQUATE TO DETERMINE CONTACT RESISTANCE WITH ACCURACY REQUIRED BY SP-100
- PLANS EXIST TO IMPROVE TEST METHODS

CHART 16

ISSUE #10: THERMOELECTRIC MATERIALS: SiGe, SiGe/GaP OR OTHER

FUNCTION: DIRECT CONVERSION OF HEAT FLUX TO ELECTRICAL POWER

REQUIREMENTS:

- STABLE UNDER OPERATING CONDITIONS
- COMBINED n-TYPE AND p-TYPE FIGURE OF MERIT OF $Z=0.85 \times 10^{-3}/K$ AVERAGE FROM 550 C TO 1000 C AT END OF LIFE

IMPACT:

- SYSTEM WEIGHT IS NEARLY PROPORTIONAL TO FIGURE OF MERIT
- CURRENT SYSTEM STUDIES ARE BASED ON $Z=0.85 \times 10^{-3}/K$

STATUS:

- CURRENT SiGe HAS AN AVERAGE $Z=0.61 \times 10^{-3}/K$ (GE DATA) BEST SiGe/GaP TO DATE, FROM GE-DATA, IS 2% LOWER
- RESULTS FROM THE DOE IMPROVED THERMOELECTRIC MATERIALS PROGRAM AT GE SUGGEST $Z=0.67 \times 10^{-3}/K$ IS POSSIBLE WITH SiGe
- VANDERSANDE (JPL) HAS REPORTED $Z=1.0$ TO $1.2 \times 10^{-3}/K$ FOR n-TYPE SiGe/GaP ON 2 OR 3 SAMPLES AFTER ANNEALING
- COMBINED n-TYPE SiGe/GaP (JPL DATA) AND p-TYPE SiGe (GE DATA) GIVES AVERAGE $Z=0.73$ TO $0.83 \times 10^{-3}/K$
- USE OF CURRENT SiGe MEANS A 25% WEIGHT OR POWER PENALTY COMPARED TO CURRENT DESIGN STUDIES

CHART 17

ISSUE #11: MODULE GLASSING

FUNCTION: ELECTRICAL ISOLATION, STRUCTURAL "GLUE" AND VAPOR SUPPRESSION

REQUIREMENTS:

- CHEMICAL STABILTY UNDER OPERATING VOLTAGES AND TEMPERATURES
- SOFTENING AND RECRYSTALIZATION PROPERTIES CONSISTENT WITH ASSEMBLY
- LOW VAPOR PRESSURE
- IMPERMEABLE TO Si, Ge, P, B (AND Ga, FOR FLIGHT)

IMPACT:

- CLOSE-PACKED DEVICE COMPACT NOT VIABLE WITHOUT SOME SOLUTION

STATUS:

- ELECTRICAL FAILURES IN MULTICOUPLES OBSERVED IN 1986 (MOD-RTG)
- NATIONAL PANEL STUDIED THE FAILURES
- NO CONCENSUS YET EXISTS ON DETAILED FAILURE MECHANISM
- CURRENT MOD-RTG EE2/EE9 GLASS-SiGe/GaP SYSTEM NOT ACCEPTABLE
- ONE MOD-RTG DEVICE BUILT WITH NO GaP FAILED IN AN ENTIRELY
  DIFFERENT MANNER AND ONLY AFTER MUCH MORE SEVERE TESTING
- POSSIBLE "FIXES" BEING IMPLEMENTED
- SP-100 ENVIRONMENT IS DIFFERENT:
  - VOLTAGE ENVIRONMENT IS LESS SEVERE ON GLASSES
  - GEOMETRY LESS SENSITIVE TO SINGLE POINT FAILURES
  - GES DOES NOT USE SiGe/GaP (BUT FLIGHT SYSTEM DOES)

CHART 18

ISSUE #12: JOINING OF ELECTRODE TO T/E MATERIALS, COLD SIDE

FUNCTION: COMPLETE THE ELECTRICAL PATH TO THE THERMOELECTRICS

REQUIREMENTS:

- LOW ELECTRICAL CONTACT RESISTANCE
- HIGH THERMAL CONDUCTIVITY
- NOT TOO HOT TO DAMAGE MATERIALS (EG. GLASS, SiGe)
- HOT ENOUGH TO BE STABLE FOR YEARS AT OPERATION TEMPERATURE
- SUFFICIENT MECHANICAL STRENGTH
- SURVIVE SHORT TERM EXCURSIONS TO HIGH TEMPERATURES

IMPACT:

- LESS POWER OUTPUT

STATUS:

- CONTACT RESISTANCE IS MORE IMPORTANT TO SP-100 THAN RTG's
  - SHORTER LEGS MAKE ELECTRODES A LARGER FRACTION OF TOTAL LOSS
- EXISTING SiMo TECHNOLOGY CAN BE READILY ADAPTED TO SP-100
  - PERFORMANCE PENALTY NOT WELL KNOWN
- EXISTING TEST METHODS ARE INADEQUATE TO DETERMINE CONTACT RESISTANCE WITH ACCURACY REQUIRED BY SP-100
- PLANS EXIST TO IMPROVE TEST METHODS
- BASELINE COLD SIDE ELECTRODE IS TUNGSTEN
  - JOINING TECHNIQUES MUST BE ADVANCED

CHART 19

ISSUE #13: COLD SIDE ELECTRODE MATERIAL

FUNCTION: COMPLETE THE ELECTRICAL CIRCUIT BETWEEN LEGS

REQUIREMENTS:

- THERMAL EXPANSION MATCH TO SiGe
- HIGH THERMAL CONDUCTIVITY
- LOW ELECTRICAL RESISTIVITY
- CHEMICAL COMPATIBILITY
- JOINABLE TO SiGe WITH LOW SPECIFIC CONTACT RESISTANCE
- JOINABLE TO LOW VOLTAGE INSULATOR
- JOINABLE TO CELL-TO-CELL INTERCONNECTION STRAP
- SURVIVE SHORT TERM EXCURSIONS TO HIGH TEMPERATURES

IMPACT:

- LESS POWER OUTPUT

STATUS

- ELECTRODE PERFORMANCE IS MORE IMPORTANT TO SP-100 THAN RT
  - SHORTER LEGS MAKE ELECTRODES A LARGER FRACTION OF TO
- EXISTING SiMo TECHNOLOGY CAN BE READILY ADAPTED TO SP-100
  - PERFORMANCE PENALTY CONSIDERED LARGE
- TUNGSTEN IDENTIFIED AS PRIME CANDIDATE
  - LOW ELECTRICAL RESISTIVITY, HIGH THERMAL CONDUCTIVIT
- EXPERIENCE WITH TUNGSTEN INDICATED FAILURES DUE TO WSi FO
  - OK AT LOWER TEMPERATURES, SP-100 OPERATES HOTTER

CHART 20

ISSUE #14 CELL TO CELL ELECTRICAL STRAP

FUNCTION: COMPLETE SYSTEM ELECTRICAL CIRCUIT BETWEEN CELLS

REQUIREMENTS:

- LOW ELECTRICAL RESISTANCE
- JOINABLE TO COLD SIDE ELECTRODE MATERIAL
- CHEMICALLY COMPATIBLE WITH COLD SIDE ELECTRODE MATERIAL
- TRANSMIT SMALL FORCES BACK INTO CELL
- FIT IN A SPACE 0.05" WIDE
- SURVIVE SHORT TERM EXCURSIONS TO HIGH TEMPERATURES

IMPACT:

- SOME FAILURES COULD CAUSE POWER LOSS FROM LARGE STRINGS OF CELLS
- COMPLICATES ASSEMBLY PROCEEDURES

STATUS:

- DESIGN WORK ON TUNGSTEN STRAPS INITIATED
- STRAP AND ATTACHMENT TECHNIQUES NOT IDENTIFIED FOR ALTERNATE COLD SIDE ELECTRODE MATERIALS

ISSUE #15: JOINING OF ELECTRODE TO LOW VOLTAGE INSULATOR, COLD SIDE

FUNCTION: COMPLETE THE HEAT PATH TO THE MODULE

REQUIREMENTS:

- HIGH THERMAL CONDUCTIVITY
- NOT TOO HOT TO DAMAGE MATERIALS OR PREVIOUSLY MADE BONDS
- HOT ENOUGH TO BE STABLE FOR YEARS AT OPERATION TEMPERATURE
- SUFFICIENT MECHANICAL STRENGTH
- SURVIVE SHORT TERM EXCURSIONS TO HIGH TEMPERATURES

IMPACT:

CLOSE PACKED DEVICE CONCEPT FAILS WITHOUT FUNCTIONAL LOW VOLTAGE INSULATOR AND JOINING TECHNOLOGY

STATUS:

- EXISTING GLASSES (NOT EE2/EE9) HAVE BEEN BONDED TO TUNGSTEN BUT ARE NOT SUITABLE TO SP-100 OPERATING TEMPERATURES
- BONDING TECHNOLOGY DEPENDS ON CHOICE OF ELECTRODE MATERIAL

CHART 22

ISSUE #16 COLD SIDE LOW VOLTAGE INSULATOR

FUNCTION: ELECTRICALLY ISOLATE A MODULE FROM COMPLIANT PAD

REQUIREMENTS:

- SIMILAR TO HOT INSULATOR BUT LESS SEVERE DUE TO LOWER TEMPERATURE
- THERMAL EXPANSION MATCH
- HIGH THERMAL CONDUCTIVITY (K) TO MINIMIZE TEMPERATURE DROP
- HIGH ELECTRICAL RESISTIVITY (R) TO MINIMIZE ELECTRICAL POWER LOSS
  - FIGURE OF MERIT = R*K, 300 V^2/K IS PROBABLY ACCEPTABLE
- CHEMICAL COMPATIBILITY (THERMODYNAMIC)
- STABILITY IN MODERATE ELECTRIC FIELD (200 V/cm)
- JOINABLE TO COMPLIANT PAD AND ELECTRODES
- SURVIVE SHORT TERM EXCURSIONS TO HIGH TEMPERATURES

IMPACT:

- MODULES LOSE POWER IF GLASS FAILS

STATUS:

- EE2/EE9 GLASS IDENTIFIED
- IDENTICAL GLASS USED FOR MODULE GLASSING
- FOR THIS APPLICATION, EXISTING GLASS SHOULD BE ADEQUATE

CHART 23

ISSUE #17: JOINING OF LOW VOLTAGE INSULATOR TO COMPLIANT PAD, COLD SIDE

FUNCTION: COMPLETE THE HEAT PATH TO THE MODULE

REQUIREMENTS:

- HIGH THERMAL CONDUCTIVITY
- NOT TOO HOT TO DAMAGE MATERIALS OR PREVIOUSLY MADE BONDS
- SUFFICIENT MECHANICAL STRENGTH
- MUST BE EFFECTED WITHOUT CRUSHING COMPLIANT PAD
- SURVIVE SHORT TERM EXCURSIONS TO HIGH TEMEPRATURES

IMPACT:

CONDUCTIVELY COUPLED CONCEPT FAILS WITHOUT FUNCTIONAL JOINT

STATUS:

EXPECT TO REQUIRE METALLIZATION OF LOW VOLTAGE INSULATOR

CHART 24

ISSUE #18: COMPLIANT PAD, COLD SIDE

FUNCTION: ACCOMODATE THERMAL EXPANSION BETWEEN PRIMARY HEAT LOOP, TRANSMITED THROUGH CELL, AND HEAT REJECTION SYSTEM LOOP

REQUIREMENTS:

- MECHANICAL INTEGRITY
- HIGH THERMAL CONDUCTIVITY
- TRANSMITS SMALL FORCES INTO THERMOELECTRIC MODULE
- INTERNAL CHEMICAL COMPATIBILITY
- JOINABLE TO HIGH AND LOW VOLTAGE INSULATOR
- SURVIVE SHORT TERM EXCURSIONS TO HIGH TEMEPRATURES

IMPACT:

- CONDUCTIVELY COUPLED CONCEPT FAILS WITHOUT FUNCTIONAL PAD
- SYSTEM PERFORMANCE IS STRONGLY DRIVEN BY PAD PERFORMANCE

STATUS:

- INITIAL DEVELOPMENT UNDER IRD RESULTED IN TEST MODULE
  - O POOR THERMAL PERFORMANCE

CHART 24

ISSUE #18: COMPLIANT PAD, COLD SIDE

FUNCTION: ACCOMODATE THERMAL EXPANSION BETWEEN PRIMARY HEAT LOOP, TRANSMITED THROUGH CELL, AND HEAT REJECTION SYSTEM LOOP

REQUIREMENTS:

- MECHANICAL INTEGRITY
- HIGH THERMAL CONDUCTIVITY
- TRANSMITS SMALL FORCES INTO THERMOELECTRIC MODULE
- INTERNAL CHEMICAL COMPATIBILITY
- JOINABLE TO HIGH AND LOW VOLTAGE INSULATOR
- SURVIVE SHORT TERM EXCURSIONS TO HIGH TEMEPRATURES

IMPACT:

- CONDUCTIVELY COUPLED CONCEPT FAILS WITHOUT FUNCTIONAL PAD
- SYSTEM PERFORMANCE IS STRONGLY DRIVEN BY PAD PERFORMANCE

STATUS:

- INITIAL DEVELOPMENT UNDER IRD RESULTED IN TEST MODULE
  - POOR THERMAL PERFORMANCE
  - MANY FIBERS BROKEN
- ACCEPTABLE PAD HAS NOT BEEN DEMONSTRATED

CHART 25

ISSUE #19: JOINING OF COMPLIANT PAD TO INSULATOR, COLD SIDE

FUNCTION: COMPLETE THE HEAT PATH TO THE MODULE

REQUIREMENTS:

- HIGH THERMAL CONDUCTIVITY
- NOT TOO HOT TO DAMAGE MATERIALS OR PREVIOUSLY MADE BONDS
- HOT ENOUGH TO BE STABLE FOR YEARS AT OPERATION TEMPERATURE
- SUFFICIENT MECHANICAL STRENGTH
- MUST BE EFFECTED WITHOUT CRUSHING COMPLIANT PAD
- SURVIVE SHORT TERM EXCURSIONS TO HIGH TEMPERATURES

IMPACT:

- CONDUCTIVELY COUPLED CONCEPT FAILS WITHOUT FUNCTIONAL JOINT

STATUS:

- EXPECT TO REQUIRE METALLIZED INSULATOR

CHART 26

ISSUE #20: COLD SIDE HIGH VOLTAGE ELECTRICAL INSULATOR

FUNCTION: ELECTRICALLY ISOLATE EACH CELL FROM COMMON STRUCTURAL ELEMENTS

REQUIREMENTS:

- THERMAL EXPANSION MATCH
- HIGH THERMAL CONDUCTIVITY (K) TO MINIMIZE TEMPERATURE DROP
- HIGH ELECTRICAL RESISTIVITY (R) TO MINIMIZE ELECTRICAL POWER LOSS
  - FIGURE OF MERIT = R*K, GOAL OF 2,000,000 V^2/K
- CHEMICAL COMPATIBILITY (THERMODYNAMIC)
- STABILITY IN HIGH ELECTRIC FIELD (4000 V/cm)
- JOINABLE TO HEAT REJECTION SYSTEM AND COMPLIANT PAD
- SURVIVE SHORT EXCURSIONS TO HIGH TEMPERATURES

IMPACT:

- CONDUCTIVELY COUPLED CONCEPT FAILS WITHOUT FUNCTIONAL INSULATOR
- SYSTEM PERFORMANCE IS DIRECTLY RELATED TO INSULATOR F.O.M.

STATUS:

- CONFIDENCE IS QUITE HIGH THAT Al_2O_3, IN SOME FORM, IS SATISFACTORY
- LOWER TEMPERATURE MAKES ALL THE DIFFERENCE

CHART 27

ISSUE #21: JOINING COLD SIDE ELECTRICAL INSULATOR TO HEAT REJECTION SYST

FUNCTION: COMPLETE THE HEAT PATH TO THE MODULE

REQUIREMENTS:

- HIGH THERMAL CONDUCTIVITY
- NOT TO HOT TO DAMAGE MATERIALS OR PREVIOUSLY MADE BONDS
- HOT ENOUGH TO BE STABLE FOR YEARS AT OPERATION TEMPERATURE
- SUFFICIENT MECHANICAL STRENGTH
- CHEMICAL COMPATIBILITY WITH INSULATOR AND Nb1Zr

IMPACT:

- CONDUCTIVELY COUPLED CONCEPT FAILS WITHOUT FUNCTIONAL JOINT

STATUS:

- SIMILAR BONDS HAVE BEEN EFFECTED
- EXISTING TECHNOLOGY CAN BE ADAPTED TO SP-100 WITH HIGH CONFIDENCE