M&R 1123
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MASTER

BRAYTON ISOTOPE POWER SYSTEM
(BIPS)
SUPERALLOY GROUND DEMONSTRATION SYSTEM
(GDS-S)
DETAIL DESIGN REVIEW

31-2701

September 12, 1977

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

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(GDS-S)
DETAIL DESIGN REVIEW

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September 12, 1977

Prepared by Engineering Staff/RDG

Initial Issue
Approved by *F. X. Dobler*
F. X. Dobler, BIPS Assistant
Program Manager

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1.0 INTRODUCTION

BRAYTON ISOTOPE POWER SYSTEM
(BIPS)
SUPERALLOY GROUND DEMONSTRATION SYSTEM
(GDS-S)
DETAIL DESIGN REVIEW

1.0 INTRODUCTION AND MEETING ACTION ITEMS

1.1 Introduction

This document, prepared by the AiResearch Manufacturing Company of Arizona, a division of the Garrett Corporation, contains the material presented at the GDS-S design review meeting held at Phoenix, Arizona on September 7 and 8, 1977.

This design review was specifically scoped to examine the Hastelloy-X Heat Source Heat Exchanger (HSHX) and the Hastelloy-X bellows. These are new components required to upgrade the Workhorse Loop (WHL) to the GDS configuration.

Additional topics covered in support of those items were: reliability; materials; and the WHL-to-GDS conversion sequence.

1.2 Meeting Action Items

Table 1 contains the action items resulting from the individual presentations and the government critique conducted after the meeting.

TABLE 1

ACTION ITEMS
CONTRACTOR/IN-HOUSE BIPS-S DETAIL DESIGN REVIEW
SEPTEMBER 7 AND 8, 1977

1. AIRESEARCH - Summarize and complete the matrix identifying the controlling design criteria for each design component including the material presented on the bellows and the SAHSA at this meeting.
2. AIRESEARCH/ORNL - Prior to testing the link-type bellows at ORNL, perform pretest inspection so that after test, damage (fretting, galling, or burnishing) can be measured.
3. AIRESEARCH/ORNL - Revise the bellows creep tests to include periodic helium leak check to explore grain boundary leak path formation.
4. AIRESEARCH/ORNL - Re-define the thermal cycle for the -467 (turbine discharge) bellows that has been provided for early testing at ORNL. Also, change test plan so that bellows will be tested to destruction.
5. FSED - Provide the data and/or available literature that supports the concern for grain boundary leakage resulting from creep damage in thin tubing.
6. ORNL - Provide 7,000-hour creep test data on Hastelloy-X.
7. AIRESEARCH - Provide ORNL bellows weld samples for material property investigations.
8. AIRESEARCH - Perform further examination of the bellows seal weld samples (i.e., polishing, etching and metallographic examination).
9. *AIRESEARCH - If possible, invoke the requirement to perform squirm and proof pressure tests simultaneously at bellows vendors as part of acceptance testing.
10. ALL - Review ORNL bellows test program and schedule to insure that as much information as possible is generated in time for contractor evaluation at the conclusion of Phase I.
11. AIRESEARCH - Check stress condition due to asymmetric fitup of bellows to duct joints.

*Incorporated as part of acceptance tests for future orders.

TABLE 1 (Contd)

12. AIRESEARCH - Review the SAHSA design for capability to accommodate the three FS thermal transients listed below:
 - a. FS IHS fueling
 - b. FS in orbit start-up after cold soaking
 - c. FS on the launch pad start-up
13. ERDA - Define the temperature limitations which exist for the MHW PICS for the following two cases:
 - a. Upper and lower bound for I_R PICS
 - b. Upper bound for PT3008 PICS
14. MARSCOM - Review the currently existing data for long-term interaction between gold base braze alloy (PALNIRO) and Hastelloy alloy X.
15. AIRESEARCH - Provide ERDA program manager BIPS-S GDS performance predictions prior to initiating testing. Also, provide, as they become available, ORNL bellows performance predictions.

BRAYTON ISOTOPE POWER SYSTEM

MS 4175-6

PURPOSE

REVIEW DESIGN OF COMPONENTS NOT PREVIOUSLY
COVERED IN BIPS-R DDR.

- a. SAHSA
- b. BELLOWS

ERDA DIPS PHASE I PLAN

ASSEMBLE AND TEST PHASE (UPDATED)

MAJOR MILESTONES GDS-PHASE I

	<u>EST</u>	<u>ACT</u>	ASSEMBLY AND TEST PHASE
1.	7/12/77	7/12/77	PUBLISH HASTELLOY-X DESIGN DATA REPORT
2.	8/5/77	8/27/77	COMPLETE WHL ASSEMBLY
3.	9/5/77	9/2/77	FIRST SYSTEM HOT TEST AT DESIGN SPEED (52,000 RPM)
4.	10/29/77		DESIGN POINT OPERATION, WHL
5.	2/1/78		WHL TEST REPORT
6.	3/1/78		SUBMIT PHASE II PLAN
7.	3/15/78		COMPLETE GDS PERFORMANCE TESTS
8.	3/15/78		START 1000-HR GDS ENDURANCE TEST
9.	5/1/78		COMPLETE 1000-HR GDS TEST
10.	6/30/78		SUBMIT PHASE I FINAL REPORT

SUPERALLOY GDS DESIGN REVIEW BIPS PROGRAM AGENDA

WEDNESDAY, SEPTEMBER 7, 1977

9:00 — 9:30	INTRODUCTION	J. McCormick
9:30 — 11:00	SYSTEM DESCRIPTION	
	Differences between WHL and GDS	F. Dobler
	How Conversion Effected	F. Dobler/A. Pakvis
	Controls Function	P. Post
11:00 — 12:30	MATERIAL PROPERTIES	L. Matsch/J. Hadley
12:30 — 1:00	LUNCH	
1:00 — 3:00	RELIABILITY	L. Matsch
3:00 — 5:00	BELLOWS DESIGN AND FABRICATION	G. Roll/T. Vishwanath

THURSDAY, SEPTEMBER 8, 1977

9:00 — 12:30	SAHSA DESIGN AND FABRICATION	
	Design Analysis	J. Killackey/R. Graves
	HSHX Fabrication Status	F. Dobler
	HSA Fabrication Status	R. Hemler

GDS-S 1300 W_e @ 2 HSA WITH MBR

1349 WATTS
OUTPUT (GROSS)

NET OUTPUT 1305 W_e
NET EFFICIENCY 0.272

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GDS-R

2.0 SYSTEM DESCRIPTION

2.1 DIFFERENCES BETWEEN WHL AND GDS

WHL TO GDS-S CONVERSION

- HASTELLOY-X HEAT EXCHANGER INSTALLED IN HSA
- ALL NICKEL MULTI-FOIL SYSTEM USED IN HSA (FOR GDS ONLY)
- ACS BELLOWS ELIMINATED
- NEW BELLOWS IN AND OUT OF HSA
- NEW 2 1/2 IN. DUCTING WITH PRE-INSTALLATION OF FOIL INSULATION

COMPARISON OF BIPS-R GDS TO BIPS-S GDS

2.0 SYSTEM DESCRIPTION

2.2 HOW CONVERSION EFFECTED

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WHL DISASSEMBLY PROCEDURE

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UNBOLT 432-1 FROM 407-1
UNBOLT TURBINE PLENUM

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2.0 SYSTEM DESCRIPTION

2.3 CONTROLS FUNCTION

BIPS-R/BIPS-S DESIGN GOALS COMPARED

DESIGN GOAL	BIPS-R CONTROL	BIPS-S CONTROL
RELIABILITY	0.99 FOR 5 YEARS	SAME
PERFORMANCE	BOM 1.3 KW EOM 1.2 KW	SAME SAME
POWER QUALITY	SC-76-312008 (MIL-STD-704B FOR 120 VDC)	SAME SAME SAME
WEIGHT	10-15 LBS	SAME

SIMPLIFIED BLOCK DIAGRAM

PERFORMANCE VERSUS TIME

PERFORMANCE VERSUS TIME

START INVERTER

- SYNCHRONOUS START
- CONTROLLED FREQUENCY → CONTROLLED TORQUE ANGLE
- BIPS-S MINI-BRU ELECTRICALLY IDENTICAL TO BIPS MINI-BRU

DIGITAL CONTROL

- **RELIABLE**
 - REDUNDANT MICROPROCESSORS
 - SELF CHECK CAPABILITY
- **EFFICIENT**
 - LOW POWER CONSUMPTION
 - PROGRAMMABLE PERFORMANCE
- **FLEXIBLE**
 - REPROGRAMMABLE
- **ACCURATE**
 - SPEED - < 0.1%
 - POWER - < 1%

3.0 MATERIAL PROPERTIES

DESIGN CRITERIA – CREEP MATERIALS DATA

LARSON-MILLER MODEL:

$$T (C + \text{LOG } t) = \sum_{i=0}^3 a_i (\text{LOG } \sigma)^i$$

WHERE C, a_i ARE DETERMINED BY REGRESSION ANALYSIS OF DATA.

HASTELLOY X CREEP IN AIR

HASTELLOY X CREEP IN AIR

COMPARISON OF HASTELLOY-X CREEP AND STRESS-RUPTURE
PROPERTIES, AIR VERSUS HELIUM

$t = 61,320$ HOURS

LARSON MILLER PARAMETER = $(T + 460) (20 + \log t)$

<u>TEMPERATURE</u>	<u>1% CREEP STRESS (KSI)</u>		<u>-3σ RUPTURE STRESS (KSI)</u>	
	<u>AIR</u>	<u>HELIUM</u>	<u>AIR</u>	<u>HELIUM</u>
1250°F	10.2 (9.8)*	12.4	12.8	16.1
1450°F	3.7 (3.5)*	6.4	4.6	6.5

*ORNL CORRESPONDENCE, H.E. MCCOY, ORNL, TO J. HADLEY, AIRPHX, 9-2-77.

DESIGN CRITERIA – MARGINS FOR UNCERTAINTY

PREDICTED TEMPERATURES

- +50°F, HEAT SOURCE HT EX; +25°F ELSEWHERE

MATERIALS PROPERTIES (PROPERTY SCATTER AND 7 YEARS EXTRAPOLATION)

- MINUS 3 STANDARD DEVIATIONS, STRESS RUPTURE
- RUPTURE STRESS $\div 1.2$

DESIGN CRITERIA – CREEP – RUPTURE

DESIGN STRESS IS DETERMINED TO BE THE LESSER OF:

- NOMINAL STRESS OF CAUSE 1% CREEP, 7 YEARS
- (MINUS THREE STANDARD DEVIATION RUPTURE STRESS,
7 YEARS) $\div$ 1.2
 - FACTOR 1.2 APPLIED TO ACCOUNT FOR TIME EXTRAPOLATION
OF L.M. DATA TO 7 YEARS
- FOR REGIONS WHERE PEAK STRESS, DUE TO BENDING, GEOMETRY,
OR THERMAL STRESS, EXCEEDS ABOVE CRITERIA, CREEP ANALYSIS
IS CONDUCTED.

DESIGN CRITERIA – CREEP – STRESS RELAXATION

- NORTON POWER LAW: $\frac{d\epsilon}{dt} = K \sigma^n$

ϵ = STRAIN
 t = TIME
 σ = STRESS
 K, n , EMPIRICAL CONSTANTS
 $K = K(T)$
 $n = n(T)$
 T = TEMPERATURE

$$\frac{\Delta\epsilon}{\Delta t} \approx \frac{d\epsilon}{dt} = K \sigma^n$$

$$\ln (\Delta\epsilon_i) - \ln (\Delta t_i) = \ln K + n \ln T_i$$

$\Downarrow$
 $K(T), n(T)$

DESIGN CRITERIA – CREEP – STRESS RELAXATION

- GENERALIZED APPLICATION, THREE DIMENSIONAL STATE

$$\dot{\epsilon}_{ij} = C J_2^m \sigma_{ij}$$

$$\dot{\epsilon}_{ij} = \text{STRAIN RATE TENSOR COMPONENT}$$

$$C = \frac{K}{2} (3)^{\left(\frac{n+1}{2}\right)}$$

$$m = (n-1)/2$$

$$J_2 = \text{SECOND STRESS INVARIANT}$$

$$\sigma_{ij} = \text{DEVIATORIC STRESS COMPONENT}$$

COMBINED CREEP – LOW CYCLE FATIGUE

- CREEP DAMAGE AND L.C.F. DAMAGE COMBINE LINEARLY

t_s = MISSION LIFE

N_s = EQUIVALENT NUMBER OF CYCLES APPLIED DURING t_s

t_f = COMPONENT LIFE TO RUPTURE ONLY

N_f = COMPONENT CYCLIC LIFE TO LCF FAILURE

t_l = COMBINED LIFE OF COMPONENT

- $$t_l = t_s \left[\frac{t_s}{t_f} + \frac{N_s}{N_f} \right]^{-1}$$

4.0 RELIABILITY

BELLOWS RELIABILITY DESIGN REVIEW – SOME QUALITATIVE ASPECTS

DESIGN CRITERIA – CREEP DEFORMATION

- NORTON POWER LAW: $\frac{d\epsilon}{dt} = K \sigma^n$

ϵ = STRAIN
 t = TIME
 σ = STRESS
 K, n , EMPIRICAL CONSTANTS

FUNDAMENTAL FACTORS TO SUCCESSFUL (RELIABLE) BELLOWS

- WELL WITHIN MANUFACTURING PROCESS CAPABILITY
- REPEATABILITY OF MANUFACTURING PROCESS
- CONTROL OF MANUFACTURING PROCESS
- INSPECTABILITY, CRITICAL MANUFACTURING PROCESSES
- ANALYTICAL PREDICTION ACCURACY/AMENABILITY TO ANALYSIS
- TRADE STUDIES INVOLVING BOUNDARY CONDITIONS (SYSTEM OPTIMIZATION)
- TRADE-OFFS AMONG IDEALIZED POTENTIAL RELIABILITY WITH OTHER FACTORS, I.E.,

- EXPERIMENTAL DATA, E.G.: MATERIALS
- ORGANIZATIONAL PARTICIPATION IN DESIGN (E.G., MFG., Q.C., ENGRG, ETC.)
- ORGANIZATIONAL COMMITMENT

BELLOWS RELIABILITY - JUNCTION OF BELLOWS PLIES TO FLANGE

- GAS LEAKS TO SPACE BETWEEN ADJACENT PLIES (REDUNDANCY)
- WELD PENETRATION
- WELD STRESSES DUE TO PRESSURE AND TEMPERATURE GRADIENT (TRANSIENT)
- MANUFACTURING PROCESS CAPABILITY
- WELD QUALITY ASSURANCE CONSIDERATIONS

BELLOWS RELIABILITY DESIGN OBJECTIVES, FLANGE JUNCTION

- COMPLETE BONDING OF ADJACENT PLIES TO
 - TO FLANGE
 - TO EACH OTHER
- MINIMIZATION OF BENDING AND SHEAR STRESSES THROUGH WELD JUNCTION
- WELD MANUFACTURING PROCESS
 - WELL WITHIN STATE OF ART
 - CONTROLLABLE
 - INSPECTABLE
 - REPRODUCIBLE
- QUALITY ASSURANCE METHODS
 - DETECT FLAWS, DEFECTS
 - DISCRIMINATE

PREVIOUS EXPERIENCE,
COMPATIBILITY WITH
OTHER REQUIREMENTS

X-RAY IMAGE
ENHANCEMENT

DESIGN FEATURES, CONVOLUTED TUBING FLANGE WELD

- NO BENDING AND SHEAR STRESSES TRANSMITTED ACROSS WELD DUE TO THERMAL TRANSIENT RESPONSE, PRESSURE LOAD
- WELD INSPECTABILITY, ID AND OD

THIS

INSTEAD OF THIS

- E-BEAM WELDING UNIFORM (LARGE) THICKNESS MEMBERS

- E-BEAM WELDING OF MATCHING CONTOURS

- E-BEAM WELDING FROM OD, NOT ID (IMPOSSIBLE FROM ID)

BELLOWS RELIABILITY - FLANGE JUNCTION DESIGN CONCEPT

RELIABILITY OBJECTIVES, CONVOLUTED TUBING TO FLANGE WELD

1. MANUFACTURING PROCESS CAPABILITY
2. Q.C. INSPECTABILITY
3. BENIGN ENVIRONMENT (LOW STRESS LEVELS AT WELD(S))
4. MINIMIZED DESIGN COMPLEXITY CONSISTENT WITH FUNCTIONAL OBJECTIVES

- A. SEAM WELD ADJACENT PLIES (ITEM 1 ABOVE)

- B. DRESS SURFACE, SEAM WELDED PLIES (ITEMS 1 AND 2 ABOVE)

- C. WELD TO FLANGE MEMBER (ITEMS 1, 2, 3, AND 4 ABOVE SERVED)

BELLOWS RELIABILITY - FLANGE JUNCTION
FEASIBILITY EVALUATION
(HASTELLOY - X)

10 MIL FLAT SPECIMENS
(BELLOWS)

30 MIL FLAT SPECIMENS
(FLANGE)

BELLOWS RELIABILITY - FLANGE JUNCTION
FEASIBILITY EVALUATION - HASTELLOY X
SEAM WELD - 3 10 MIL FLAT SPECIMENS

ACTUAL SEAM WELDED SAMPLE -
TOP VIEW

BELLOWS RELIABILITY - FLANGE JUNCTION
FEASIBILITY EVALUATION - HASTELLOY X
SEAM WELD - 3 10 MIL FLAT SPECIMENS

TRANSVERSE

LONGITUDINAL

ETCHED SPECIMEN - LONGITUDINAL AND TRANSVERSE
SECTIONS, 20X SIZE

BELLOWS RELIABILITY - FLANGE JUNCTION
FEASIBILITY EVALUATION - HASTELLOY X
SEAM WELD - 3 10 MIL FLAT SPECIMENS

END OF "NUGGET", WELD PENETRATION
INTO PLIES

BELLOWS RELIABILITY - FLANGE JUNCTION
FEASIBILITY EVALUATION, HASTELLOY X
BUTT WELD, 3-10 MIL SPECIMENS TO 30 MIL SPECIMEN

ELECTRON BEAM WELD THROUGH RESISTANCE WELD AT
1.5 MAG (TOP SURFACE VIEW)

TOP VIEW, BUTT WELD
FOLLOWING SEAM WELD

BELLOWS RELIABILITY - FLANGE JUNCTION
FEASIBILITY EVALUATION, HASTELLOY X
E-BEAM BUTT WELD, 3-10 MIL SPECIMENS TO 30 MIL SPECIMEN

TRANSVERSE SECTION THROUGH (3) PLY
RESISTANCE WELD AND ELECTRON BEAM
BUTT JOINT SAMPLE.

20X

75X

TRANSVERSE SECTION, 3 PLY SEAM WELD
FOLLOWED BY E-BEAM BUTT WELD
(SAME SECTION, BOTH PHOTOS)

BELLOWS RELIABILITY - WELD JUNCTION

IMAGE ENCHACEMENT IDENTIFYING FLAW

SECTIONED VIEW OF WELD (50X) SHOWING FLAW

BELLOWS RELIABILITY - WELD JUNCTION

WELD FLAW, 100X

WELD FLAW 500X SIZE

BELLOWS RELIABILITY – REDUNDANCY

**BELLOWS RELIABILITY DESIGN REVIEW
SUMMARY OF AREAS RESOLVED, UNCERTAINTIES/PROBLEMS**

AREAS WELL IN HAND

- **ANALYTICAL DESIGN METHODS**
 - PREDICTION OF STRESSES
 - PREDICTION OF COMPLIANCE PARAMETERS
 - ANALYTICAL MODELING OF CONTOUR VARIATIONS
 - SELECTION OF DESIGN STRESSES (CONSERVATIVE)
 - RECOGNITION OF ADJACENT PLY INTERACTIONS
- **MATERIALS PROPERTY DATA - HASTELLOY X**
- **FUNCTIONAL FEASIBILITY OF BELLOWS WITH RESPECT TO SYSTEM OBJECTIVES**

UNCERTAINTIES/PROBLEMS

- **MANUFACTURING PROCESS CONTROLS (VENDORS)**
- **TUBING SEAM WELD**
 - WELDED VS SEAMLESS
 - MATERIALS PROPERTIES/STRESS RELIEF, WELDED TUBING
 - DIMENSIONAL CONTROLS/TOLERANCES
 - PROCESS CONTROLS/INSPECTABILITY
- **CONVOLUTED TUBING - FLANGE WELD**
 - MFG. PROCESS CAPABILITY
 - NOTIONS OF REDUNDANCY
- **INCOMPLETE DESIGN PROBLEM STATEMENT**
 - SYSTEM DYNAMIC RESPONSE (INTUITION NOT SUFFICIENT)
- **PERSPECTIVE OF SYSTEM RELIABILITY**
- **QUANTIFIED RELIABILITY, BELLOWS (PROBABILISTIC APPROACH)**

5.0 BELLOWS DESIGN AND FABRICATION

BELLOWS UPDATE FROM DDR

- SOURCE INSPECTION ESTABLISHED FOR C-103 BELLOW FABRICATION
- WORKHORSE LOOP BELLOWS RECEIVED AND INSPECTED
- SQUIRM TESTS PERFORMED ON:

3605418	ACCEPTABLE
3605420	ACCEPTABLE
3605421	UNACCEPTABLE, NEW PARTS BEING MADE
3605466	MARGINALLY ACCEPTABLE
- INCREASED UNDERSTANDING BY AIRESEARCH AND BELLOWS MANUFACTURERS OF FABRICATION ABILITIES AND LIMITATIONS THROUGH EXTENSIVE MECHANICAL AND METALLURGICAL TESTING AND EXAMINATION
 - RADIOGRAPHIC IMAGE ENHANCEMENT
 - SPRING RATE TESTS; EXTENSIONAL AND BENDING
 - SQUIRM TESTS
 - DIMENSIONAL ANALYSIS OF CONVOLUTES
 - MICROSCOPIC ANALYSIS OF SECTIONED CONVOLUTES AND WELDS
- VALUABLE DESIGN AND RELIABILITY DATA WILL BE OBTAINED FROM ORNL BELLOWS TESTING

BELLOWS DESIGN USAGE

BELLOWS DESIGN	MATERIAL	WHL	USAGE		ORNL	REMARKS
			GDS-R	GDS-S		
3605418-1, -2	HAST-X	X	X	X	X	BELLOWS DESIGN SAME- END FLANGES DIFFERENT
3605419-1, 3605467-1	HAST-X	X	X		X	
3605420-1, -2, -3	347 STAIN- LESS STEEL	X	X	X	X	
3605421-1	HAST-X	X	X	X	X	
3605422-1	CB-103		X		X	
3605424-1	HAST-X		X		X	
3605466-1	HAST-X	X				REPLACES 3605422-1 AND 3605424-1 OR 3605466-1
HSA INLET/OUTLET (NEW)				X		
TURBINE EXHAUST (NEW)				X

BELLOWS INSPECTION STEPS

	RAW MATERIAL	ROLLED AND WELDED TUBES	NESTED TUBES	FORMED BELLOWS	FLANGE WELDS	FINAL ASSEMBLY
VISUAL	YES	YES	YES	YES	YES	YES
DIMENSIONAL	YES	YES		YES		YES
ULTRA-SONIC	YES					
RADIOGRAPHIC		YES			YES	
IMAGE ENHANCE		YES			YES	
HE LEAK TEST						YES
PROOF PRESSURE						YES
SPRING RATE				*		YES
CONVOLUTE SHAPE				*		YES
SQUIRM TEST						YES
ORNL TEST						YES
SECTIONING AND MICROSCOPE		YES	YES	YES		
CREEP LIFE VERIFICATION	*					

*RECOMMENDED FUTURE REQUIREMENT

METHOD OF CONDUCTING BELLOWS PROGRAM FOR FLIGHT SYSTEM

- AIRPHX WILL CONTROL DESIGN OF BELLOWS ASSEMBLY DETAILS
- FULL VENDOR PROCESS CONTROL BY AIRESEARCH Q.A. DEPARTMENT DURING BELLOWS FABRICATION
- BELLOWS ASSEMBLY WELDS CONTROLLED AND/OR PERFORMED BY AIRPHX
- FULL X-RAY IMAGE ENHANCEMENT OF ALL WELDS (REQUIRES EXTENSIVE CALIBRATION PROGRAM)
- REDESIGNS WILL BETTER REFLECT ABILITIES AND LIMITATIONS OF BELLOWS FABRICATION PROCESS
- REDESIGNS WILL REFLECT RESULTS OF EXPERIENCE GAINED THROUGH INITIAL HARDWARE FABRICATION AND TESTING, INCLUDING ORNL TESTS

TWO WELD METHODS EMPLOYED BY MBC

SSP WELD METHODS

RECOMMENDED FOR FUTURE BELLOWS

ADVANTAGES

- RESISTANCE SEAM SEAL PLIES FROM CONTAMINATION
- SURFACE OF CUT THROUGH NUGGET OPEN FOR INSPECTION (X-RAY, 20 X VISUAL, LEAK CHECK)
- RESISTANCE SEAM HOLDS PLIES AS ONE SHEET FOR WELDING TO END FLANGES
- E-BEAM SPIKE CONTAINED INSIDE NUGGET TO RETAIN INTEGRITY OF SEAM WELD
- ALLOWS BUTT WELDING OF LIKE THICKNESS MATERIAL

BELLOWS DESIGN

BELLOWS REQUIREMENTS FOR FS

BASIC

- CONTAIN PRESSURE, ACCOMMODATE MOTION, LIMIT FLANGE LOADS

SERVICE

- 100 START/STOP CYCLES (300 HR)
- 1 START/STOP CYCLE + 5200 DIURNAL CYCLES (7 YR)
- REDUNDANCY

INSTALLATION

- DUCT GEOMETRY
- THERMAL MOVEMENTS (STEADY STATE AND TRANSIENT)
- ALLOWABLE FLANGE LOADS
- SHOCK AND VIBRATION

BELLOWS SERVICE REQUIREMENTS FOR FS

S-18150

BELLOWS DESIGN CRITERIA

ALLOWABLE STRESS

● PRESSURE LOADING

A. SHORT TERM PRESSURE CONTAINMENT

$$\text{YIELD} = F_{TY}/1.5$$

$$\text{BURST} = F_{TU}/2.5$$

B. LONG TERM PRESSURE CONTAINMENT

$$1\% \text{ TYPICAL CREEP STRESS} = \left[\sigma_{1\%, 7 \text{ YR}} \right] / 1.2$$

● THERMAL LOADING

$$F_{TY}$$

● PRESSURE AND THERMAL LOADING

$$2 F_{TY}$$

$$\text{MIN. CREEP RUPTURE STRESS} = \left[\sigma_{CR., 7 \text{ YR}} \right] / 1.2$$

SQUIRM PRESSURE AT OPERATING TEMPERATURE

$$\bullet P_S (\text{MIN}) = 1.5 \times \text{OPERATING PRESSURE}$$

BELLOWS TYPES

SINGLE BELLOWS

- AXIAL, LATERAL, AND ROTATIONAL MOTION
- RELATIVELY HIGHER LATERAL STIFFNESS
- NOT PRESSURE BALANCED

LINK-TYPE

- PRESSURE BALANCED
- PURE ROTATION
- MULTIPLE LINKS TO MINIMIZE STIFFNESS OF ASSEMBLY

DOUBLE BELLOWS

- AXIAL, LATERAL, AND ROTATIONAL MOTION
- RELATIVELY LOWER LATERAL STIFFNESS
- NOT PRESSURE BALANCED

LINK-TYPE

BELLOWS

PRESSURE CONTAINMENT PARAMETRIC STUDY

CONVOLUTION VARIABLES

$$\frac{h}{R} = 0.05 - 0.30$$

$$\frac{w}{h} = 0.50 - 2.00$$

$$t = 0.004 - 0.016 \text{ IN.}$$

STIFFNESS PARAMETRIC STUDY

$$K_{AXIAL} = \frac{N F_{AXIAL}}{\delta_{AXIAL}}, P_S = \left[0.64 \left(\frac{\pi K_{AXIAL}}{2L} \right) - \frac{K_{AXIAL} \delta_{AXIAL}}{\pi R^2} \right]$$

MAXIMUM EQUIVALENT AXIAL DISPLACEMENT =

$$\delta_{EQ.} = \left[\delta_{AXIAL} + \frac{6 R_0 \delta_{LAT.}}{L} + \theta R_0 \right]$$

$$\text{MAXIMUM STRESS DUE TO } \delta_{EQ.} = \frac{\delta_{EQ.} \sigma_{MAX.}}{\delta_{AXIAL}}$$

AXIAL MOVEMENT

$$F_{AXIAL} = K_{AXIAL} \delta_{AXIAL}$$

LATERAL MOVEMENT

$$F_{LAT.} = K_{LAT.} \delta_{LAT.}, \quad M_{LAT.} = \frac{3(R_0)^2 K_{AXIAL} \delta_{LAT.}}{L}$$

$$K_{LAT.} = 6.3 \left(\frac{R_0}{L} \right)^2 K_{AXIAL}$$

ANGULAR MOVEMENT

$$M_{ANG.} = K_{BEND.} \theta$$

$$K_{BEND.} = \frac{1}{2} K_{AXIAL} (R_0)^2$$

BELLOWS DESIGN

INPUT

MATERIAL
NUMBER OF PLIES
THICKNESS PER PLY
ACTIVE LENGTH
CONVOLUTION SHAPE
LENGTH BETWEEN BELLOWS
3D DEFLECTIONS

ANALYSIS

OUTPUT

FLANGE LOADS
LIFE
STABILITY LIMIT
(SQUIRM)

- REVIEW COMPUTER OUTPUT, SELECT BEST DESIGN
- PREPARE PROCUREMENT SPECIFICATIONS

SUMMARY OF BELLOWS DESIGNS FOR FS WITH ONE PLY REDUNDANCY FOR 2-HSA OPERATING CONDITIONS

BELLOWS LOCATION	I OUTLET HSA	II INLET HSA	III TURBINE OUTLET MINI-BRU
BELLOWS PART NUMBER	—	—	—
TYPE	SINGLE	SINGLE	SINGLE
INSIDE DIAMETER, IN.	1.92	1.92	2.50
MATERIAL	HAST-X	HAST-X	HAST-X
NUMBER OF PLIES	4	4	3
THICKNESS PER PLY, IN.	0.010	0.012	0.010
ACTIVE LENGTH, IN.	4.95	8.55	4.95
AXIAL STIFFNESS, LB/IN.	950	1880	875
LATERAL STIFFNESS, LB/IN.	435	250	665
BENDING STIFFNESS, IN.-LB/RAD	845	1445	1300

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SUMMARY OF BELLOWS DESIGNS FOR FS WITH ONE PLY REDUNDANCY FOR 2-HSA OPERATING CONDITIONS

BELLOWS LOCATION	IV-IX* LP INLET, HP OUTLET MBR	X* COMPRESSOR OUTLET MINI-BRU	XI-XVII* (EXCEPT XIV) INLET & OUTLET RADIATOR
BELLOWS PART NUMBER	3605418	3605421	3605420
TYPE	3-LINK	SINGLE	3-LINK
INSIDE DIAMETER, IN.	2.84	1.47	2.84
MATERIAL	HAST-X	HAST-X	AISI-347
NUMBER OF PLIES	3	3	2
THICKNESS PER PLY, IN.	0.010	0.006	0.008
ACTIVE LENGTH, IN.	3.87	2.92	3.1
AXIAL STIFFNESS, LB/IN.	760	675	314
LATERAL STIFFNESS, LB/IN.	895	375	577
BENDING STIFFNESS, IN.-LB/RAD	1065	250	440

* AS MANUFACTURED HARDWARE BELLOWS

DESIGN MARGIN FOR FS BELLOWS

BELLOWS	DESIGN MARGIN AT OPERATING TEMP. FOR					
	YIELD	BURST	1% CREEP	CREEP RUPTURE	FATIGUE	SQUIRM
1	4.05	13.00	0.52	1.16	0.31(160*)	0.62
2	7.71	25.11	4.75	7.70	0.59(280*)	0.69
3	3.59	13.90	2.02	4.04	0.45(200*)	0.50
4-9	2.63	10.52	0.15	0.63	HIGH	1.12
10	7.34	24.18	HIGH	HIGH	0.65(300*)	1.47
11-17 Except 14	1.10	6.75	HIGH	HIGH	HIGH	0.59
14	1.52	8.23	HIGH	HIGH	0.65(300*)	0.60

GOVERNING DESIGN MARGIN

* ESTIMATED START-STOP CYCLES

LIFE FRACTION ANALYSIS OF CRITICAL BELLOWS FOR FS

	BELLOWS LOCATION	REQUIREMENTS		
		100 S/S CYCLES, 300 HR	7 YR	
			1 S/S CYCLE	5200 DIURNAL CYCLES
ESTIMATED LIFE, CYCLES	HSA OUTLET	160	1	5200
	HSA INLET	280	1	5200
	TURBINE OUTLET	200	1	5200
PERCENTAGE OF LIFE CONSUMED TO SATISFY THE REQUIREMENTS	HSA OUTLET	63%	2%	4%
	HSA INLET	36%	2%	3%
	TURBINE OUTLET	45%	2%	8%

SUMMARY OF GDS-S BELLOWS DESIGNS FOR FS CONDITIONS — ONE PLY REDUNDANCY FOR 2-HSA OPERATING CONDITIONS

BELLOWS LOCATION	II INLET HSA	III* TURBINE OUTLET MINI-BRU
BELLOWS PART NUMBER	—	3605467
TYPE	SINGLE	SINGLE
INSIDE DIAMETER, IN.	1.92	2.50
MATERIAL	HAST-X	HAST-X
NUMBER OF PLIES	4	3
THICKNESS PER PLY, IN.	0.010	0.006
ACTIVE LENGTH, IN.	4.95	2.82
AXIAL STIFFNESS, LB/IN.	1030	273
LATERAL STIFFNESS, LB/IN.	470	445
BENDING STIFFNESS, IN.-LB/RAD	915	280

* AS MANUFACTURED HARDWARE BELLOWS

GDS-S (5 INCH LONG) HSA INLET BELLOWS FOR FS CONDITIONS

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1/1/0

GDS-S (5 INCH LONG) HSA INLET BELLOWS FOR FS CONDITIONS

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GDS-S (5 INCH LONG) HSA INLET BELLOWS FOR GDS TEST CONDITIONS

GDS-S (5 INCH LONG) HSA INLET BELLOWS FOR GDS TEST CONDITIONS

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GDS-S (3 INCH LONG) TURBINE OUTLET BELLOWS FOR FS CONDITIONS

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GDS-S (3 INCH LONG) TURBINE OUTLET BELLOWS FOR FS CONDITIONS

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GDS-S (3 INCH LONG) TURBINE OUTLET BELLOWS FOR GDS TEST CONDITIONS

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GDS-S (3 INCH LONG) TURBINE OUTLET BELLOWS FOR GDS TEST CONDITIONS

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GDS-S (5 INCH LONG) HSA OUTLET BELLOWS FOR GDS TEST CONDITIONS

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GDS-S (5 INCH LONG) HSA OUTLET BELLOWS FOR GDS TEST CONDITIONS

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BELLOWS TESTING

VENDOR ACCEPTANCE

- PROOF PRESS. = 1.5 x OPERATING PRESS.
AT ROOM TEMP.

$$\left\{ \frac{\text{YIELD STRESS AT ROOM TEMP.}}{\text{YIELD STRESS AT OPERATING TEMP.}} \right\}$$

- AXIAL STIFFNESS

- ROOM TEMPERATURE SQUIRM FOR CRITICAL BELLOWS

DESIGN VERIFICATION (ORNL)

- DESTRUCTIVE TESTS

BURST/SQUIRM

CREEP RUPTURE

FATIGUE

AXIAL STIFFNESS WITH PRESSURE AND TEMP.

- NON DESTRUCTIVE TESTS

R.T. STIFFNESS (AXIAL, LATERAL, BENDING)

EQUIVALENT AXIAL DEFLECTION FORMULA VERIFICATION

BELLOWS SQUIRM PRESSURE TEST RESULTS

- GARRETT THEORETICAL FORMULA
 - △—△ EXPERIMENTAL RESULTS (R.W. GRAVES, UCLA, DEC. 1960)
 - EXPERIMENTAL RESULTS (T.M. TRAINER, EDWARDS AIR FORCE BASE, CALIFORNIA, MARCH 1968)
 - TEST DATA AT GARRETT
- (1) BIPS-WHL-3605466
 - (2) BIPS-GDS-3605418
 - (3) BIPS-GDS-3605420
 - (4) BIPS-GDS-3605421
 - (5) BIPS-GDS-3605421

BELLOWS CREEP TEST

SCHEMATIC

DIMENSIONAL INSPECTION

BELLOWS FATIGUE TEST SCHEMATIC

LOAD CYCLE FOR BELLOWS FATIGUE TEST

L_1 = INSTALLATION LOAD AT ROOM TEMPERATURE = $f (+\delta_C)$

L_2 = LOAD AT OPERATING TEMPERATURE = $f (p, -\delta_H)$

$+\delta_C$ = EXTENSION AT R.T., IN.

$-\delta_H$ = COMPRESSION AT OPERATING TEMPERATURE, IN.

p = OPERATING PRESSURE, PSIG

GDS BELLOWS TEST MATRIX

TEST PARAMETERS	BELLOWS PART NUMBER				
	3605422 SINGLE	3605419 SINGLE	3605418 LINK	3605421 SINGLE	3605420 SINGLE
MATERIAL	CB-103	HAST-X	HAST-X	HAST-X	AISI347
OPERATING TEMP., °F	1600	1330	1303	168	60
OPERATING PRES., p, PSIG	100	67	100	100	67
ELEVATED TEMP. FOR 1% CREEP LIFE IN 1000 HRS, °F	1835	1540	1525	--	--
EQUIV. AXIAL EXTENSION AT R.T., δ_C IN.	+0.23	+0.42	+3.5*DEG.	+0.26	+0.15
EQUIV. AXIAL COMPRESSION AT OPERATING TEMP., δ_H IN.	-0.23	-0.42	-3.5*DEG.	-0.26	-0.15
HOLD TIME FOR CREEP RELAXATION PER CYCLE, MIN.	60	60	60	0	0

* ANGULAR ROTATIONS IN OPPOSITE DIRECTIONS

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GDS BELLOWS TEST MATRIX (CONT.)

TEST PARAMETERS	BELLOWS PART NUMBER				
	3605422 SINGLE	3605419 SINGLE	3605418 LINK	3605421 SINGLE	3605420 SINGLE
AXIAL COMPRESSION FOR SQUIRM TEST, IN.	0.075	0.080	0	0.017	0.075
LATERAL OFFSET FOR SQUIRM TEST, IN.	0.102	0.106	0	0.118	0.045
PROOF PRESSURE AT R.T., PSIG	300	160	233	157	121
NO. OF BELLOWS TO BE TESTED FOR FATIGUE	3	3	3	3	3
NO. OF BELLOWS TO BE TESTED FOR CREEP RUPTURE	3	3	3	--	--
NO. OF BELLOWS TO BE TESTED FOR BURST/ SQUIRM	1(3*)	1(3*)	1(3*)	1(3*)	2(4*)
TOTAL NO. OF BELLOWS TO BE TESTED	7	7	7	4	5

* RECOMMENDATION BASED ON THE RELIABILITY BUT NOT INCLUDED
IN THE TEST PLAN

PRELIMINARY LOW CYCLE FATIGUE TESTS AT ORNL TO CORRELATE BELLOWS ANALYTICAL METHODS

• GDS-S TURBINE OUTLET BELLOWS

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PRELIMINARY LOW CYCLE FATIGUE (LCF) TESTS FOR GDS-S (3 INCH LONG) TURBINE OUTLET BELLOWS

AXIAL TENSION, IN.	0.317	0.317	0.317	0.317	0.317	0.317
COLD CONDITION AT ROOM TEMPERATURE PRESSURE = 0						
HOT CONDITIONS AT OPERATING TEMPERATURE						
HOLD TIME/CYCLE (T), HR	0.25	0.5	6.0	6.0	2.0	10.0
LCF REQUIRED, CYCLES	2	4	14	14	10	15
PRESSURE, PSIG	73	39	68	39	68	39
OPERATING TEMP., °F	1330	1330	1126	1109	1126	986
AXIAL COMPRESSION, IN.	0.345	0.345	0.345	0.345	0.345	0.325

PRELIMINARY LOW CYCLE FATIGUE (LCF) TESTS FOR GDS-S (3 INCH LONG) TURBINE OUTLET BELLOWS

SYSTEM	WHL	WHL	WHL	WHL	FS	GDS-S
COLD CONDITION AT ROOM TEMPERATURE PRESSURE = 0
HOT CONDITIONS AT OPERATING TEMPERATURE
HOLD TIME/CYCLE (T), HR	0.50	2.5	21.5	21.5	12	80
LCF REQUIRED, CYCLES	2	4	14	14	10	15
ESTIMATED LIFE, CYCLES	50	42	66	66	2900	57
LIFE FRACTION, %	4	10	21	21	1	27
CUMULATIVE LIFE FRACTION, %	4	14	35	56	57	84

6.0 SAHSA DESIGN AND FABRICATION

6.1 DESIGN ANALYSIS

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA

A DIVISION OF THE GARRETT CORPORATION

PHOENIX, ARIZONA

HASTELLOY-X HSHX

CONFIGURATION:

10-TURN COIL 1.560 DIAMETER TUBING, 0.050 WALL

FEATURES:

- INTERCHANGEABLE WITH C-103 HSHX WITH NO HSA MODS
- CONTINUOUS ONE PIECE COIL WITH END PIECES WELDED ON
- 100% X-RAY INSPECTABLE

MATERIAL:

HASTELLOY-X TUBING WELDED AND DRAWN

SUPERALLOY HSHX

- **10 TURNS**

- 1.56 IN. TUBE OD**

- 0.050 IN. TUBE WALL (GDS)**

- 9.42 IN. MEAN COIL DIA**

- 300 IN. TOTAL TUBE LG**

- **HASTELLOY X MATERIAL**

- **MATES WITH EXISTING HOUSING
HSIS, AND SUPPORTS**

SUPERALLOY HSA THERMAL ANALYZER MODEL

S-17937

PREDICTED PERFORMANCE - SUPERALLOY HSHX

SINGLE COIL CONFIGURATION

PARAMETER	SYSTEM CONFIGURATION		SYSTEM REQUIREMENT
	2-HSA	3-HSA	
FLOW RATE, LB/SEC	0.1243	0.1233	0.1243
PRESSURE, PSIA	64.5	115	115 MAX
FLUID INLET TEMP., °F	1103	1101	1103
FLUID OUTLET TEMP., °F	1394	1394	≥1300
PRESSURE DROP, $\Delta P/P$	0.00536	0.0016	0.003*
MAX. METAL TEMP., °F	1448	1449	1450
MAX. EHS SURFACE TEMP., °F	1507	1507	N/S
HSA HEAT LOSS, PERCENT	5.8	5.8	15 MAX.

* DESIGN GOAL

BASIS FOR PREDICTED PERFORMANCE

Pressure Drop

Ito Correlation: $f_c = 0.079 (d/D)^{0.1} Re^{-0.2} = .00827$

$$f_c/f_s = 1.44 \text{ at } Re = 32500$$

$$(\text{Fairchild test: } f_c/f_s = 1.50 \text{ at } d/D = .154)$$

Heat Transfer

Seban & McLaughlin
Correlation: $Nu = 0.023 Re^{0.85} Pr^{0.4} (d/D)^{0.1}$

$$h_c = 20.3 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$$

$$h_c/h_s = 1.3$$

STARTUP TRANSIENT - ZERO FLOW

STARTUP TRANSIENT - POSITIVE FLOW

AUXILIARY COOLING SYSTEM PERFORMANCE

- FILLED WITH HELIUM AT ONE ATMOSPHERE PRESSURE
- EQUIPMENT ON THE LAUNCH PAD AT 120 F AMBIENT
- MAXIMUM COCOON TEMPERATURE <380 F

S-17973

HEAT EXCHANGER MOUNTING PROVISIONS

AFT END (OUTLET) SHOWN

SECTION AA

HSHX COIL-TO-COIL SUPPORTS

SECTION BB

DESIGN CONSIDERATIONS

PRESSURE CONTAINMENT

- 3 HSA CASE, P = 115 PSIA
- OPERATING TEMPERATURE + 50°F

UNWINDING LOAD

- REACT INTERNALLY

THERMAL STRESSES

- ALONG TUBE LENGTH
- ACROSS TUBE DIAMETER

DYNAMIC LOAD

- VIBRATION
- 50 G INERTIAL LOAD

LIFE ESTIMATES

- LONG TERM CREEP: 7 YEARS
- FATIGUE LIFE DUE TO CYCLIC CREEP DAMAGE AND ACCUMULATED PLASTIC STRAIN

STRESS SUMMARY

FLIGHT SYSTEM DESIGN

COMPONENT	MAT'L	DESIGN CRITERIA	STRESS, PSI	DESIGN MARGIN*
PIN (.180 DIA)	WASP- ALLOY	ENDURANCE LIMIT (45,000 PSI)	41700 (50 g's)	+0.10
BRACKET (.120 THK)	HAST X	BEARING YIELD STRESS (32,900 PSI)	29800 (50 g's)	+0.10
	HAST X	ENDURANCE LIMIT (28,000 PSI)	16730 (BENDING) (50 g's)	+0.67
COILED TUBE (.055 WALL)**	HAST X	50°F TEMP MARGIN 1.0% CREEP STRESS (2300 PSI)	1840 (HOOP)	+0.25
ELBOW (.100 WALL)	HAST X	50°F TEMP MARGIN 1.0% CREEP STRESS (1650 PSI)	1320 (HOOP)	+0.25

*POSITIVE MARGIN MEANS THE DESIGN
CRITERIA IS EXCEEDED

** FLIGHT SYSTEM (GDS = .050 WALL)

SINGLE TUBE HELICAL COIL THERMAL STRESS MODEL

S-17972

RESONANT FREQUENCY ANALYSIS UNBRAZED COIL

SYSTEM CONFIGURATION	RESONANT FREQUENCY, HZ			
	FIRST	SECOND	THIRD	FOURTH
NO STRAPS - COIL HELD RADIALLY AT INLET END - FIXED AT OUTLET END	14 ⁽¹⁾	19 ⁽²⁾	23 ⁽³⁾	39 ⁽⁶⁾
0.012 STRAPS - COIL HELD RADIALLY AT INLET END - FIXED AT OUTLET END	27 ⁽³⁾	56 ⁽⁴⁾	60 ⁽²⁾	91 ⁽⁵⁾
0.024 STRAPS - COIL HELD RADIALLY AT INLET END - FIXED AT OUTLET END	28 ⁽³⁾	59 ⁽⁴⁾	81 ⁽²⁾	95 ⁽⁵⁾
0.024 STRAPS - COIL FIXED AT BOTH ENDS	28 ⁽³⁾	59 ⁽⁴⁾	82 ⁽²⁾	95 ⁽⁵⁾

(1) AXIAL STRETCHING MODE
 (2) TORSIONAL MODE
 (3) FIRST LATERAL MODE

(4) SECOND LATERAL MODE
 (5) THIRD LATERAL MODE
 (6) MODE NOT DETERMINED

STIFFNESS OF BRAZED COIL DESIGN

.20 X .030 STRIP
BRAZED IN PLACE

TOROIDAL SHELL MODEL USED TO
REPRESENT A SINGLE LOOP OF COIL.

• RESULTS FOR 0.050" WALL THICKNESS

$$K_{AXIAL} = \frac{2\pi (4.68 \text{ IN}) (100 \text{ LB/IN})}{2 (0.0032 \text{ IN})}$$

$$= \underline{\underline{460,000 \text{ LBS/IN/LOOP}}}$$

NATURAL FREQUENCY OF BRAZED COIL VIBRATING LONGITUDINALLY

WALL THICKNESS = 0.050 IN

WEIGHT OF COIL = 24 LBS.

$$f_n = \frac{n \pi}{2 \pi} \sqrt{\frac{g \cdot K_{AXIAL}}{W \cdot N_{COILS}}}$$

FIRST MODE: $\left(n = \frac{1}{2}\right)$

$$f_1 = \frac{1}{4} \sqrt{\frac{386 (460,000)}{(24) (10)}} = \underline{\underline{215 \text{ HZ}}}$$

NATURAL FREQUENCY OF BRAZED COIL VIBRATING IN FLEXURE

$$f_n = \frac{C_n}{2\pi} \sqrt{\frac{g \cdot E \cdot I}{(W/L) \cdot L^4}} \quad (\text{UNIFORM BEAM})$$

$$(EI)_{\text{EQ. CYLINDER}} = \frac{1}{2} \bar{R}^2 L \frac{K_{\text{axial}}}{N_{\text{coils}}}$$

$$f_n = \frac{C_n}{2\pi} \cdot \frac{\bar{R}}{L} \cdot \sqrt{\frac{g}{2}} \cdot \sqrt{\frac{K_{\text{axial}}}{W \cdot N_{\text{coils}}}}$$

END CONDITIONS	C_1	f_1 (FIRST MODE)
CLAMPED-FREE	3.52	90 HZ
HINGED-HINGED	9.87	250 HZ
CLAMPED-HINGED	15.4	390 HZ
CLAMPED-CLAMPED	22.0	560 HZ

SHEAR STRESS IN BRAZE JOINT BETWEEN ADJACENT COIL LOOPS

- **PRESSURE LOADING**

STEADY STATE = 1.3 LB/IN.

- **THERMAL LOADING**

TRANSIENT = 200 LB/IN.

STEADY STATE = 50 LB/IN.

- **BRAZE JOINT AREA**

(50% COVERAGE) = 0.09 IN. /IN.

- **SHEAR STRESS**

TRANSIENT (860° F) = $\frac{200 + 1.3}{.09} = 2200$ PSI

STEADY STATE (1320°F) = $\frac{50 + 1.3}{.09} = 570$ PSI

THERMAL STRESS AND LIFE ESTIMATE IN BRAZE JOINT

CRITERIA	STRESS, PSIA	STRESS CONCENTRATION FACTOR	CYCLES TO FAILURE
SURFACE STRESS	4,200	2	530
		3	320

0.20 X 0.030 STRIP
BRAZED IN PLACE

SINGLE COIL FINITE ELEMENT MODEL

**ENDS REPRESENTED
BY BOUNDARY CONDITIONS**

ELBOW FINITE ELEMENT MODEL

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6.0 SAHSA DESIGN AND FABRICATION

6.2 HSHX FABRICATION STATUS

COIL FABRICABILITY

- ALL VENDORS CONTACTED INDICATED COIL WAS FEASIBLE - TECHNIQUE AND AVAILABLE EQUIPMENT WERE LIMITING, NOT PROCESS
- 3 VENDORS RESPONDED WITH FIRM COST QUOTES
 - SAFFRAN ENGINEERING CO, ST. CLAIR SHORES, MI.
 - J. B. PRECISION, TUSTIN, CA.
 - DOUGLAS AIRCRAFT, LONG BEACH, CA.
- CRES AND HASTELLOY-X TRIAL COILS SATISFACTORILY COMPLETED BY SAFFRAN