~~SECRET~~

TID/SNA-9

N8000R:71-002

JULY, 1971

ENGINE/COMPONENT DESIGN STATUS REVIEW

PHASE I

FOUR ONGOING COMPONENTS

PRESENTATION TO SNSO

APRIL 6, 7, 8, 1971

MASTER

AEROJET NUCLEAR SYSTEMS COMPANY

A DIVISION OF AEROJET-GENERAL

DISTRIBUTION OF THIS DOCUMENT UNLIMITED

N2462

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TID/SNA--9

N8000R:71-002

ENGINE/COMPONENT DESIGN STATUS REVIEW.

PHASE I.

FOUR ONGOING COMPONENTS

PRESENTATIONS TO SNSO,

SACRAMENTO,

APRIL 6, 7, 8, 1971

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Classification Category

UNCLASSIFIED

Classifying Officer

Date

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

26

AGENDA
ENGINE/COMPONENT DESIGN STATUS REVIEW
FOUR ONGOING COMPONENTS
PHASE I

OPENING REMARKS_____C. K. LEEPER

INTRODUCTION_____W. E. CAMPBELL

NOZZLE EXTENSION_____L. A. SHURLEY

TURBOPUMP _____N. A. EDLEBECK

VALVES AND ACTUATORS_____L. D. JOHNSON/E. H. HILL

ANSC ACTION ITEMS - TOTAL _____W. E. CAMPBELL

ENGINE/COMPONENT DESIGN STATUS REVIEW

PHASE I - FOUR ONGOING COMPONENTS

APRIL 6-8, 1971

E/CDSR

PLANNED SEQUENCE

ENGINE REVIEW

METHODS STATUS

MATERIALS STATUS

COMPONENTS REVIEW

RELIABILITY SUMMARY

PERFORMANCE SUMMARY

AEROJET NUCLEAR SYSTEMS COMPANY

E/CDSR

ACTUAL SEQUENCE

FOUR KEY COMPONENT REVIEWS

ENGINE REVIEW

METHODS STATUS

MATERIALS STATUS

RESIDUAL COMPONENT STATUSES

RELIABILITY SUMMARY

PERFORMANCE SUMMARY

E/CDSR

OBJECTIVE

STATUS	-	CONCEPTS
	-	ACHIEVEMENTS
	-	PROBLEMS
PLANS	-	DESIGN
	-	DEVELOPMENT
FEEDBACK	-	SNSO REACTIONS

COMPONENT ACHIEVEMENTS

EXTENSION: CONCEPT AND MATERIAL
PROCESS AND FACILITY

TURBOPUMP: DESIGN AND ANALYSIS
TESTS

VALVES: CONCEPTS AND ANALYSIS
COMPONENT TESTS
ELECTRONICS COMPONENTS

E/CDSR

PROBLEMS

TECHNICAL

DETERMINATION OF BEARING CAPACITY

SPACE STORAGE PLAN

CONTAMINATION - VALVES AND TURBOPUMP

ENGINE CHILLDOWN METHOD AND PENALTY

SCHEDULAR

BEARING TEST RATE

PROBABILISTIC DESIGN PROGRESS

DEFINITION OF REMAINING REQUIREMENTS

DEFINITION/SCOPE

PROBABILISTIC DESIGN PROGRESS

TPA ROTOR STRUCTURAL ADEQUACY

REQUIREMENTS TRACEABILITY

VALVE DESIGN PROGRESS

AEROJET NUCLEAR SYSTEMS COMPANY

E/CDSR

RULES OF ORDER

CHAIRMAN CONTROLS

CLARIFICATION - IMMEDIATE

SUPPLEMENTATION - BY ACTION ITEM

RESOLUTION - BY SPLINTER SESSION

RECORD - BY SCRIBE

AEROJET NUCLEAR SYSTEMS COMPANY

E/CDSR

LOGISTICS

ALL E/CDSR MEETINGS HERE

SPLINTER MEETINGS - AS ANNOUNCED

EXHIBIT - LOBBY

LUNCH - RESERVED AT CAFETERIA

TUESDAY DINNER - CARL GREER, 6:30 P.M.

FACILITIES - DUE NORTH

AEROJET NUCLEAR SYSTEMS COMPANY

**ENGINE/COMPONENT
DESIGN STATUS REVIEW
PHASE I
4 ONGOING COMPONENTS
APRIL 6-7-8, 1971**

AEROJET NUCLEAR SYSTEMS COMPANY

E/CDSR AGENDA - PHASE 1

COMPONENT STATUS REVIEW

INTRODUCTION AND OBJECTIVES

COMPONENT STATUS REVIEW

- I. INTRODUCTION AND REVIEW SCOPE
- II. REQUIREMENTS
- III. CONCEPT DESCRIPTION
- IV. ACCOMPLISHMENTS
- V. DESIGN ANALYSIS
- VI. SUBCOMPONENT/EQUIPMENT DEVELOPMENT STATUS
- VII. NEAR TERM DEVELOPMENT PROGRAM

NOZZLE EXTENSION

COMPONENT STATUS REVIEW

- I. INTRODUCTION AND REVIEW SCOPE
- II. REQUIREMENTS
- III. CONCEPT DESCRIPTION
- IV. ACCOMPLISHMENTS
- V. DESIGN ANALYSIS
- VI. SUBCOMPONENT/EQUIPMENT
DEVELOPMENT STATUS
- VII. NEAR TERM DEVELOPMENT PROGRAM
- VIII. SUMMARY

REQUIREMENTS

PRIMARY

PERFORMANCE:

AUGMENT ENGINE THRUST TO 75,000 LBS (NOMINAL)

AUGMENT ENGINE SPECIFIC IMPULSE TO 825 SEC (NOMINAL)

ENVIRONMENTAL:

RECOVERY TEMPERATURE 3950°R

WALL PRESSURE 2.2 PSIA

DURATION:

10 HRS AT T_0 = 4318°R (MAX)

2 HRS AT T_0 = 4568°R (MAX)

RELIABILITY ALLOCATION:

.95836

DESIGN

INTERFACING WITH THE PRIMARY NOZZLE AT

AREA RATIO OF 24:1

EXIT AREA RATIO 100:1

MINIMUM RESONANT FREQUENCY CONSISTENT WITH
ENGINE REQUIREMENT

AEROJET NUCLEAR SYSTEMS COMPANY

NOZZLE EXTENSION

$F = 75,713 \text{ LB} \pm 424 \text{ LB}$

$I_s = 825.3 \text{ SEC} \pm .56\%$

- FIBROUS REINFORCED GRAPHITE COMPOSITE

$F = 69,000 \text{ LB}$

$I_s = 765 \text{ SEC}$

$\epsilon = 24:1$
54.92 DIA

$\epsilon = 100:1$
112.10 DIA

139.40

CANDIDATE FABRIC ORIENTATION FOR LINER

TAPE WRAP

SHINGLE LAP

ROSETTE

AEROJET NUCLEAR SYSTEMS COMPANY

GRAPHITE FABRIC

3-D TUFTED LINER FABRIC

OBJECTIVE

PREVENT DELAMINATIONS

PROJECTS FIBERS FOR CELL WALL TO LINER BONDING

WOVEN TO FIT NOZZLE EXTENSION CURVATURE

CELL SIZE SELECTION

CRITERIA

- MAXIMIZE NATURAL FREQUENCY
- MINIMIZE MOLDING DIE COST
- MINIMIZE LAYUP TIME AND COST
- LIMIT DIE BLOCK CURVATURES TO CIRCUMFERENTIAL DIRECTION

RESULTING RESONANT FREQUENCY

- 14 CPC WITH 4000 CELLS

WAYS TO IMPROVE NATURAL FREQUENCY

- INCREASE CELL HEIGHT
- INCREASE CELL THICKNESS
- USE CELL MATERIAL OF HIGHER MODULUS
- WRAP O.D.
- ADD HOOP BANDS

CELL WALL ATTACHMENT OPTIONS

CONFIGURATION 1

CONFIGURATION 2

SELECTED
CONFIGURATION

CONFIGURATION 3

AEROJET NUCLEAR SYSTEMS COMPANY

ACCOMPLISHMENTS

- PERFORMANCE TARGET MET
- GRAPHITE EROSION TEST DATA ANALYZED
- SELECTED BASIC MATERIAL FOR NOZZLE EXTENSION CONSTRUCTION
- SELECTED FLANGE CONCEPT BASED ON THERMAL AND STRESS ANALYSES
- C-002 SPECIFICATION ISSUED
- FMA (MODES AND MECHANISMS) ISSUED
- DESIGNED AND PROCURED TOOLING (PARTIAL)
- FURNACE FABRICATION (80% COMPLETE)
- FACILITY PREPARATION FOR FURNACE INITIATED

EROSION TESTING

OBJECTIVE:

DETERMINE THE GRAPHITE EROSION
RATES IN HOT SUPERSONIC HYDROGEN

AGCarb-101 SPECIMEN TESTER

EROSION SPECIMEN TEST CONDITION

TEST ENVIRONMENT	NATURAL ENVIRONMENT
PRESSURE, PSIA 1.07 TO 13.7	0.3 TO 2.2
TEMPERATURE, °R 2117-3912	3100 (MAX)
DURATION, HR 1.0	10.0

CYCLIC REGRESSION DATA

TWO SPECIMENS WERE TESTED FOR TWO HALF-HOUR RUNS

PLENUM GAS TEMP °R	PLENUM GAS PRESSURE PSIA	DURATION MINUTES	SPECIMEN TEMP °R	SPECIMEN WALL PRESSURE PSIA	REGRESSION IN x 10 ³
4511	217	30	2954	11.9	4.6/4.3
				2.5	0.8/0.9
4628	186	30	2968	9.8	1.3/1.6
				2.2	0.5/0.5
4651	147	30	3912	8.0	4.6/5.3
				1.7	1.2/1.5
4640	143	29	3805	7.5	2.0/1/5
				1.6	0.8/1.1

- STAGNATION
PRESSURE = 450 PSIA
- STAGNATION
TEMPERATURE = 4250°R

EROSION RATE,
IN/HR ($\times 10^3$)

FULL-SCALE NOZZLE EXTENSION

PREDICTED GRAPHITE EROSION RATE *

* DETERMINED FROM SUB-SCALE TEST

FROM TD 70-13

11-10-69

A BACKUP SKIRT EXTENSION CONCEPT SHALL BE DEVELOPED.

PRIMARY CONSIDERATION SHOULD BE GIVEN TO METALLIC

CONSTRUCTION OF CONVENTIONAL MATERIALS UTILIZING

FILM COOLING.

FILM-COOLED NOZZLE EXTENSION

- CRES 347
- $T_{MAX} = 2400^{\circ}R$
- COOLANT FLOW RATE = 2.35 LB/SEC

GAS SIDE WALL
TEMPERATURE,
 $^{\circ}R$

FILM/REGENERATIVELY COOLED NOZZLE EXTENSION

- RETURN TUBE
- $T_{MAX} = 1060^{\circ}R$
- COOLANT FLOW RATE = 3.1 LB/SEC

EFFECT OF FILM COOLING ON I_{sp}

COLUMBIUM NOZZLE EXTENSION

AEROJET NUCLEAR SYSTEMS COMPANY

NOZZLE EXTENSION COMPARISON

	ALUMINUM TUBE	COLUMBIUM	CRES 347 FILM COOLED	GRAPHITE
ATTAINABLE PERFORMANCE	804 SEC	825 SEC	799 SEC	825 SEC
FABRICABILITY	FAIR	GOOD (APOLLO)	GOOD	TBD
WEIGHT	525 LB	600 LB	610 LB	580 LB
SECONDARY EMISSIONS	NIL	UNKNOWN	TOLERABLE	NIL
COMPATIBILITY WITH NOZZLE FLANGE	GOOD	POOR	GOOD	FAIR
COMPATIBILITY WITH HYDROGEN	GOOD	REQUIRES DEV	GOOD	TOLERABLE

PERFORMANCE OUTWEIGHS ALL OTHER CONSIDERATION

CONCLUSION:

RETAIN GRAPHITE NOZZLE EXTENSION CONCEPT

DESIGN

NOZZLE-TO-NOZZLE EXTENSION JOINT SELECTION

- CONCEPTS CONCEIVED OVER 30
- COMPLETED THERMAL ANALYSES 14
- COMPLETED STRESS ANALYSES 7
- SELECTED CONCEPT NO. 30 FOR
FURTHER REFINEMENTS

NOZZLE/GRAPHITE COMPOSITE SKIRT EXTENSION INTERFACE

CONCEPT NO. 30

NOZZLE-TO-NOZZLE EXTENSION INTERFACE TEMPERATURE DISTRIBUTION

CONCEPT NO. 30

NOZZLE EXTENSION FLANGE STRESS DISTRIBUTION

STRESS LEVELS, PSI				
LOCATION	RADIAL, σ_R	AXIAL, σ_Z	HOOPE, σ_θ	SHEAR, τ_{RZ}
24	- 15	- 64	- 7163	28
28	435	263	- 5645	538
32	- 503	120	- 5123	154
56	- 119	248	- 4580	306
75	170	853	- 3993	1100
83	- 250	1385	- 4165	1500
89	-1453	-2956	- 6463	-1062
98	- 549	-2615	- 6806	- 665
95	48	1654	- 5907	- 398
67	- 39	330	- 6687	- 23

MATERIAL PROPERTIES (FLANGE)

		AGCarb-101 LAMINATE (RN-S-0549)	3D LOCK-TO-LOCK (4350:MM 70-423) 3 SPECIMENS	REQUIRED * (PREVIOUS CHART)
TENSILE	BLOCK	644	293	1000
	WARP	11,266	3,645	3500
	FILL	4,563	1,761	-
COMPRESSION	BLOCK		5,780	3000
	WARP	9,506	5,780	6000
	FILL		4,440	15000
SHEAR	WARP	1,348	810	3000
	FILL		778	

* ARRIVED AT: FACTOR OF TWO APPLIED TO COMPUTED STRESSES

J VALUE (RELIABILITY) VS % VARIANCE IN STRESS AND STRENGTH

NOZZLE EXTENSION

RELIABILITY DETERMINATION PROCESS

1. RELIABILITY = $f(J)$;

$$J = \frac{\text{STRENGTH}_{(\text{MEAN})} - \text{STRESS}_{(\text{MEAN})}}{\sqrt{\text{STRENGTH VARIANCE}^2 + [\text{STRESS (MAX-NOM) } 1/3]^2}}$$

2. STRENGTH: ASSUMED 2 x COMPUTED STRESSES
 TENSILE
 COMPRESSIVE
 SHEAR

> ALL AXIS

3. STRESS (THERMAL) = $E \alpha \Delta T / 2 (1 - V)$

E	MODULUS OF ELASTICITY	ASSUME $\leq$ LAMINATES
α	COEFFICIENT OF THERMAL EXPAN.	ASSUME $\leq$ LAMINATES
V	POISSONS RATIO	ASSUME $\leq$ LAMINATES
K	THERMAL CONDUCTIVITY	ASSUME $\geq$ LAMINATES
$\Delta T = (Q/A) 1/K = h(T_r - T_w) 1/K$		CALCULATE

RELIABILITY DETERMINATION PROCESS (CONT)

4. MODEL DEFINES DEVELOPMENT PROGRAM PARAMETERS

5. DETERMINE ACCEPTABLE VARIANCE LIMITS IN:
STRENGTH AND STRESS
INFLUENCING PARAMETERS
(USE PROGRESSION OF VARIANCE - IF NECESSARY)

6. USE QUANTIFIED MEANS

$$J = f(\alpha, K, V, S)$$

FOR ASSESSING PROGRESS TOWARDS DEVELOPMENT/
RELIABILITY GOAL

FAILURE MODES

- I. THE NOZZLE EXTENSION FAILS TO AUGMENT THE ENGINE THRUST TO THE MINIMUM REQUIRED OF THE EXTENSION
- II. THE NOZZLE EXTENSION THRUST AUGMENTATION IS NOT DIRECTED ALONG THE SPECIFIED THRUST VECTOR
- III. THE NOZZLE EXTENSION RESONANT FREQUENCY IS BELOW THE REQUIRED VALUE

FAILURE MECHANISMS

- A. A PORTION OF THE NOZZLE EXTENSION TEARS AWAY
102 LOWER TIER MECHANISMS
APPLICABLE TO MODES I, II, III
- B. NOZZLE EXTENSION FLANGE AT NOZZLE INTERFACE FAILS
131 LOWER TIER MECHANISMS
APPLICABLE TO MODES I, II
- C. FASTENERS DO NOT HOLD NOZZLE EXTENSION TO NOZZLE
20 LOWER TIER MECHANISMS
APPLICABLE TO MODES I, II
- D. CONTOUR IMPERFECT
14 LOWER TIER MECHANISMS
APPLICABLE TO MODES I, II, III
- E. VIBRATORY EFFECTS
32 LOWER TIER MECHANISMS
APPLICABLE TO MODES I, III
- F. LEAKAGE
13 LOWER TIER MECHANISMS
APPLICABLE TO MODES I, II

RELIABILITY STATUS

ALL FAILURE MODES DEFINED

ALL MECHANISMS DEFINED AND SEGREGATED BY MODE

PROBABILISTIC MODELLING INITIATED AT PART/MECHANISM LEVEL

STRESS CALCS INITIATED AT CRITICAL LOCATIONS

MATERIALS DATA PLAN AND TARGET PROPERTIES
OUTLINED AND UNDERWAY

BASED ON MODEL OF CRITICAL MECHANISM

UNRESOLVED PROBLEMS

MATERIAL PROPERTIES TEST DATA

FABRICATION TECHNIQUE

INTREMOLD III MODEL

INTREMOLD III

COMPARED WITH A LAMINATED COMPOSITE

ADVANTAGES

ALL STRAIGHT FIBERS

FIBERS AVAILABLE IN RADIAL DIRECTION

MORE DIRECT APPROACH TO ATTAINMENT OF REQUIRED STRENGTH

PROPERTIES MAY BE TAILORED TO APPROACH ISOTROPY

DISADVANTAGES

COST

TRANSITION TO SHELL - INTEGRATED JOINT OR
ADDITIONAL MECHANICAL JOINT

INTREMOLD III YARN SELECTION

STRAND DATA		
YARN	E ($\times 10^6$)	F _{tu} (KSI)
WYB 85-1/2	6	40
WYB 125-1/5	6	67

COMPOSITE DATA *			
YARN	LOAD DIRECTION	E ($\times 10^6$)	F _{tu} (KSI)
WYB 85-1/2	ALONG YARN	1.7	5.43
	ALONG HELIX ANGLE BISECTOR	1.3	2.83
WYB 125-1/5	ALONG YARN	1.7	TBD

* 30% AREA RATIO

ADVANTAGES OF WYB 125-1/5:

LOW MODULUS/STRENGTH RATIO

67% INCREASE IN FIBER STRENGTH WITH NO MODULUS INCREASE

LOW COST COMPARED TO HIGH MODULUS YARNS

EXTENSION MATERIAL SUMMARY

PART	OPTIONS	PREVIOUS APPLICATIONS	CHARACTERISTICS
FLANGE	INTREMOLD III LAMINATE { SHINGLE ROSETTE TAPE 3-D INTERWOVEN	REENTRY VEHICLES IN CURED STATE (NON-GRAPHITIZED) SOLID MOTOR NOZZLES LIQUID ENGINE RESEARCH PROJECTS NONE	PROPERTY TAILORING ALONG 3 AXES LOW CROSS-PLY PROPERTIES UNKNOWN
SHELL (LINER)	INTREMOLD III LAMINATE { SHINGLE ROSETTE TAPE 3-D TUFTED	REENTRY VEHICLES IN CURED STATE (NON-GRAPHITIZED) SOLID MOTOR NOZZLES LIQUID ENGINE RESEARCH PROJECTS NONE-NEW CONCEPT	COSTLY PROBABLY ADEQUATE NEEDS MACERATION PROBABLY GOOD
STIFFENER	COARSE SINGLE LAYER WEAVE WEB	DEVELOPED ON TITAN USING GLASS HONEYCOMB CELLS (2000 CELLS)	BONDS TO SHELL (LINER)

INTREMOLD III CYLINDER

INTREMOLD III FLANGE FABRICATION DEVELOPMENT

NEAR TERM PLAN NO. 1

AEROJET NUCLEAR SYSTEMS COMPANY

FLANGE TO LINER ATTACHMENT

CONCEPT NO. 1

AEROJET NUCLEAR SYSTEMS COMPANY

FLANGE TO LINER ATTACHMENT

CONCEPT NO. 2

INTREMOLD III FLANGE FABRICATION DEVELOPMENT

NEAR TERM PLAN NO. 2

FIBROUS GRAPHITE MATERIALS
DEVELOPMENT PROGRAM

AEROJET NUCLEAR SYSTEMS COMPANY

NOZZLE EXTENSION MATERIAL DEVELOPMENT

GRAPHITE FABRICS

RESINS

CARBONACEOUS DENSIFIERS

HONEYCOMB TO LINER ATTACHMENT

PROCESSING PARAMETER

LINER FABRICS - 3-D TUFTED LINER

CY 71-72 M-6 PLAN

PROPERTY	NO. OF TESTS
TENSILE, BLOCK, FILL, WARP	21
INTERLAMINAR SHEAR, FILL, WARP	14
COMPRESSION, BLOCK, WARP	14
MODULUS, BLOCK, FILL, WARP	6

FLANGE FABRIC

CY 71-72 M-6 PLAN

INTREMOLD III SUBSCALE DEVELOPMENT			NO. OF TESTS
HOOP TENSILE			
AXIAL TENSILE/COMPRESSIVE	24 SPEC/CYLINDER		144
BLOCK TENSILE/COMPRESSIVE			
MODULUS			
BLOCK			
WARP	2 SPEC/DIRECTION		36
FILL			
SELECT 2 BEST WEAVES			
CTE	BLOCK, WARP, FILL		12
K	BLOCK		4
WOVEN, SPECIAL ORDER (2 TYPES)			
BLOCK			
WARP			
FILL	TENSILE/COMPRESSIVE		18
SHEAR			6
MODULUS			2
COMMERCIAL WEAVES (2 TYPES)			
ROSETTE AND SHINGLE LAYUP			
SHEAR	4 SPEC EACH		16

RESIN DEVELOPMENT

OBJECTIVES

LOW SHRINKAGE

BOND STRENGTH

LOW MODULUS

ACCOMPLISHMENTS

EVALUATED 9 RESINS

SELECTED 2 RESINS FOR FURTHER TESTING

- (1) US POLYMERIC RESIN
EXHIBITS LOWEST SHRINKAGE (1%)
WITH AVERAGE STRENGTH 150 PSI*
- (2) EVERCOAT CHEMICAL GRADE EC-260
EXHIBITS HIGHEST STRENGTH 250 PSI *
WITH AVERAGE SHRINKAGE OF 5%

* NO DENSIFICATION ADDITIVES INCLUDED

RESIN DEVELOPMENT

CY 71-72 M-6 PLAN

OBJECTIVE

OBTAIN BEST COMPROMISE BETWEEN BOND
STRENGTH AND SHRINKAGE

RESINS SYSTEMS TO BE TESTED

1. EVERCOAT 260 + US POLYMERIC FILLER
2. EVERCOAT 260 + US POLYMERIC RESIN

PROPERTIES TO BE MEASURED:

	NO. OF TESTS
TENSILE, BLOCK, WARP, FILL (7 EACH)	42
COMPRESSIVE, BLOCK, WARP, FILL (7 EACH)	42
SHEAR, WARP, FILL (7 EACH)	28
MODULUS, BLOCK, WARP	12

CARBONACEOUS DENSIFIERS DEVELOPMENT

OBJECTIVES

LOW VISCOSITY AT 250°F

HIGH CARBON CONTENT

40% CARBON YIELD/CYCLE (MIN)

ACCOMPLISHMENTS

25 SYSTEMS SCREENED FOR CARBON
CONTENT AND VISCOSITY

19 SYSTEMS RETAINED FOR FURTHER
TESTING WITH RESPECT TO STRENGTH

CARBONACEOUS DENSIFIERS DEVELOPMENT

CY 71-72 M-6 PLAN

SCREEN 19 SYSTEMS COMPRISING 24 COMPOSITIONS

	NO. OF TESTS
TENSILE, BLOCK (3 SPECIMENS/COMP)	72
SHEAR, WARP (3 SPECIMENS/COMP)	72
MODULUS, WARP (1 SPECIMEN/COMP)	24

SELECT BEST TWO FROM ABOVE

TENSILE, BLOCK, WARP, FILL (7 SPEC/DIRECTION)	42
COMPRESSIVE, BLOCK, WARP, FILL (7 SPEC/DIRECTION)	42
SHEAR, WARP, FILL (7 SPEC/DIRECTION)	28
MODULUS, BLOCK, WARP, FILL (2 SPEC/DIRECTION)	12
CTE, BLOCK, WARP, FILL (2 SPEC/DIRECTION)	12
K, BLOCK (2 SPEC/DIRECTION)	4

HONEYCOMB TO LINER ATTACHMENT

OBJECTIVE

OBTAIN CELL WEB TO LINER BOND STRENGTH
GREATER THAN CELL WEB STRENGTH
DEVELOP ATTACHMENT PROCEDURES

ACCOMPLISHMENT

75 CELL WEB-TO-LINER ATTACHMENT TESTS
COMPLETE (CONVEX BASE)

NO FRACTURES AT LINER TO ROOT
ATTACHMENT

WEB STRENGTH

AFTER CURE 1800 - 4300 PSI

AFTER GRAPHITIZING* 300-850 PSI

* NO DENSIFICATION

HONEYCOMB TO LINER ATTACHMENT

CY 71-72 M-6 PLAN

		<u>NO. OF TESTS</u>
USE 50° ROOT BASE (LAMINATE LINER)		
SELECT FIBER VOLUME	3 T-BARS	18
FIBER LENGTH	3 T-BARS	18
DEVELOP MACERATION TECHNIQUE		
CURVED TAPE	2 T-BAR	
CURVED ROSETTE	PANELS EACH,	72
CURVED SHINGLE	6 SPEC/PANEL	
HONEYCOMB ATTACHMENT		
CURVED TUFTED	1 PANEL	12
CURVED ROSETTE	2 PANELS	24
CURVED SHINGLE	2 PANELS	24
CURVED TAPE	2 PANELS	24

PROCESSING PARAMETERS DEVELOPMENT

OBJECTIVE

ESTABLISH MATERIAL AND MANUFACTURING
PROCESS SPECIFICATIONS

ACCOMPLISHMENTS

MATERIAL SPEC ANS-90292 ISSUED FOR:

FABRIC
RESIN
RESIN APPLICATION
DENSIFIER: TBD

PROCESS SPEC ANS-90293 ISSUED FOR:

LAYUP
CURE
POST CURE
CARBONIZATION
GRAPHITIZATION
DENSIFICATION

CY 71-72 M-6 PLAN: UPGRADE AS REQUIRED

FIBROUS GRAPHITE COMPOSITE - SHORT TERM DEVELOPMENT PLAN

AEROJET NUCLEAR SYSTEMS COMPANY

TOOLING AND EQUIPMENT FOR FULL SIZE NOZZLE EXTENSION

57

TOOL DESIGN

COMPLETED & RELEASED

STEEL LAYUP MANDREL MODULAR	T - 1050000 THRU 7
INTREMOLD DIE OVEN	T - 1050008
INTREMOLD ZINC DIES	T - 1050009, 15, 29
ROTATING LAYUP FIXTURE	T - 1050010
MANDREL AUTOCLAVE CART	T - 1050011
INTREMOLD DIE POSITIONING & CLAMPING RING	T - 1050014
BAG MANDREL	T - 1050016 THRU 19
GRAPHITE MANDREL	T - 1050025
GRAPHITE MANDREL LIFTING RING	T - 1050102
GRAPHITE MANDREL HOIST BAR	T - 1050103

IN PROCESS

RETORT & RETORT PLUMBING	T - 1050145, 148, 149
INTREMOLD III FLANGE TOOLING	SKETCHES

STEEL MANDREL ASSEMBLY - FULL SIZE

T-1050000

STEEL MANDREL MODULAR SEGMENT

T - 105001, 005, 006, 007

ROTATING LAY-UP TABLE

T-1050010

LINER DEBULK
BAG ASSEMBLY

VACUUM LINES
WITH THERMOCOUPLE
LINES INSIDE

CLAMPS
BOTH ENDS

T-1050022
PRESSURE
BAG

T-1050010
LAY-UP FIXTURE

3/

AUTOCLAVE AND TRANSPORTATION CARTS - FULL SIZE

NOTE: TOOLING NEEDED

T - 1050112

AEROJET NUCLEAR SYSTEMS COMPANY

AUTOCLAVE CART

T - 1050011

165

LINER DEBULK
ASSEMBLY TO AUTOCLAVE CART

2/

LINER ASSEMBLY AUTOCLAVE CURE

LINER MACERATION

T - 1050014

INTREMOLD DIES & CLIP

T-1050009 -1 THRU -71

ZINC DIE HEATING OVEN

T-1050008

11/

HONEYCOMB CELL LAY-UP

ZINC DIE ASSEMBLY

BAG MANDREL - FOR MOLDING RUBBER BAGS

T-1050016 THRU 19

AEROJET NUCLEAR SYSTEMS COMPANY

HONEYCOMB CELL LAY-UP

PRESSURE BAG ASSEMBLY

74

LINER DEBULK
ASSEMBLY TO AUTOCLAVE

LINER ASSEMBLY REMOVAL OF ZINC DIES

GRAPHITE MANDREL LIFTING RING

T - 1050102

1/1 SCALE

POST CURE

ASSEMBLY OF CURED LINER TO GRAPHITE MANDREL

GRAPHITE MANDREL - FULL SIZE

T-1050025

RETORT - FULL SIZE NOZZLE EXTENSION

T-1050145

POST CURE AND CARBONIZE
INSTALLATION AND REMOVAL OF LINER INTO RETORT

82/

TOOLING PROCUREMENT

<u>COMPLETED</u>		<u>DRAWING NO.</u>
1.	COLD STORAGE BOX	COMMERCIAL
2.	STEEL MANDRELS	
	MODULAR FULL SIZE	T - 1050000
	MODULAR SEGMENTS	T - 1050001 THRU 4
	FLANGES	T - 1050005
	RINGS	T - 1050006
	STUD ENDS	T - 1050007
3.	ROTATING LAYUP TABLE	T - 1050010
4.	AUTOCLAVE CART	T - 1050011
5.	ZINC DIE HEATING OVEN	
<u>IN-PROCESS</u>		
1.	INTREMOLD DIES	T - 1050009
2.	GRAPHITE MANDRELS	T - 1050025
3.	GANTRY CRANE	COMMERCIAL

63/

TOOLING NEEDED

SEGMENTED NOZZLE EXTENSION

INTREMOLD DEBULKING MACHINE

DWG/SKETCHES

PITCH HEATING SYSTEM & TANKS

SKETCHES

AUTOCLAVE MODIFICATION & LINES

SKETCHES

RUBBER BAGS & ACESSORY MATERIALS

SKETCHES

RETORT-GAS DISPOSAL SYSTEM

T-1050022

NOZZLE EXTENSION REMOVAL FIXTURE

VERTICAL MILL TRACING FIXTURE

INSPECTION TOOLS & EQUIPMENT

FULL SIZE NOZZLE EXTENSION

MACHINING FIXTURE FOR ROTATING TABLE

PRESSURE BAG MANDRELS & BAGS

TRUNNION TURN OVER FIXTURE

SKETCH

AUTOCLAVE & TRANSPORTATION CARTS

T-1050112

NOZZLE EXTENSION REMOVAL FIXTURE

INSPECTION TOOLS & FIXTURES

NOZZLE EXTENSION MANUFACTURING FACILITY

FACILITY AND EQUIPMENT CONSTRUCTION - STATUS

	PERCENT COMPLETED	COMPLETION DATE
FACILITY MODIFICATIONS		
LAYUP PIT	10	16 MAY 1971
RETORT CONTROL SYSTEM	25	16 JUNE 1971
INDUCTION FURNACE	50	16 AUGUST 1971
20 TON GANTRY CRANE		
FABRICATION	90	16 APRIL 1971
INSTALLATION	20	1 JUNE 1971
INDUCTION GRAPHITIZING FURNACE	70	31 JULY 1971
DESIGN	95	7 APRIL 1971
FABRICATION	80	21 APRIL 1971
ASSEMBLY	60	1 MAY 1971
FACTORY TEST	-	16 MAY 1971
INSTALLATION	-	4 JUNE 1971
ACTIVATION	-	15 JULY 1971
ACCE PTANCE	-	30 JULY 1971
RETORT CONTROL SYSTEM		
ATMOSPHERE CONTROL	20	16 MAY 1971
TEMPERATURE CONTROL	10	16 JUNE 1971

AEROJET NUCLEAR SYSTEMS COMPANY

ANSC ENGINEERING

PLANT ENGINEERING

FACILITY MODIFICATION DESIGN

FACILITY SAFETY

PROJECT

SPECIFICATIONS AND REQUIREMENTS

TECHNICAL EVALUATION OF QUOTATIONS

DESIGN REVIEW - 160 DRAWINGS REVIEWED

SUPPLIER SURVEILLANCE

QUALITY ASSURANCE

SUPPLIER SURVEILLANCE

SAFETY

EQUIPMENT OPERATING PROCEDURES

PLANT LAYOUT - PLAN VIEW

COOLING WATER
HEAT EXCHANGER

ROADWAY

ELECTRICAL SUBSTATIONS

INERT GAS SUPPLY

EVAPORATORS

GA_r

LA_r

LN₂

EMERGENCY
GENERATOR

MOTOR CONTROL
CENTER

DOORWAY
16' x 16'

GANTRY
CRANE

LAYUP
STATION

RESISTANCE FURNACE

INDUCTION GRAPHITIZING FURNACE

BLDG 2005

BLDG 2004

DOORWAY
12' x 12'

AUTOCLAVE

AEROJET NUCLEAR SYSTEMS COMPANY

PLANT LAYOUT - VERTICAL SECTION

INDUCTION GRAPHITIZING FURNACE ASSEMBLY

SECTION A-A

TEMPERATURE POWER CONTROL SYSTEMS

INDUCTION GRAPHITIZING FURNACE CHAMBER

SUMMARY

	COMPLETION DATE
FACILITY MODIFICATIONS	16 AUGUST 1971
GANTRY CRANE	1 JUNE 1971
INDUCTION GRAPHITIZING FURNACE	31 JULY 1971

100

NOZZLE EXTENSION PROJECT STATUS SUMMARY

CHOICE OF GRAPHITE CONCEPT STILL VALID

FILM-COOLED CONCEPTS NOT BETTER THAN
 $A_e/A_t = 30:1$ OPTIMUM CONTOUR

DETERMINED EROSION RATES ARE ACCEPTABLE

SELECTED FIBER FOR INTREMOLD III MATERIAL

FMA (MODES AND MECHANISMS) ISSUED

NEED TO DEVELOP FABRICATION TECHNIQUES

NEED TO IMPROVE MATERIAL PROPERTIES

NEED TO ACQUIRE MATERIAL DATA

TOOLING AND EQUIPMENT - APPROXIMATELY 50%
COMPLETE TOWARD FULL SCALE LAYUP

TURBOPUMP

2

REVIEW CONTENT

SUMMARY OF REQUIREMENTS

DESCRIPTION OF CONCEPT

SIGNIFICANT ACCOMPLISHMENTS

SUMMARY OF DESIGN ANALYSIS

SUMMARY OF RELIABILITY DESIGN
PROGRESS

STATUS OF SUBCOMPONENT
DEVELOPMENT PROGRAMS

DEVELOPMENT PLAN SUMMARY

AEROJET NUCLEAR SYSTEMS COMPANY

TIME POSITION OF REVIEW

AEROJET NUCLEAR SYSTEMS COMPANY

REQUIREMENTS SUMMARY

BASIC ARRANGEMENT

DUAL PARALLEL TPA OPERATION - NORMAL MODE

SINGLE TPA OPERATION - MALFUNCTION MODE

NO BOOST PUMPS

PERFORMANCE

FLOW RATE $\approx$ 45 LBS/SEC - NORMAL MODE (100% THRUST)

PRESSURE RISE - LOWEST POSSIBLE (CONSIDERING OVERALL
ENGINE REQUIREMENTS)

THROTTLING - NORMAL MODE (60% THRUST)

NPSP - 2 PSI - 28 PSI SAT. TANK - MALFUNCTION MODE

0 PSI - 26 PSI SAT. TANK - NORMAL MODE (GOAL)

FUNCTIONAL

DUTY CYCLE - 10 HOURS - 60 STARTS

RELIABILITY - .999831 (SINGLE TPA)

DIAGNOSTIC/TREND DATA CAPABILITY

INTERFACE LINE SIZES - PI 9.5 IN., PO 5 IN., TI/TO 7.5 IN.

INTERFACE LOADS - 1.5 x C (ENGINE LOADS - STEADY STATE)

CHILLDOWN - MINIMIZE TIME AND COOLANT CONSUMPTION

DESCRIPTION OF SELECTED CONCEPT

AEROJET NUCLEAR SYSTEMS COMPANY

DESCRIPTION OF SELECTED CONCEPT

TRADE STUDY RESULTS

2 STAGE CENTRIFUGAL PUMP

2 STAGE AXIAL TURBINE

27,000 RPM

NPSP - 2 PSI - 28 PSIA SAT. TANK

80% MALFUNCTION THRUST

PREDICTED PUL... PERFORMANCE MAP

OPERATING POINTS

	MODE	% THRUST
1	NORMAL	100
2	NORMAL THROTTLED	60
3	MALFUNCTION	80
4	MALFUNCTION THROTTLED	60

*PUMP SPEED & EFFICIENCY
AT PUMP INLET TEMP =
40.25°R, $P_V = 26$ PSI

PREDICTED TURBINE PERFORMANCE

$$A_{SI} = 8.45 \text{ IN}^2$$

- NORMAL MODE
- MALFUNCTION MODE
- THROTTLED - NORMAL MODE
- △ THROTTLED - MALFUNCTION MODE

TOTAL PRESSURE RATIO

COMPUTED WEIGHT, 770LBS

SIGNIFICANT ACCOMPLISHMENTS SINCE FEBRUARY 1970

SELECTION OF MAJOR INTERNAL CONCEPTS

DESIGN SUPPORT TESTS

TURBINE AIR FLOW - INLET/EXHAUST MANIFOLD

DIAGNOSTICS - SHAFT DISPLACEMENT/BEARING TEMPERATURE RISE

BLADE VIBRATION - STATORS/SECOND STAGE ROTOR (UNSHROUDED)

MATERIALS DATA ACCRUAL

PRELIMINARY FRACTURE MECHANICS (Ti)

TITANIUM SPECIFICATIONS

TITANIUM MATERIAL ORDERED

BEARING TESTS

60MM - DUPLEX BALL

50MM - ROLLER

65MM - DUPLEX BALL

PRELIMINARY STRESS ANALYSIS KEY PARTS

FAILURE MODE ANALYSIS INITIATED

DEFINED FACILITY REQUIREMENTS

SINGLE TPA TESTS

BEARING TESTS

AEROJET NUCLEAR SYSTEMS COMPANY

SUMMARY OF DESIGN ANALYSIS

SUMMARY OF DESIGN ANALYSIS

FLUID DYNAMICS

FLUID LOADS

ROTOR DYNAMICS

BALANCER ANALYSIS

NUCLEAR

THERMAL

INTERFACE LOADS

STRUCTURAL

FLUID DYNAMICS SUMMARY

AEROJET NUCLEAR SYSTEMS COMPANY

METHOD OF ANALYSIS

PUMP FLOW PASSAGES

COMPUTERIZED SOLUTION OF EQUATION DEFINING
ASYMMETRIC FLOW FORCES ON FLUID USING
METHOD OF CHARACTERISTICS

INDUCER

INDUCER DESIGN PARAMETERS

		<u>NO. 1</u>	<u>NO. 2</u>
INLET TIP DIAMETER		6.9 IN	6.9 IN
INLET HUB/TIP RATIO		0.398	0.398
DISCHARGE TIP DIAMETER		6.46 IN	6.46 IN
DISCHARGE HUB/TIP RATIO		.683	.683
INLET TIP BLADE ANGLE		8.5°	8.5°
INLET TIP FLOW COEFFICIENT		0.076	0.076
BLADE NUMBER		4 + 4	4 + 4
BLADE DISCHARGE ANGLE	TIP	16°	15.°5
	MEAN	18.3°	20°
	HUB	24°	27.°6
DISCHARGE TIP HEAD COEFFICIENT		.210	.230
MATERIAL		A-110-AT-ELI	A-110-AT-ELI

FIRST STAGE IMPELLER

18

FIRST STAGE IMPELLER

DISCHARGE DIAMETER		10.95 IN
DISCHARGE PORT WIDTH		0.52 IN
DISCHARGE BLADE ANGLE		30°
BLADE NUMBER		8
INLET TIP DIAMETER		6.53 IN
HUB/TIP RATIO		0.70
BLADE INLET ANGLE	TIP	16°
	MEAN	21°
	HUB	26°
DISCHARGE FLOW COEFFICIENT		0.105
MATERIAL		A-110-AT-ELI

FIRST STAGE IMPELLER

IDEAL HEAD DISTRIBUTION

RELATIVE VELOCITY DISTRIBUTION

CROSSOVER

21

CROSSOVER

MAJOR DESIGN PARAMETERS

NUMBER OF PASSAGES	11
INLET BASE CIRCLE DIAMETER	11.7 IN
EXIT MEAN DIAMETER	7.32 IN
INLET MEAN VANE ANGLE	11°
EXIT VANE ANGLE	90°
INLET PASSAGE HEIGHT	0.630 IN
INLET THROAT AT VANE OVERLAP	0.590 IN
MEAN PASSAGE WRAP ANGLE	68.15°
MEAN TURNING RADIUS TO PASSAGE HEIGHT RATIO (MERIDIONAL PLANE)	1.44
MEAN TOTAL PASSAGE LENGTH	6.96 IN

CROSSOVER PASSAGE - VELOCITY DISTRIBUTION

SECOND STAGE IMPELLER

AEROJET NUCLEAR SYSTEMS COMPANY

24

SECOND STAGE IMPELLER

DISCHARGE DIAMETER		10.75 IN
DISCHARGE PORT WIDTH		0.56 IN
DISCHARGE BLADE ANGLE		25°
BLADE NUMBER		8
INLET TIP DIAMETER		6.25 IN
HUB/TIP RATIO		0.735
BLADE INLET ANGLE	TIP	18°
	MEAN	21°
	HUB	24°
DISCHARGE FLOW COEFFICIENT		0.115
MATERIAL		A-110-AT-ELI

27

IDEAL HEAD DISTRIBUTION

SECOND STAGE IMPELLER

— TIP
 - · - MEAN
 --- HUB

RELATIVE VELOCITY DISTRIBUTION

SECOND STAGE DIFFUSER VANES

MAJOR DESIGN PARAMETERS

NUMBER OF VANES	9
INLET BASE CIRCLE DIAMETER	11.7 IN.
EXIT BASE CIRCLE DIAMETER	16.2 IN.
BASE CIRCLE DIAMETER RATIO	1.3
INLET MEAN VANE ANGLE	11°
EXIT MEAN VANE ANGLE	18°
PASSAGE WIDTH	0.600 IN.
SOLIDITY	1.46
AREA RATIO	2.1

21 SECOND STAGE DIFFUSER VANES

PREDICTED NONCAVITATING PERFORMANCE AT DESIGN POINT

OVERALL

INLET FLUID TEMPERATURE	36.4°R
SPEED	27,000 RPM
FLOW RATE (NET)	58 LB/S
ISENTROPIC HEAD RISE	49,530
EFFICIENCY	.68
REHEAT FACTOR	1.018

FIRST STAGE PERFORMANCE

IMPELLER FLOW RATE	60.3 LB/S
FLOW COEFFICIENT	.105
HEAD COEFFICIENT	.487
ISENTROPIC HEAD RISE	25,500 FT
EFFICIENCY *	.71

SECOND STAGE PERFORMANCE

IMPELLER FLOW RATE	67 LB/S
FLOW COEFFICIENT	.115
HEAD COEFFICIENT	.500
ISENTROPIC HEAD RISE	24,930 FT
EFFICIENCY *	.68

* LEAKAGE LOSSES CHARGED TO STAGE

FLUID DYNAMICS ANALYSIS SUMMARY

PUMP

METHOD DEVELOPED TO PREDICT VELOCITY
DISTRIBUTIONS

FLOW PASSAGE DESIGN COMPLETED

PERFORMANCE PREDICTION COMPLETED

VARIANCE COMPUTATIONS IN PROCESS

METHODS OF ANALYSIS
TURBINE

METHOD

1.	DESIGN POINT PERFORMANCE
PREDICTION	"MULTISTAGE AXIAL FLOW PERFORMANCE
ANALYSIS PROGRAM", AGC REPORT NO.
7740R-70-032, JAN 1970.
2.	BLADE SURFACE VELOCITY
DISTRIBUTION	"FORTRAN PROGRAM FOR CALCULATING
TRANSONIC VELOCITIES ON A BLADE-TO
BLADE STREAM SURFACE OF A TURBO-
MACHINE", NASA TN D-5427, SEPT 1969.
3.	OFF-DESIGN PERFORMANCE
PREDICTION	"ANALYTICAL PROCEDURE AND COMPUTER
PROGRAM FOR DETERMINING THE OFF-
DESIGN PERFORMANCE OF AXIAL FLOW
TURBINES, NASA CR-710, FEB 1967.

31

TURBINE MEAN DESIGN POINT VELOCITY DIAGRAM

FIRST STAGE

TURBINE BLADING
FIRST STAGE STATOR

HUB

TIP

STACKED PROFILES

MAJOR DESIGN PARAMETERS	HUB	MEAN	TIP
NUMBER OF BLADES		42	
CHORD, IN	0.897	0.989	1.080
SOLIDITY	1.431	1.433	1.434
ASPECT RATIO		0.851	
BLADE INLET ANGLE, DEGREES	0	0	0
BLADE EXIT ANGLE, DEGREES	71.6	70.1	68.6

TURBINE BLADE SURFACE VELOCITY DISTRIBUTION FIRST STAGE STATOR

FIRST STAGE ROTOR

HUB

TIP

STACKED PROFILES

MAJOR DESIGN PARAMETERS	HUB	MEAN	TIP
NUMBER OF BLADES		51	
CHORD, IN	0.831	0.865	0.899
SOLIDITY	1.609	1.522	1.450
ASPECT RATIO		0.973	
BLADE INLET ANGLE, DEGREES	47.4	32.4	12.6
BLADE EXIT ANGLE, DEGREES	64.5	66.2	67.6

TURBINE BLADE SURFACE VELOCITY DISTRIBUTION

FLUID DYNAMIC ANALYSIS SUMMARY

TURBINE

METHOD TO DEFINE BLADE FABRICATION
COORDINATES DEVELOPED

FLOW PASSAGE DESIGN COMPLETED

PERFORMANCE PREDICTIONS COMPLETED

VARIANCE COMPUTATIONS IN PROCESS

37

FLUID LOADS SUMMARY

AEROJET NUCLEAR SYSTEMS COMPANY

37

ASYMMETRICAL FLUID RADIAL LOADS SUMMARY

SOURCE

PUMP VOLUTE FLOW MALDISTRIBUTION

INDUCER CAVITATION

TURBINE MANIFOLD FLOW MALDISTRIBUTION

37/

VOLUTE FLOW MALDISTRIBUTION

* REQUIRES EXPERIMENTAL VERIFICATION

AEROJET NUCLEAR SYSTEMS COMPANY

RADIAL LOAD ON CENTRIFUGAL PUMP IMPELLER

$N_S = 1200$ AT Q_D (REF 1)

** REF 1 ASME PAPER 59-HYD-2, FIG 6.9

*** REF 2 AEROJET NERVA MOD 3 PUMP, 1962

FLUID RADIAL LOADS

CAVITATION INDUCED LOADING

SOURCE

ASYMMETRICAL CAVITATION

CAVITATION INDUCED FLOW OSCILLATIONS

LOAD DESCRIPTION

NON SYNCHRONOUS ROTATING RADIAL LOAD

PHENOMENON NOTED ON FOLLOWING PUMPS

MK 25

MK 29 (F)

MK 10 (LO₂)

FLUID RADIAL LOAD SUMMARY

TURBINE MANIFOLD FLOW MALDISTRIBUTION

SOURCE

TURBINE INLET FLOW MALDISTRIBUTION

TURBINE EXHAUST MANIFOLD MALDISTRIBUTION

LOAD DESCRIPTION

UNIDIRECTIONAL, NON-ROTATING

43/

ESTIMATED FLUID RADIAL LOADS SUMMARY - 27,000 RPM

* REQUIRES EXPERIMENTAL CONFIRMATION

** OCCURS ONLY AT SPECIFIC NPSP VALUES &
REQUIRES EXPERIMENTAL CONFIRMATION

THRUST BALANCER SUMMARY

AEROJET NUCLEAR SYSTEMS COMPANY

STABILITY NOMINAL MODE

THRUST BALANCER SUMMARY

● PREDICTED OPERATING POSITIONS

ROTOR DYNAMICS SUMMARY

DYNAMIC ANALYSIS SUMMARY - TPA CRITICAL SPEED

1118101 "B" CHANGE TITANIUM ROTOR

— ROTOR ONLY

--- ROTOR & HOUSING ON SPRINGS
100,000 LB/IN AT TRUNNIONS
50,000 LB/IN AT TURBINE END

ROTOR AND HOUSING NORMALIZED DISPLACEMENT NEAR RESONANCE AT 2370 RPM

FIRST SYSTEM RESONANCE

ROTOR

— DYNAMIC CENTERLINE
 - - - GEOMETRIC CENTERLINE

HOUSING

8/

ROTOR AND HOUSING NORMALIZED DISPLACEMENT NEAR RESONANCE AT 3400 RPM

SECOND SYSTEM RESONANCE

ROTOR

— DYNAMIC CENTERLINE
- - - GEOMETRIC CENTERLINE

HOUSING

AEROJET NUCLEAR SYSTEMS COMPANY

51 ROTOR AND HOUSING NORMALIZED DISPLACEMENT NEAR RESONANCE AT 37,800 RPM

ROTOR CONICAL MODE

ROTOR

— DYNAMIC CENTERLINE
 - - - GEOMETRIC CENTERLINE

HOUSING

52

ROTOR AND HOUSING NORMALIZED DISPLACEMENT NEAR RESONANCE AT 42,200 RPM

ROTOR CIRCULAR WHIRL

ROTOR

— DYNAMIC CENTERLINE
 - - - GEOMETRIC CENTERLINE

HOUSING

AEROJET NUCLEAR SYSTEMS COMPANY

53/

ROTOR AND HOUSING NORMALIZED DISPLACEMENT NEAR RESONANCE AT 48,500 RPM

THIRD SYSTEM RESONANCE

ROTOR

HOUSING

ROTOR AND HOUSING NORMALIZED DISPLACEMENT NEAR RESONANCE AT 58,500 RPM

SHAFT BENDING MODE

ROTOR

— DYNAMIC CENTERLINE
--- GEOMETRIC CENTERLINE

HOUSING

AEROJET NUCLEAR SYSTEMS COMPANY

TPA CRITICAL SPEED

AEROJET NUCLEAR SYSTEMS COMPANY

56

37

TPA CRITICAL SPEED

————— TITANIUM
- - - - - A286

57

ROTOR JOINT STIFFNESS INFLUENCE ON CRITICAL SPEED

1118101 "B" CHANGE TITANIUM ROTOR BEARING SPRING RATE = 1×10^6 LB/IN PER BEARING

ROTOR SKETCH

MODEL I

MODEL II

MODEL III

MODEL IV

MODEL V

BEARING LOAD SUMMARY

TITANIUM ROTOR AT 27,000 RPM

- PREDICTED BEARING LOADS FOR MASS UNBALANCE & MINIMUM UNIDIRECTIONAL VOLUTE FORCE TO SUPPRESS BEARING CARTRIDGE CLEARANCES

R = ROTATING LOAD DUE TO MASS UNBALANCE (LBS)
 U = UNIDIRECTIONAL LOAD DUE TO VOLUTE (LBS)
 (MINIMUM VALUE REQUIRED TO SUPPRESS BEARING
 CARTRIDGE CLEARANCES AT 30,000 RPM)

MECHANICAL BEARING LOAD SUMMARY

- A-286 ROTOR UP TO 27,000 RPM
- PREDICTED BEARING LOADS FOR MASS UNBALANCED AND MINIMUM UNIDIRECTIONAL VOLUTE FORCE TO SUPPRESS BEARING CARTRIDGE CLEARANCES

R = ROTATING LOAD DUE TO MASS UNBALANCE (LBS)

U = UNIDIRECTIONAL LOAD DUE TO VOLUTE (LBS)

(MINIMUM VALUE REQUIRED TO SUPPRESS BEARING CARTRIDGE CLEARANCES AT 30,000 RPM)

BEARING LOAD SUMMARY

TITANIUM ROTOR AT 27,000 RPM

PREDICTED BEARING LOADS FOR MASS UNBALANCE AND EXPECTED UNIDIRECTIONAL VOLUTE FORCE

C = CAVITATION INDUCED LOAD (LBS) FOR BRG CLEARANCE = 0.0 *

R = ROTATING LOAD DUE TO MASS UNBALANCE (LBS)

U = UNIDIRECTIONAL LOAD DUE TO VOLUTE (LBS)

(UTILIZES HIGH SPEED BALANCE)

*(NEGLECTING ROTOR INERTIA LOADS)

AEROJET NUCLEAR SYSTEMS COMPANY

CRITICAL SPEED BEARING LOADS SUMMARY

SELECTION

CONFIGURATION - OVERHUNG FIRST IMPELLER AND TURBINE

HIGH SPEED BALANCE

TITANIUM ROTOR

RESULTS

LOWEST BEARING LOADS

MINIMIZED DAMPING DEPENDENCY

MINIMIZED POSSIBILITY OF SUB SYNCHRONOUS WHIRL

HIGHEST STRUCTURAL MARGINS OF SAFETY

AEROJET NUCLEAR SYSTEMS COMPANY

NUCLEAR HEATING/MATERIAL EFFECTS SUMMARY

AEROJET NUCLEAR SYSTEMS COMPANY

NUCLEAR ANALYSIS SUMMARY - HEATING EFFECTS

REGION	MATERIAL	HEATING RATE, BTU/IN ³ -SEC	
		AVERAGE	MAXIMUM LOCAL
1	310	2.85×10^{-3}	3.80×10^{-3}
2	ti	1.38×10^{-3}	1.55×10^{-3}
3	ti	1.17×10^{-3}	1.28×10^{-3}
4	310	3.42×10^{-3}	3.80×10^{-3}

ESTIMATED SPECIFICATION EXTREME

NUCLEAR ANALYSIS SUMMARY

MATERIAL DAMAGE EFFECTS *

REGION	MATERIAL	TOTAL FLUENCE*	ESTIMATED ALLOWABLE FLUENCE **	RATIO <u>ALLOWABLE</u> TO TOTAL
		$n/cm^2 > 1 \text{ Mev}$	$n/cm^2 > 1 \text{ Mev}$	
1,2,3,4	310,347,718	7×10^{16}	1×10^{18}	14
2,3	ti	7×10^{16}	3×10^{17}	4
2,3	A-286	7×10^{16}	1×10^{18}	14

		RADS-C	RADS-C	
3	PBI-GLASS	1×10^8	1×10^9	10
3	PBI-GRAPHITE	1×10^8	1×10^9	10

* ESTIMATED SPECIFICATION EXTREME

** BASIS-CHANGE FROM DUCTILE TO BRITTLE CRITERIA
REQUIRED OR DAMAGE THRESHOLD

1/

THERMAL ANALYSIS SUMMARY

AEROJET NUCLEAR SYSTEMS COMPANY

COMPONENT THERMAL ANALYSIS SUMMARY

		TPA LAYOUT	NUCLEAR HEATING	STEADY STATE	TRANSIENT
INDUCER HOUSING		A	X	X	X
INDUCER		A	X	X	X
PUMP HOUSING	HOUSING	A	X	X	X
	EXIT VOLUTE	A	X	X	
FIRST IMPELLER		A	X	X	X
SECOND IMPELLER		B	X	X	X
PUMP BACKPLATE HOUSING		B	X	X	X
TURBINE HOUSING	HOUSING	B	X	X	
	INLET TORUS	B	X	X	
FIRST TURBINE ROTOR		A	X	X	X
SECOND TURBINE ROTOR		A	X	X	X
ROTOR TIE BOLTS		A	X	X	X
TURBINE EXHAUST MANIFOLD		B	X	X	X

LOCAL TEMPERATURE IN ROTATING COMPONENTS, °R 1.

LOCAL TEMPERATURE IN HOUSINGS, °R

STEADY STATE

THERMAL ANALYSIS SUMMARY

CHILLDOWN

OPTIONS

TANK PRESSURE - VENT OVERBOARD

TANK PRESSURE VENT THROUGH ENGINE

ELECTRIC RECIRCULATION PUMPS - RETURN TO TANK

COMBINATION MODE

TANK PRESSURE - VENT THROUGH ENGINE

IDLE MODE - DISCHARGE THROUGH ENGINE
AND RECIRCULATE TO TANK (PUMP
DISCHARGE CONTROL) IN PARALLEL

COMBINATION MODE

TANK PRESSURE - VENT THROUGH ENGINE

IDLE MODE - DISCHARGE THROUGH ENGINE
(TURBINE CONTROL)

AEROJET NUCLEAR SYSTEMS COMPANY

CHILLDOWN STUDY ASSUMPTIONS

SOLAR SHIELDING

INITIAL FEED SYSTEM TEMPERATURE - 400°R

TANK CONDITIONS - SATURATED LIQUID AT 15 PSIA

TOTAL HEAT TO BE REMOVED - 25,000 BTU/TPA

CHILL TIME - DEPENDENT ON MISSION

SLOW CHILL - 1 TO 3 HOURS

FAST CHILL - 3 TO 10 MINUTES

CHILLDOWN

ANALYSIS REQUIRED

TRANSIENT HEAT TRANSFER ANALYSIS OF PUMPS DURING START
TO FULL POWER OPERATION

PURPOSE

PROVIDE INPUT FOR ENGINE START ANALYSIS
PREDICT STATE CONDITIONS IN PUMP DURING START TRANSIENT
ESTABLISH PUMP START CRITERIA BASED ON PREDICTED STATE CONDITIONS
PREDICT PROPELLANT PENALTY REQUIRED TO CONDITION PUMP

12

CHILLDOWN

PUMP CHILLDOWN DATA TO BE ESTABLISHED

INDUCER INLET, FIRST AND SECOND IMPELLER,
DISCHARGE QUALITY VS TIME AND SPEED

PUMP PRESSURE RISE VS TIME AND SPEED

THRUST BALANCER CAPACITY VS TIME AND SPEED

AXIAL THRUST VS TIME AND SPEED

BEARING COOLANT FLUID CONDITIONS

METAL TEMPERATURE AT CRITICAL LOCATIONS

DEFINE PUMP Q/N VS TIME FOR STARTUP ANALYSIS

13

CHILLDOWN MODE DESCRIPTION

FAST CHILL

TANK PRESSURE CHILL

INITIATES CHILL OF FLUID PASSAGES

INITIATES CHILL OF BEARINGS AND BALANCER

PUMP WINDMILLS AT APPROXIMATELY 50 RPM

IDLE MODE CHILL (POWERED)

COMPLETES REQUIRED FLUID PASSAGE CONDITIONING

COMPLETES REQUIRED FLUID CONDITIONING OF BEARINGS AND BALANCER

PUMP SPEED ALLOWED TO INCREASE AS CHILLDOWN PROGRESSES

THERMAL ANALYSIS SUMMARY

SCHEMATIC OF PUMP SPEED VS TIME - START TO FULL POWER

CHILLDOWN MODEL

USES CINDA TRANSIENT HEAT TRANSFER PROGRAM

TURBOPUMP REPRESENTED BY 450 METAL NODES - 150
FLUID NODES

USES HYDROGEN PROPERTIES DECK TO PREDICT PUMP
STATE POINT DURING POWERED OPERATION

USES PROPELLANT FLOW SCHEDULE FROM NETAP PROGRAM

AEROJET NUCLEAR SYSTEMS COMPANY

CHILLDOWN

THERMAL MODEL *

* ASSUMES CONSTANT PRESSURES IN TPA DURING TANK PRESSURE CHILL

TPA CHILLDOWN

78

CHILL TIME VS LH₂ USED

79

THERMAL ANALYSIS SUMMARY

STEADY STATE/TRANSIENT

PRELIMINARY STEADY STATE ANALYSIS OF MAJOR
COMPONENTS COMPLETED

PRELIMINARY TRANSIENT ANALYSIS OF CRITICAL COMPONENTS
ARE 80% COMPLETED

LOW STEADY STATE AND TRANSIENT THERMAL GRADIENTS

CHILLDOWN

BASIC METHODS INVESTIGATED

THERMAL MODEL BEING MODIFIED TO COVER
TOTAL TRANSIENT RANGE

ANALYSIS OF PRELIMINARY RESULTS CONTINUING

STRUCTURAL ANALYSIS SUMMARY

B1

FAILURE CRITERIA FOR TITANIUM COMPONENTS

ROTORS	STEADY STATE LOADING DISC BURST	FRACTURE MECHANICS
	LOW CYCLE FATIGUE 60 CYCLES	FRACTURE MECHANICS (CRACK PROPAGATION)
BLADES	STEADY STATE LOADING	FRACTURE MECHANICS
	HIGH CYCLE FATIGUE > 10^5 CYCLES	CONVENTIONAL FATIGUE ANALYSIS (S-N CURVES AND GOODMAN DIAGRAMS)

FRACTURE MECHANICS RELIABILITY MODEL

$$\text{MARGIN OF SAFETY (M.S.)} = \frac{0.80 \sigma_c}{\text{MSI}} - 1$$

MSI = MAXIMUM STRESS INTENSITY

83

FRACTURE MECHANICS ANALYSIS ASSUMPTIONS

THE CRACK IS AT THE POINT OF MAXIMUM TENSILE STRESS

THE CRACK IS ORIENTED NORMAL TO THE DIRECTION OF
THE MAXIMUM TENSILE STRESS

THE STRESS FIELD REMAINS CONSTANT AS THE CRACK
PROPAGATES RADially INTO THE DISC

FRACTURE MECHANICS - DEFINITION OF TERMS

TERM	EQUATION	DESCRIPTION
K_{IC} or K_{Ii}	(MATERIAL PROPERTY)	CRITICAL STRESS INTENSITY FACTOR
a_i	(NDT INSPECTION THRESHOLD)	INITIAL CRACK LENGTH
a_m		CRITICAL CRACK SIZE
σ_c	$\frac{K_{IC}}{1.1 \sqrt{\pi \frac{a_m}{Q}}}$ or $\frac{K_{Ii}}{1.1 \sqrt{\pi \frac{a_i}{Q}}}$	STRESS AT WHICH CATASTROPHIC FRACTURE OCCURS
Q	(SNPO-C-1, PG 11)	FLAW SHAPE FACTOR
N_f	$\frac{\ln \left(\frac{a_m}{a_i} \right)}{\left(\frac{\Delta \sigma}{k} \right)^{1/\beta} \left[\frac{1}{\cos \left(\frac{\pi \Delta \sigma}{4T} \right)} - 1 \right]}$	CYCLES TO FAILURE
$\Delta \sigma$		STRESS RANGE
T		ULTIMATE TENSILE STRENGTH
β, k		EXPONENT AND COEFFICIENT OF PLASTIC STRESS-STRAIN LAW

$$\Delta \sigma = k \epsilon_p^\beta$$

BS

INITIAL FLAW DEPTH, a_i

1. THE MINIMUM DETECTABLE FLAW SIZE ON THE SURFACE IS ASSUMED TO BE .048 IN.
2. MAXIMUM FLAW DEPTH CORRESPONDS TO ALL $a/2c$ RATIO OF 0.5
3. MAXIMUM INITIAL FLAW DEPTH, $a_i = .024$ IN.

FRACTURE MECHANICS MARGIN OF SAFETY FOR TPA ROTORS

37

CRITICAL STRESS INTENSITY FACTOR

1. TITANIUM 5 Al-2.5Sn ELI AT -423°F PANCAKE FORGING
MEAN K_{IC} = 71.6 ksi $\sqrt{\text{in}}$ PER DRM M-4, 2-17-71
(.99-.95) K_{IC} = 44.9
2. TITANIUM 5 Al-2.5 Sn ELI AT -160°F
MEAN K_{II} = 53 ksi $\sqrt{\text{in}}$ = $\frac{52.7 + 53.3 + 62.1 + 39.1}{4}$
60 CYCLES
(.99-.95) K_{II} = $\frac{44.9}{71.6} \times 53 = 33$ ksi $\sqrt{\text{in}}$
60 CYCLES
3. VERIFICATION OF K_{II} AND TYPE A STATISTICAL DATA TO BE SUPPLIED
IN ACCORDANCE WITH MATERIAL TEST PLAN M-4, LINE 2

B8

1.11187
22

.99/.95 ULTIMATE TENSILE STRENGTH AND YIELD STRENGTH

39

CRACK PROPAGATION PARAMETERS β & k

1. BASED UPON EXPERIMENTS PERFORMED BY TIFFANY ET AL ON 5 Al 2.5Sn ELI TITANIUM PLATE AT ROOM TEMP, -320°F AND -423°F
2. USING $\beta = 0.5$ AND $k = 2 \times \text{UTS}$ RESULTS IN A LOWER BOUND K_{II}/K_{IC} VS N CURVE FOR ALL TIFFANY DATA POINTS
3. THEREFORE $\beta = 0.5$ AND $k = 2 \times \text{UTS}$ WERE USED TO PREDICT CRACK PROPAGATION IN TPA ROTORS
4. VERIFICATION OF CRACK PROPAGATION CHARACTERISTICS AND STATISTICAL DATA TO BE SUPPLIED BY MATERIAL TEST PLAN M-4, LINE 2 (K_{II})

B10

TIFFANY (BOEING) DATA - LOW CYCLE FATIGUE TITANIUM 5Al 2.5Sn ELI (PLATE)

"BEST FIT" FOR TIFFANY DATA (LINEAR REGRESSION ANALYSIS)				
TEMP, °R	β	k	$D_s(\beta)$	$D_s(k)$
R.T.	.210	168,000	.144	88,800
-320	.334	634,000	.127	361,000
-423	.500	2 x UTS

$$N_f = \frac{2 \ln \left(\frac{K_{IC}}{K_{II}} \right)}{\left(\frac{\Delta \sigma}{k} \right)^{1/\beta} \left[\frac{1}{\cos \left(\frac{\pi \Delta \sigma}{4T} \right)} - 1 \right]}$$

B11

SUMMARY OF FRACTURE MECHANICS DATA AND SAFETY MARGINS FOR TPA ROTORS

	IMPELLER 1ST STAGE	IMPELLER 2ND STAGE	TURBINE ROTOR 1ST STAGE	TURBINE ROTOR 2ND STAGE
TEMPERATURE, °F	-423	-423	-160	-160
INITIAL FLAW SIZE (a_i)	.024	.024	.024	.024
a/2C RATIO	0.5	0.5	0.5	0.5
CRITICAL STRESS INTEN.,, $\text{ksi}\sqrt{\text{in}}$	44.9	44.9	33	33
ULTIMATE TENSILE STR, (T)	199,000	199,000	147,000	147,000
YIELD STRENGTH, PSI	173,000	173,000	134,000	134,000
β	0.5	0.5	0.5	0.5
$k = 2 \times \text{UTS}$	398,000	398,000	294,000	294,000
STRESS CYCLES, N	60	60	60	60
STRESS RANGE, $\Delta\sigma$ PSI	56,746	43,703	57,450	61,222
FRACTURE STRESS, σ_c PSI	158,000	158,000	120,000	120,000
FRACTURE MECHANICS BURST MARGIN OF SAFETY	+ 1.23	+ 1.89	+ 0.67	+ 0.57

B12

1-

BLADE FATIGUE FRACTURE ANALYSIS

ALL BLADES CONTAIN UNDETECTABLE FLAWS

THE BLADES ARE ASSUMED TO HAVE UNDETECTABLE FLAWS TO THE SAME PROBABILITY LEVEL AS THOSE EXISTENT IN STANDARD FATIGUE SPECIMENS WITH REGARD TO SIZE, DISTRIBUTION AND ORIENTATION

IN HIGH CYCLE FATIGUE A MAJOR PART OF THE FATIGUE LIFE IS ABSORBED IN CRACK NUCLEATION; FRACTURE MECHANICS CANNOT AS YET PREDICT NUCLEATION AND PROPAGATION IN HIGH CYCLE FATIGUE

THEREFORE, CONVENTIONAL FATIGUE ANALYSIS FOR BLADES IS THE CORRECT APPROACH

MATERIALS PROGRAM M-4, LINE 1 WILL PROVIDE FATIGUE STRENGTH DATA AT 40°R USING STANDARD FATIGUE SPECIMENS. MATERIALS PROGRAM M-4, LINE 17 WILL PROVIDE FATIGUE STRENGTH DATA IN ROOM TEMP GASEOUS H₂ AND AIR FOR TURBINE BLADES

BLADE HIGH CYCLE FATIGUE
(MODIFIED GOODMAN DIAGRAM)

314

NOTCH VS UNNOTCHED SPECIMEN

MATERIAL

- 5Al-2.5Sn-TITANIUM ALLOY
- - - 301 STAINLESS STEEL
- 2014-T6 ALUMINUM
- - - INCONEL 718

MATERIALS DATA AND MATURITY STATUS

LINE	COMPONENT	FORM	PROPERTY	TEST CONDITIONS		FACILITY	SPEC NO. (GOAL)	LOTS	CY 71 CY 72																			
				TEMP, ^o R	ATMOS.				M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	
1	TPA ROTOR	F/DIE F	FATIGUE	40	LH ₂	0	100 (M)	2	D		t		r		(f)										(t)			A
2	TPA ROTOR	DIE F	K _{II}	540 300 40	GH ₂ LH ₂	0	144 (D)	4	D				m		f										t		r	A
3	TPA ROTOR	F	K _{IC}	40	LH ₂	A	8 (D)	1	D																			
5	TPA ROTOR	F	PHYSICAL PROPERTIES (ν , E)	540	AIR	A	4 (M) (2 PANCAKE, 2 DIE F)	2	D					m		f			t									C
16	ROTOR	DIE F	K _{IC}	540	AIR	A	35 (D)	2	D					m			f		t									A
17	BLADE	DIE F	HIGH CYCLE FATIGUE	540	AIR GH ₂	0	60 (D)	2	D					m					t									A

* COMPLETED

1316

+

BLADE FATIGUE TESTING REVERSED BENDING

317

BLADE FATIGUE TESTING

COMBINED STEADY STATE - ALTERNATING STRESSES

LOT/HEAT AND PART STRENGTH CONTROL APPROACH

MINIMIZE HEAT-TO-HEAT AND WITHIN-HEAT VARIABILITY BY PROVIDING
INDIVIDUAL MATERIAL CONTROL SPECS FOR SPONGE, BILLET AND FORGING

MAINTAIN TIGHT CONTROL OF FORGING CHEMICAL ANALYSIS

MINIMUM ACCEPTANCE FORGING STRENGTH IS 100,000 PSI AT ROOM TEMP

MAXIMUM ACCEPTABLE FLAW SIZE IN FORGING IS 1/64

MINIMUM ACCEPTANCE K_{IC} FOR FORGING IS 26 ksi $\sqrt{\text{in}}$ AT ROOM TEMP

ACCEPTANCE BASED ON TEST BARS FROM EVERY FORGING RECEIVED

FRACTURE MECHANICS METHODS ARE APPLICABLE
TO DISCS

FRACTURE MECHANICS METHODS FOR HIGH CYCLE
FATIGUE ARE BEYOND THE STATE-OF-THE-ART

CONVENTIONAL FATIGUE ANALYSIS IS THE CORRECT
APPROACH FOR BLADES

STRESS ANALYSIS SUMMARY

PUMP OPERATING LIMITS

* PUMP INLET CONDITIONS:
 $T = 40.25^{\circ}\text{R}$, $P_T = 26 \text{ PSI}$

TPA INTERFACE LOAD SUMMARY

INTERFACE	X AXIS		V AXIS		W AXIS	
	M_x	F_x	M_v	F_v	M_w	F_w
PUMP INLET	23	910	426	0	98	48
PUMP EXHAUST	71000	1380	4550	166	35250	4800
TURBINE INLET	39740	404	4240	1661	3088	8068
TURBINE EXHAUST	11817	1659	8660	3438	23520	2687
TOTAL DEFLECTION	0.0004 RADIALLY (PUMP NLET TO TURBINE EXIT)

HOUSING	M.S. γ^*
PUMP INLET	-
PUMP DISCHARGE	0.20
TURBINE INLET	1.4
TURBINE EXHAUST	0.70

* NORMAL MODE (INCLUDING THERMAL & PRESSURE)

83

MINIMUM MARGIN OF SAFETY FOR .9₈0 RELIABILITY

MS BASIS	*MINIMUM MS REQUIRED
GENERAL PRIMARY (YIELD STRENGTH)	.10
LOCAL PRIMARY (YIELD STRENGTH)	.30

* STRESS VARIANCE $\leq$ 10%
STRENGTH VARIANCE $\leq$ 5%

COMPONENT MARGINS OF SAFETY
FRACTURE MECHANICS ANALYSIS
TPA ROTOR DISCS
TITANIUM

COMPONENT	ANAL LEVEL	M.S. NORMAL MODE	M.S. MALF. MODE	M.S. MECH. DESIGN POINT	σ MAX MALF. MODE	LAYOUT
INDUCER	P	3.67	3.06	2.28	31,172	B
FIRST IMPELLER	P	2.20	1.52	1.23	50,192	B
SECOND IMPELLER	P	3.20	2.64	1.89	34,769	A
FIRST TURBINE ROTOR	P	1.44	.99	.67	48,240	B
SECOND TURBINE ROTOR	P	1.26	.93	.57	49,868	B

COMPONENT MARGINS OF SAFETY

TPA ROTOR DISC BURST

COMPONENT	MATERIAL	ANA. LEVEL	M.S. NORM. MODE	M.S. MALF. MODE	① M.S. MECH DESIGN POINT	② M.S. MECH DESIGN POINT	* σ_{MAX} MALF. MODE (KSI)	LAYOUT
INDUCER	Ti	P	1.27	.98	.77	.32	31.2	B
	A-286	P	1.11	.97	.78	.40	32.0	A
FIRST IMPELLER	Ti	P	.88	.73	.58	.18	50.2	B
	A-286	P	.64	.54	.39	.14	61.3	A
SECOND IMPELLER	Ti	P	1.16	.99	.78	.34	34.8	A
	A-286	P	.62	.50	.35	.028	63.0	A
FIRST TURBINE ROTOR	Ti	P	.56	.41	.32	.23	48.2	B
	A-286	P				.165		
SECOND TURBINE ROTOR	Ti	P	.42	.30	.18	.06	49.9	B
	A-286	P				.175		

① 30,000 RPM, OPERATING CONDITIONS & MAXIMUM THERMAL GRADIENTS

② 30,000 RPM, ROOM TEMP - HIGH SPEED BALANCE

86

SECOND ROTOR TANGENTIAL ISOSTRESS MAP - MALFUNCTION MODE

SPEED - 30,000 RPM
THERMAL - STEADY STATE
MATERIAL - TITANIUM

ISOSTRESS PLOT - MAXIMUM THERMAL GRADIENT
SECOND STAGE IMPELLER

(12 SECONDS AFTER PSOV OPENS.)

COMPONENT MARGINS OF SAFETY

TPA ROTOR SHROUDS

COMPONENT	MATERIAL	ANA. LEVEL	M.S. NORM. MODE	M.S. MALF. MODE	1 M.S. MECH DESIGN POINT	2 M.S. MECH DESIGN POINT	σ MAX MALF. MODE (KSI)	LAYOUT
FIRST IMPELLER	Ti	P	1.34	1.06	.67	.003	71.4	B
	A-286	P	+.11	-.02	-.21	-.51	185**	B
SECOND IMPELLER	Ti	P	1.36	1.07	.68	.003	71.1	B
	A-286	P	+.12	-.02	-.21	-.51	186**	B
FIRST ROTOR	Ti	P	2.10	1.64	1.14	.57	43.8	B
	A-286	P	.32	.13	-.09	-.20	79.3	
SECOND ROTOR	Ti	P	1.83	1.41	.96	.42	48.6	B
	A-286	P	.20	.025	-.18	-.28	88.0	

1 30,000 RPM, TPA OPERATING CONDITIONS

2 30,000 RPM - ROOM TEMP - HIGH SPEED BALANCE

** STRESS INTENSITY PER SNPO-C-1

COMPONENT MARGINS OF SAFETY

TPA HOUSINGS *

COMPONENT		MATERIAL	ANA. LEVEL	M.S. NORM. MODE	M.S. MALF. MODE	M.S. MECH. DESIGN POINT	1 M.S. PROOF COND.	1 σ MAX PROOF COND. (KSI)	LAYOUT
INDUCER HOUSING		310	P	IN PROCESS					B
PUMP HOUSING	CROSSOVER VANES	310	P	2.4	2.4	1.8	.9	40	B
	EXIT GUIDE VANES	310	P	1.0	1.2	1.0	.5	119	B
	VOLUTE	310	E	0.2	0.2	0.2	.2	61	B
AFT BEARING HOUSING		718	P	5 +	5 +	5 +	5 +	21	B
TURBINE INLET HOUSING	INLET TORUS	310	E	1.4	1.4	1.4	1.4	16	B
	INLET GUIDE VANES	310	P	.66	.7	.6	.4	71	B
	EXIT GUIDE VANES	310	P	.8	1.1	.7	.6	27	B
EXHAUST MANIFOLD		310	E	.7					B
PUMP TIE BOLT		A-286	P	.33			.33	128	A
TURBINE TIE BOLT		A-286	P	.33			.33	128	A

1 MAX STRESS INTENSITY PER SNPO-C-1

* STEADY STATE THERMAL

TITANIUM ENDURANCE LIMIT

MODIFIED GOODMAN DIAGRAM

INDUCER BLADES

MATERIAL - TITANIUM

● NORMAL MODE, M.S. = 0.28

▲ MALFUNCTION MODE, M.S. = 0.81

■ MECHANICAL DESIGN, M.S. = 0.56

AEROJET NUCLEAR SYSTEMS COMPANY

92

MODIFIED GOODMAN DIAGRAM FIRST STAGE TURBINE ROTOR BLADES

MATERIAL - TITANIUM

- NORMAL MODE, M.S. = 1.48
- ▲ MALFUNCTION MODE, M.S. = 1.66
- MECHANICAL DESIGN, M.S. = 1.42

13

MODIFIED GOODMAN DIAGRAM

SECOND STAGE TURBINE ROTOR BLADES

MATERIAL - TITANIUM

● NORMAL MODE, M.S. = 2.21

▲ MALFUNCTION MODE, M.S. = 1.82

■ MECHANICAL DESIGN, M.S. = 1.35

AEROJET NUCLEAR SYSTEMS COMPANY

14

FATIGUE STRENGTH

A-286

95

MODIFIED GOODMAN DIAGRAM
1ST STAGE STATOR BLADES

	<u>MODE</u>	<u>M.S.</u>
○	NORMAL	3.67
△	MALFUNCTION	2.82
□	MECH DESIGN	1.78

MODIFIED GOODMAN DIAGRAM
2ND STAGE STATOR BLADES

	MODE	M.S.
●	NORMAL	2.95
▲	MALFUNCTION	2.50
■	MECH DESIGN	1.94

MATERIAL: A-286

BLADE MATERIAL QUALIFICATION TEST SUMMARY

9b

INDUCER BLADE MATERIAL QUALIFICATION TEST SUMMARY

FORGING FLEXURAL SPECIMENS

99

COMPONENT MARGINS OF SAFETY TPA ROTOR BLADES

COMPONENT	MATERIAL	ANA. LEVEL	M.S. NORM. MODE	M.S. MALF. MODE	① M.S. MECH DESIGN POINT	② M.S. MECH DESIGN POINT	* σ MAX MALF. MODE (KSI)	LAYOUT
INDUCER	Ti	E	.28	.81	.56	8.44	21.3 / 18.9	A
	A-286	E	.37	.91	.64	3.60	23.0 / 18.9	A
FIRST TURBINE ROTOR	Ti	E	1.48	1.66	1.42	5.08	20.6 / 5.6	A
	A-286	E	.96	.69	.41	2.09	39.2 / 5.6	A
SECOND TURBINE ROTOR	Ti	E	2.21	1.82	1.35	5.03	23.0 / 4.4	B
	A-286	E	1.36	1.05	.69	2.07	33.1 / 4.4	B
FIRST STATOR	A-286	E	3.67	2.82	1.78		17.4 / 2.3	A
SECOND STATOR	A-286	E	2.95	2.50	1.94		14.8 / 5.0	A

* σ ALT = 100% σ GB FOR INDUCER BLADES (PEAK TO PEAK)
 = 30% σ GB FOR TURBINE BLADES (PEAK TO PEAK)

① 30,000 RPM, OPERATING CONDITIONS

② 30,000 RPM, ROOM TEMP - HIGH SPEED BALANCE

BLADE FREQUENCY/OPERATING CRITERIA

NO FUNDAMENTAL IN TRANSIENT OR STEADY STATE OPERATING RANGE

(0 —→ 30,000 RPM)

NO HARMONICS IN STEADY STATE OPERATING RANGE

(19,000 —→ 30,000 RPM)

AEROJET NUCLEAR SYSTEMS COMPANY

10¹

NORMALIZED RESPONSE FOR SINGLE ISOLATED BLADE
INITIAL SECOND STAGE STATOR BLADE
TRAILING EDGE FLAPPING MODE

102

FIRST AND SECOND STAGE STATOR CAMPBELL DIAGRAM

103

FIRST AND SECOND STAGE ROTOR CAMPBELL DIAGRAM

TURBINE BLADING FREQUENCY SUMMARY

	1ST STAGE		2ND STAGE	
	STATOR	ROTOR	STATOR	ROTOR
INITIAL BLADING				
MEASURED	27,000		23,700	-
PREDICTED (NASTRAN)	25,000	IN PROCESS	23,200	22,900
MODIFIED BLADING				
PREDICTED (NASTRAN)	30,000	24,900	28,800	-
REQUIRED RANGE	27,000-30,400	22,200-25,000	27,000-30,400	22,200-25,000

ALL FREQUENCIES SHOWN ARE PEAK FREQUENCIES

STRUCTURAL ANALYSIS SUMMARY

AFT BEARING HOUSING ISOSTRESS MAP (TENSION)

MATERIAL - 718

CONDITIONS - NORMAL MODE

106

STRUCTURAL SUMMARY

PRELIMINARY ANALYSIS COMPLETED FOR MAJOR COMPONENTS

LARGE ROTOR DISCS MARGINS OF SAFETY BASED ON FRACTURE
MECHANICS

POSITIVE MARGINS OF SAFETY ON ALL MAJOR COMPONENTS
FOR PRIME CONFIGURATION

ENDURANCE LIMIT OF BLADING TO BE ESTABLISHED

TURBINE STATOR BLADING PROFILES BEING REDESIGNED TO
RAISE FREQUENCY

LOW STRESS LEVEL IN 718 AFT BEARING HOUSING

RELIABILITY DESIGN SUMMARY

105

TURBOPUMP FAILURE MODES

FAILURE TO START

LOW PERFORMANCE

PREMATURE STOP

THE ALLOCATED TURBOPUMP RELIABILITY IS .999831

AEROJET NUCLEAR SYSTEMS COMPANY

RELIABILITY DESIGN SUMMARY - INFORMATION IDENTIFIED IN FMA'S

MAJOR MECHANISMS OF FAILURE TO START MODE

LOSS OF CLEARANCE

INSUFFICIENT TORQUE MARGIN FOR STARTING

INITIAL FMA COMPLETED; STEPS 1 THROUGH 5

AEROJET NUCLEAR SYSTEMS COMPANY

MAJOR MECHANISMS OF LOW PERFORMANCE MODE

PUMP HEAD RISE

PUMP EFFICIENCY

TURBINE FLOW RATE

TURBINE EFFICIENCY

◦ FMA STEPS 1 THROUGH 5 IN PROCESS

AEROJET NUCLEAR SYSTEMS COMPANY

112

MAJOR MECHANISMS OF PREMATURE STOP MODE

- * FAILURE TO MAINTAIN ROTOR/HOUSING CLEARANCES
- * FAILURE TO MAINTAIN ROTOR ASSEMBLY STACK-UP
- FAILURE TO MAINTAIN STRUCTURAL DEFLECTIONS WITHIN LIMITS
- FAILURE TO MAINTAIN INTERNAL PRESSURE DISTRIBUTIONS
- FAILURE TO LIMIT EXCESSIVE TPA ORIGINATING FLUID OR MECH DYNAMIC LOADS
- ** FAILURE OF BLADING TO HAVE ADEQUATE FATIGUE CAPABILITY
- ** FAILURE TO MAINTAIN ROTOR STRUCTURAL INTEGRITY FOR SPEED RANGE
- FAILURE TO CONTAIN FLOWS AND PRESSURE
- * FAILURE OF COUPLINGS TO TRANSMIT TORQUE
- * FAILURE OF INSTRUMENTATION TO PROVIDE TREND AND DIAGNOSTIC DATA
- * FAILURE TO PROVIDE ADEQUATE BEARING COOLANT
- * FAILURE TO MAINTAIN TPA MOUNTING POSITION
- * FAILURE TO PROVIDE RADIAL ROTOR LOAD SUPPORT
- * FAILURE TO PROVIDE AXIAL ROTOR LOAD SUPPORT

- * FMA, STEPS 1 THROUGH 5 COMPLETE
- ** IN PROCESS

PROBABILISTIC RELIABILITY MODELING (IN PROCESS)

INTERNAL FLOW DISTRIBUTION
(INCLUDES THRUST BALANCER POSITION)

BLADE FATIGUE

TPA PERFORMANCE

BEARING LIFE

LABYRINTH CLEARANCE

DISC BURST

RADIAL ROTOR BEARING LOADING

114

BEARING WEAR AS BALL DIAMETER VARIATION VS TIME

RELIABILITY DETERMINATION BASED ON WEAR

- SPEED = 27,000 RPM
- LH₂ ENVIRONMENT

$$J = VBF - BV$$

$$\sqrt{D^2_{VBF} + D^2_{BV}}$$

AEROJET NUCLEAR SYSTEMS COMPANY

PREDICTED BALL BEARING RELIABILITY BASED ON FATIGUE

- SPEED = 27,000 RPM
- TALLIAN MODIFICATION OF WEIBULL DISTRIBUTION
- OIL FATIGUE LIFE/LOAD RELATIONSHIPS ASSUMED

DISC BURST MODELLING APPROACH

PURPOSE: TO ESTABLISH THE RELIABILITY OF 2ND STAGE TURBINE ROTOR DISC
RELATIVE TO ITS BURST SPEED

ASSUMPTION: DUCTILE ANALYSIS IS GOVERNING CRITERIA

STRESS CONSIDERATIONS *	STRENGTH CONSIDERATIONS
GEOMETRY SPEED LOADING	ULTIMATE STRENGTH YIELD STRENGTH ELONGATION

* AVG & MAX TANGENTIAL STRESS

LABYRINTH CLEARANCE MODE

PURPOSE: TO ASSESS THE PROBABILITY OF A LABYRINTH CLEARANCE GOING TO ZERO

1ST STAGE IMPELLER SHROUD LABYRINTH

* INCREASING RADIAL CLEARANCE TO $.008 \left(\begin{smallmatrix} + .001 \\ - .001 \end{smallmatrix} \text{ TOLERANCE} \right)$ WILL INCREASE "R" VALUE TO $.9_{13}$

LOSS OF LABYRINTH CLEARANCE

RELIABILITY SUMMARY

LOCATION	CLEARANCE *	RELIABILITY *
1ST STAGE IMPELLER SHROUD	.008/.006	.9 ₈ ⁶⁷
AFT PUMP END BEARING	.005/.003	.9 ₂ ⁷
2ND STAGE TURBINE ROTOR	.012/.010	.9 ₁₅
2ND STAGE TURBINE STATOR	.008/.006	.9 ₁₁ ⁶³

* STEADY STATE

RELIABILITY (LOSS OF CLEARANCE) & FLOW RATE VS RADIAL CLEARANCE

AFT PUMP END BEARING LABYRINTH

STEADY STATE, NORMAL MODE

120

LOSS OF THRUST BALANCER CLEARANCE

RELIABILITY SUMMARY

LOCATION	CLEARANCE *	RELIABILITY *
IMPELLER O.D. ORIFICE	.0075	.9 ₈ ⁷⁵
IMPELLER HUB ORIFICE	.0125	>.9 ₁₅

* STEADY STATE

TPA BLADING FATIGUE MODELLING APPROACH

PURPOSE: TO ASSURE THAT THE FATIGUE LIFE OF ALL BLADING, WITHIN THE TPA, WILL MEET OR SURPASS THE DUTY CYCLE REQUIREMENTS

STRESS INFLUENCES

OPERATING SPEED
CENTRIFUGAL STRESS
BENDING STRESS

AERODYNAMIC EFFECTS
GAS BENDING STRESS
GAS OSCILLATING STRESS

PROXIMITY TO RESONANCE
DYNAMIC LOAD AMPLIFICATION

VERIFICATION - MEASURE STRESS LEVELS
DURING COMPONENT TESTING

MATERIAL STRENGTH INFLUENCE

LOW CYCLE
STRAIN
STRAIN HARDENING EXPONENT

HIGH CYCLE
ALTERNATING STRESS LEVEL
NUMBER OF CYCLES

ENVIRONMENT
GEOMETRY
FABRICATION TECHNIQUES

VERIFICATION - BLADE TESTING AND QC
DEVELOPMENT

* ALLOWS FOR DATA POPULATION

12

RELIABILITY EFFORT BY DDR

INITIAL FMA'S WILL BE UPDATED

FIRST ITERATION PROBABILISTIC MODELS WILL BE DONE ON THE FOLLOWING:

INDUCER - CENTRIFUGAL, BENDING AND FATIGUE

IMPELLER

BLADING - CENTRIFUGAL, BENDING AND FATIGUE

SHROUD - BURST

DISC - BURST

TURBINE ROTORS

BLADING - CENTRIFUGAL, POWER BENDING AND FATIGUE

SHROUD - BURST

DISC - BURST

TURBINE STATORS - POWER BENDING AND FATIGUE

TIE BOLTS - PRELOAD RETENTION

ROTOR CRITICAL CLEARANCES - PRESSURE DISTRIBUTION AND
DIMENSIONAL VARIATION

AEROJET NUCLEAR SYSTEMS COMPANY

MECHANISM RELIABILITY SUMMARY

PART	MECHANISM	* COMPUTED R FOR MECHANISM	** ALLOCATED R
FIRST IMPELLER	LOSS OF SHROUD LABYRINTH CLEARANCE	.9 ₈ ⁶⁷	.9 ₆ ¹³
BEARING LABYRINTH	LOSS OF CLEARANCE	.9 ₂ ⁷	.9 ₆ ¹²
SECOND ROTOR	LOSS OF SHROUD LABYRINTH CLEARANCE	.9 ₁₅	.9 ₅ ⁶⁹
SECOND STATOR	LOSS OF LABYRINTH CLEARANCE	.9 ₁₁ ⁶³	.9 ₅ ⁷⁸
THRUST BALANCER	O.D. LAND RUB	.9 ₈ ⁷⁵	.9 ₅ ⁷²
THRUST BALANCE	HUB LAND RUB	.9 ₁₅	.9 ₅ ⁷²
INDUCER	LOSS OF BLADE TIP CLEARANCE	.9 ₁₅	.9 ₅ ⁷²
FIRST ROTOR	BLADE FATIGUE	.9 ₁₀ ⁴	.9 ₅ ⁷⁶
FIRST STATOR	BLADE FATIGUE	.9 ₈ ²⁵	.9 ₅ ⁸¹

* NORMAL MODE, STEADY STATE

** ALLOCATED R FOR PREMATURE STOP FAILURE MODE

RELIABILITY DESIGN SUMMARY

THE FAILURE MODE ANALYSIS FOR "FAILURE TO START" IS COMPLETE

THE FAILURE MODE ANALYSIS FOR "LOW PERFORMANCE" IS IN PROCESS

FAILURE MODE ANALYSIS FOR ELEVEN OF THE FOURTEEN MAJOR MECHANISMS
OF THE "PREMATURE STOP" FAILURE MODE ARE COMPLETE

WORK HAS BEEN INITIATED ON SEVEN PROBABILISTIC MODELS

AEROJET NUCLEAR SYSTEMS COMPANY

SUBCOMPONENT DEVELOPMENT PROGRAMS SUMMARY

12

MAJOR TPA DEVELOPMENT RISKS

PERFORMANCE ADEQUACY

ROTOR DISC MATERIAL ADEQUACY

BLADING STRUCTURAL ADEQUACY

BEARING ADEQUACY

TURBOPUMP EXTERNAL LOADING

ROTOR ASSEMBLY ADEQUACY

ENGINE/TPA CHILLDOWN

TPA SUBCOMPONENT DEVELOPMENT

RISKS	PROGRAMS
PERFORMANCE ADEQUACY	MANIFOLD AIR TESTS PUMP AIR TESTS LH ₂ TESTS TURBINE AIR TESTS
ROTOR DISC MATERIAL ADEQUACY	ROTOR BURST TESTS IMPELLER PHOTOELASTIC TESTS MATERIALS TESTS
BLADING STRUCTURAL ADEQUACY	TURBINE BLADE FATIGUE TESTS INDUCER BLADE FATIGUE TESTS BLADE VIBRATION TESTS (HOLOGRAPHY) STRAIN GAGED TURBINE
BEARINGS ADEQUACY	LH ₂ BEARING TESTING TURBOPUMP BEARING LOAD DETERMINATION DYNAMIC SPRING RATE MEASUREMENTS HIGH SPEED BALANCE SHAFT DYNAMICS MEASUREMENTS

TPA SUBCOMPONENT DEVELOPMENT

RISKS

TURBOPUMP EXTERNAL LOADING
ROTOR ASSEMBLY ADEQUACY
ENGINE/TPA CHILLDOWN

PROGRAMS

TURBINE INLET STRUCTURAL TESTS SINGLE TPA TESTS
ROTOR JOINT FRICTION TESTS HIGH SPEED BALANCE TIE BOLT TESTS
HEAT TRANSFER MODEL OF TPA LH ₂ SINGLE STAGE PUMP TESTS TPA TESTS

12/

PERFORMANCE ADEQUACY

PROBLEM:

UNCONFIRMED TPA PERFORMANCE

SOLUTION APPROACH: DATA PRIOR TO DDR

PUMP AIR TEST DATA

TURBINE MANIFOLD AIR TEST DATA

FIRST STAGE LH₂ SUCTION PERFORMANCE DATA

BLADING VIBRATION DATA

AEROJET NUCLEAR SYSTEMS COMPANY

13

SUBCOMPONENT DEVELOPMENT PROGRAM

PUMP AIR TEST PROGRAM

OBJECTIVES

- VERIFY PUMP PREDICTED HYDRODYNAMIC DESIGN
(EXCLUSIVE OF SUCTION AND BALANCE PISTON PERFORMANCE)
- CONFIRM RADIAL LOAD PREDICTION
- VERIFY PREDICTED PRESSURE DISTRIBUTIONS FOR AXIAL THRUST
CORRELATIONS
- VERIFY FABRICATION TECHNIQUES AND QUALIFY TOOLING

STATUS

- HARDWARE FABRICATION BEING COMPLETED

TEST SCHEDULE

- APRIL 1971

PLANNED TEST DATA

- HEAD-FLOW CHARACTERISTICS
- STALL MARGIN DEFINITION
- EFFICIENCY AND LOSS COEFFICIENT EVALUATION
- AXIAL AND PRESSURE DISTRIBUTIONS

TEST VARIABLES

- SECOND STAGE DIFFUSER VANE GEOMETRY
- SECOND STAGE INLET GUIDE VANE GEOMETRY
- SIMULATED BALANCE PISTON FLOW
- FIRST STAGE IMPELLER BACKVANES
- IMPELLER VANE TRAILING EDGE GEOMETRY

AEROJET NUCLEAR SYSTEMS COMPANY

13

SUBCOMPONENT DEVELOPMENT PROGRAMS

TURBINE AIR TEST (LeRC)

OBJECTIVES

VERIFY TURBINE BLADING PREDICTED PERFORMANCE
VERIFY TURBINE PREDICTED PRESSURE DISTRIBUTION
FOR AXIAL THRUST CORRELATIONS

STATUS

PROGRAM BEING COORDINATED WITH LeRC

TEST SCHEDULED

JANUARY 1972

AEROJET NUCLEAR SYSTEMS COMPANY

SUBCOMPONENT DEVELOPMENT PROGRAMS

TURBINE MANIFOLDS/NOZZLES AIR TESTS

OBJECTIVES

VERIFY PREDICTED PRESSURE LOSS

ESTABLISH VELOCITY/PRESSURE DISTRIBUTION

VERIFY NOZZLE DISCHARGE ANGLE

RESULTS TO DATE

PART	PRESSURE LOSS, PSI	
	(1) PREDICTED	(2) MEASURED
INLET MANIFOLD	4.5	3.6
FIRST STATOR	11.0	6.9
EXHAUST MANIFOLD (WITHOUT VANES-DIFFUSER CANTED 5°)	6.6	4.1
NOZZLE DISCHARGE ANGLE (β_2 MEAN)	20° AVE	20.4° AVE

PROPOSED FURTHER ACTION

COMPLETE VELOCITY/PRESSURE DISTRIBUTION MEASUREMENT

ESTABLISH EFFECT OF INLET VALVE FLOW DISTRIBUTION

(1) MALFUNCTION MODE PREDICTION

(2) BASED ON AIR TEST LOSS COEFFICIENT

AEROJET NUCLEAR SYSTEMS COMPANY

133

TURBINE EXHAUST MANIFOLD PRESSURE - VELOCITY DISTRIBUTION

* MALFUNCTION MODE CONDITIONS
SCALED FROM AIR TEST DATA

* DISCHARGE 400
VELOCITY, 350
FT/SEC 300

134

TURBINE INLET MANIFOLD PRESSURE DISTRIBUTION

* MALFUNCTION MODE CONDITIONS SCALED FROM AIR TEST DATA,
MEASUREMENTS AT FIRST STATOR DISCHARGE

135

SUBCOMPONENT DEVELOPMENT PROGRAMS

LH₂ PUMP TEST PROGRAM

OBJECTIVES

ESTABLISH FIRST STAGE SUCTION PERFORMANCE
VERIFY SECOND STAGE PERFORMANCE
VERIFY THRUST BALANCER OPERABILITY
INVESTIGATE CHILLDOWN CHARACTERISTICS AND
CORRELATE THERMAL MODEL
DEVELOP DIAGNOSTIC INSTRUMENTATION
PRELIMINARY CONTAMINATION EVALUATION

STATUS

HARDWARE BEING DESIGNED AND FABRICATED
FACILITY MODIFICATION IN PROCESS

TEST SCHEDULED

FIRST STAGE - AUGUST 1971
SECOND STAGE - OCTOBER 1971

FIRST STAGE LH₂ PUMP

PLANNED TEST DATA

STAGE HEAD-FLOW CHARACTERISTICS

NON-CAVITATING INDUCER/STAGE PERFORMANCE

CAVITATING INDUCER/STAGE PERFORMANCE

RADIAL LOADS EVALUATION

CHILLDOWN

INSTRUMENTATION EVALUATION

TEST VARIABLES

TWO INDUCERS

INDUCER DIAMETER

AEROJET NUCLEAR SYSTEMS COMPANY

131

SECOND STAGE LH₂ PUMP

PLANNED TEST DATA

STAGE HEAD-FLOW CHARACTERISTICS

RADIAL LOADS EVALUATION

THRUST BALANCER PERFORMANCE

CHILLDOWN

INSTRUMENTATION

PERFORMANCE ADEQUACY

		CONTRACT YEAR			
		1970	1971	1972	1973
SUBCOMPONENT TEST PROGRAMS	PUMP AIR TEST TURBINE MANIFOLD AIR TEST TURBINE AIR TESTS (LeRC) LH ₂ PUMP TESTS
TURBOPUMP PROGRAM	DESIGN SELECT CONCEPT DESIGN DRAWINGS TEST DESIGN SUPPORT FIRST TURBOPUMP SECOND TURBOPUMP
PROGRAM MILESTONES	TURBOPUMP ASSEMBLE DE-1 TURBOPUMP		△		△

ROTOR DISC MATERIAL ADEQUACY

PROBLEM

LARGE VARIANCE AND LIMITED SAMPLE SIZE ON EXISTING FRACTURE MECHANICS DATA (K_I) FOR 5Al 2.5Sn (ELI) TITANIUM

SOLUTION APPROACH

CONFIRM STRESS LEVEL AND DISTRIBUTION BY TEST

MAINTAIN CLOSE CONTROL OVER MATERIAL PROCESSING (SPONGE TO FORGING)

LIMIT DISC STRESS LEVEL AND CONTROL FLAW SIZE

TEST CONTROL SPECIMENS FROM EACH FORGING (TRUNCATION)

FRACTURE MECHANICS DATA ON MATERIAL WITH TIGHT PROCESSING CONTROL TO BE AVAILABLE PRIOR TO DDR (PARTIAL MATRIX)

140

SUBCOMPONENT DEVELOPMENT PROGRAM

IMPELLER PHOTOELASTIC TESTS

OBJECTIVE

VERIFY ANALYTICAL TECHNIQUE FOR PREDICTING IMPELLER BLADING/
SHROUD CENTRIFUGAL STRESS LEVEL AND DISTRIBUTION
PROVIDE DATA FOR RELIABILITY MODEL

STATUS

DETAIL DRAWINGS OF FIRST STAGE IMPELLER AND TEST FIXTURE RELEASED
MACHINING TECHNIQUES HAVE BEEN VERIFIED ON PLASTIC SAMPLE
TEST FACILITY AVAILABLE

TEST SCHEDULED

JULY 1971

AEROJET NUCLEAR SYSTEMS COMPANY

141

SUBCOMPONENT DEVELOPMENT PROGRAM

ROTOR BURST TESTS

OBJECTIVE

VERIFY ADEQUACY OF ROTOR

VERIFY STRUCTURAL MODEL FOR PREDICTING BURST SPEED

PROVIDE DATA FOR UPDATING OF RELIABILITY MODEL

VERIFY FABRICATION TECHNIQUE AND QUALIFY TOOLING

STATUS

DESIGN AND ANALYSIS IN PROCESS

TEST SCHEDULE

TURBINE ROTOR SET - AUGUST 1971

142

SUBCOMPONENT DEVELOPMENT PROGRAM

MATERIAL TESTS

OBJECTIVE

OBTAIN MATERIAL DATA REQUIRED TO ESTABLISH STRUCTURAL
ADEQUACY AND RELIABILITY OF TURBOPUMP COMPONENTS

DEFINE PROCESS CONTROL FOR TITANIUM ROTOR MATERIAL

OBTAIN FRACTURE MECHANICS PROPERTIES ON TITANIUM

STATUS

TITANIUM PROCESS SPECIFICATIONS (SPONGE TO FORGING)
COMPLETED

PROCUREMENT OF TPA FORGING TOOLING IN PROCESS

PROCUREMENT OF TWO TITANIUM MATERIAL HEATS IN PROCESS

TESTING

TITANIUM (KI) - SEPTEMBER - NOVEMBER 1971 - TWO HEATS

MATERIAL TESTS - K_I/K_{IC} SPECIMEN MATRIX

TEST TYPE: CYCLIC AND STEADY STATE STRESS INTENSITY PARAMETER -
USING PRE-CRACKED COMPACT TENSION SPECIMENS

MATERIAL SPECIFICATIONS: ANS-90295, ANS-90296, ANS-90297-CONTROL FROM
SPONGE THROUGH FORGING

TEST CONDITIONS			70°F 100 PSI	-160°F 1200 PSI	-423°F AMBIENT PRESS
VENDOR A	HEAT 1	2ND IMPELLER	5 (1)	5 (1)	5 (1)
		2ND ROTOR	5 (1)	5 (1)	5 (1)
	HEAT 2	2ND IMPELLER	5 (1)	5 (1)	5 (1)
		2ND ROTOR	5 (1)	5 (1)	5 (1)
VENDOR B	HEAT 1	2ND IMPELLER	5 (1)	5 (1)	5 (1)
		2ND ROTOR	5 (1)	5 (1)	5 (1)
	HEAT 2	2ND IMPELLER	5 (1)	5 (1)	5 (1)
		2ND ROTOR	5 (1)	5 (1)	5 (1)

(1) DENOTES SAMPLE REQUIREMENTS FOR K_{IC}
5 DENOTES SAMPLE REQUIREMENTS FOR K_I

ROTOR DISC MATERIAL ADEQUACY

		CONTRACT YEAR			
		1970	1971	1972	1973
ROTOR DISC DEVELOPMENT PROGRAM	SELECT TITANIUM PROCESS CONTROLS FORGINGS FOR SAMPLES DETERMINE PROPERTIES IMPELLER PHOTOELASTIC TESTS DISC BURST TESTS				
TURBOPUMP PROGRAM	DESIGN SELECT CONCEPT DESIGN DRAWINGS TEST DESIGN SUPPORT FIRST TURBOPUMP SECOND TURBOPUMP				
PROGRAM MILESTONES	TURBOPUMP DDR ASSEMBLE DE-1 TURBOPUMP				

103

BLADING STRUCTURAL ADEQUACY

PROBLEM

ENDURANCE LIMIT OF INDUCER, TURBINE ROTOR AND STATOR BLADING UNKNOWN,
CONSIDERING MATERIAL PROPERTIES, GEOMETRY, ENVIRONMENT AND FABRICATION
PROCESSING

BLADING ALTERNATING STRESS LEVEL NOT PREDICTABLE WITH SUFFICIENT
ACCURACY TO MEET RELIABILITY REQUIREMENTS

SOLUTION APPROACH

TEST PROGRAM TO ESTABLISH ACTUAL BLADING ENDURANCE LIMIT CONSIDERING
MATERIAL, GEOMETRY, ENVIRONMENT, AND FABRICATION PROCESSING

CONFIRM BLADING NATURAL FREQUENCIES EXPERIMENTALLY

CONFIRM BLADING ALTERNATING AND STEADY STATE STRESS LEVELS
EXPERIMENTALLY DURING TPA OPERATION (TURBINE ONLY)

DETERMINE DEGRADATION OF INDUCER BLADING LIFE DURING ACTUAL OPERATION

SUBCOMPONENT DEVELOPMENT PROGRAMS

BLADE VIBRATION TESTS

OBJECTIVES

IDENTIFY NATURAL FREQUENCIES OF PUMP AND TURBINE BLADING

DEVELOP & VERIFY ANALYTICAL TECHNIQUES FOR PREDICTING BLADING FREQUENCIES

DEVELOP BLADING WITH FUNDAMENTAL BLADING FREQUENCIES OUTSIDE OF OPERATING RANGE

VERIFY FABRICATION TECHNIQUE AND QUALIFY TOOLING

RESULTS TO DATE

FREQUENCIES IDENTIFIED INSIDE OPERATING RANGE FOR TURBINE STATOR BLADING

FREQUENCIES IDENTIFIED FOR UNSHROUDED SECOND STAGE TURBINE ROTOR BLADING
ARE INSIDE OPERATING RANGE

SHROUDED ROTOR BLADING SELECTED

PROPOSED FURTHER ACTION

STATORS BEING REDESIGNED TO REMOVE TRAILING EDGE MODE FROM OPERATING RANGE

COMPLETE VIBRATION TESTING PROGRAM

AEROJET NUCLEAR SYSTEMS COMPANY

FIRST STAGE TURBINE STATOR VIBRATION TEST RESULTS

◦ TRAILING EDGE FLAPPING MODE

PEAK FREQUENCIES

MEASURED: 27,000 Hz

PREDICTED (NASTRAN): 25,000 Hz

2ND STAGE TURBINE STATOR VIBRATION TEST RESULTS

- PEAK FREQUENCIES

MEASURED: 23,700 Hz

PREDICTED (NASTRAN) 23,000 Hz

SUBCOMPONENT DEVELOPMENT PROGRAMS
VIBRATION TEST RESULTS: 2ND STAGE TURBINE ROTOR UNSHROUDED BLADE

1ST BENDING MODE

MEASURED:
9,750 HZ

* PREDICTED:
8,360 HZ

1ST TORSIONAL MODE

MEASURED:
14,640 HZ

* PREDICTED:
16,994 HZ

TRAILING EDGE FLAPPING MODE (WEAK)

12,230 HZ

1ST FLAPPING MODE (VARIANT NO. 1)

24,040 HZ

* PREDICTED FREQUENCIES BASED ON NASTRAN PROGRAM

AEROJET NUCLEAR SYSTEMS COMPANY

15

TURBINE BLADING FATIGUE TESTS

OBJECTIVES

ESTABLISH BLADING ENDURANCE LIMIT CONSIDERING MATERIAL,
ENVIRONMENT, GEOMETRY AND FABRICATION METHODS

DEVELOP DATA FOR BLADING RELIABILITY ASSESSMENT

STATUS

BLADE TEST METHODS BEING DEFINED

TEST SCHEDULED

OCTOBER 1971

15

SUBCOMPONENT DEVELOPMENT PROGRAM

INDUCER BLADING FATIGUE TESTS

OBJECTIVES

ESTABLISH INDUCER BLADING FATIGUE LIFE

PROVIDE DATA FOR RELIABILITY MODEL

EVALUATE FATIGUE LIFE IMPROVEMENT TECHNIQUES IF REQUIRED

STATUS

INDUCER FABRICATION COMPLETED

TEST SCHEDULE

JUNE 1971

AEROJET NUCLEAR SYSTEMS COMPANY

SUBCOMPONENT DEVELOPMENT PROGRAM

STRAIN GAGED TURBINE BLADING TESTS

OBJECTIVES

ESTABLISH BLADING ALTERNATING AND STEADY STATE
STRESS LEVELS DURING OPERATION

DEVELOP DATA FOR BLADING RELIABILITY ASSESSMENT

STATUS

DESIGN EFFORT TO BE INITIATED EARLY IN CY 1972

TEST SCHEDULE

SOON AS POSSIBLE AFTER TEST OF FIRST TPA

BLADING STRUCTURAL ADEQUACY

		CONTRACT YEAR			
		1970	1971	1972	1973
BLADING TEST PROGRAMS	INDUCER FATIGUE				
	TURBINE BLADING FATIGUE				
	FREQUENCY TESTS				
	STRAIN GAGED TURBINE (AVAILABLE)				
TURBOPUMP PROGRAM	DESIGN				
	SELECT CONCEPT				
	DESIGN				
	DRAWINGS				
	TEST				
	DESIGN SUPPORT				
PROGRAM MILESTONES	FIRST TURBOPUMP				
	SECOND TURBOPUMP				
PROGRAM MILESTONES	TURBOPUMP DDR		△		
	ASSEMBLE DE-1 TURBOPUMP				△

BEARING ADEQUACY

PROBLEM

UNKNOWN LIFE; UNCONFIRMED LOAD MAGNITUDE AND TOLERANCE

SOLUTION APPROACH

DEFINE FAILURE MODES AND ESTABLISH RELIABILITY BY DEVELOPMENT TESTS

ESTABLISH RACE, BALL AND CAGE GEOMETRY, AND CAGE MATERIAL (IRRADIATED AND NONIRRADIATED) IN TESTER

CONFIRM PREDICTED LOADS WITH EARLY TPA TESTING

"QUALIFICATION" OF BEARINGS IN TESTER BASED ON TPA LOADS

SUBCOMPONENT DEVELOPMENT PROGRAMS

BEARING DEVELOPMENT

OBJECTIVES: DEVELOP ANGULAR CONTACT DUPLEX BALL
BEARINGS TO MEET NERVA TURBOPUMP LOAD
REQUIREMENTS AT:

LIFE = 10 HOURS

NUMBER OF STARTS = 60

RELIABILITY = .9₅₇

TYPE OF TESTS: FLUID - LH₂
LOAD/LIFE
CAGE MATERIAL/GEOMETRY

AEROJET NUCLEAR SYSTEMS COMPANY

60MM DUPLEX BALL BEARING TEST RESULTS SUMMARY

(ARMALON RETAINER)

$$DN = 1.8 \times 10^6$$

RADIAL LOAD (SET), LB	AXIAL PRELOAD, LB	DURATION 1ST BUILD, HR	TOTAL ACCUM. DURATION, HR
1000	530	11.15	17.13
2000	640	11.78	23.75
3000	1280	.49	5.17

151

DUPLEX BALL BEARING ARRANGEMENT

65 mm

65MM DUPLEX BALL BEARING TEST RESULTS SUMMARY

$$DN = 1.8 \times 10^6$$

RADIAL LOAD (SET), LB	AXIAL PRELOAD, LB	DURATION 1ST BUILD, HR	TOTAL ACCUM. DURATION, HR	RETAINER MATERIAL
1000	670	11.62	11.62	ARMALON
2000	1170	3.52	3.52	ARMALON
1000	603	.12	.12	PBI/GLASS
250	585	5.20	5.20	ARMALON
250-1000	595	2.09	2.09	PBI/GLASS (MODIFIED)

15/

BEARING SUMMARY

60MM RESULTS

CONFIRMED CONCEPT SELECTION

INDICATED WEAR AS THE MOST SIGNIFICANT FAILURE MECHANISM

65 MM RESULTS

INDICATED OUTER RACE/CARTRIDGE/HOUSING INTERFERENCE

INDICATED RETAINER WEAR MECHANISM

ESTABLISHED PRELIMINARY RETAINER GEOMETRIC DESIGN CRITERIA

INDICATED POSSIBLE BALL WEAR MECHANISMS

A) RETAINER LOADING

B) RACEWAY SURFACE ANOMALIES - GRIND CHECKS/CARBIDE SEGREGATION

ESTABLISHED TENTATIVE RACEWAY NDT METHODS/CRITERIA

160

BEARING DEVELOPMENT SCHEDULE

	1970						1971												1972								
	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S
PRE-PROTOTYPE TESTING (60MM)																											
PROTOTYPE TESTING (65MM)																											
FAILURE MODES DEFINITION																											
INITIAL SPRING RATE DETERMINED																											
RETAINER GEOM OPTIMIZATION																											
CARTRIDGE FIT OPTIMIZATION																											
FACILITY RELOCATION																											
FACILITY CHECKOUT																											
LIFE TESTS (HARDWARE AVAIL.)																											
(3 CANDIDATE RETAINER MATLS)																											
STARTUP TRANSIENT TESTS																											
LIFE TEST (HARDWARE AVAIL.)																											
(SELECTED RETAINER MATL)																											

NUMBERS - DENOTE PLANNED TEST BUILDUP

○- DENOTE ACTUALS

AEROJET NUCLEAR SYSTEMS COMPANY

BEARING ADEQUACY

AEROJET NUCLEAR SYSTEMS COMPANY

162

TURBOPUMP EXTERNAL LOADING

PROBLEM: UNDEFINED LINE/VALVE DYNAMIC LOADS; ASSUMED
STEADY STATE INTERFACE LOADS

SOLUTION APPROACH: UPDATE TPA LOADS ANALYSIS AS
INTERFACE LOADS DATA MATURES

ASSESS IMPACT ON TPA/ENGINE SYSTEM

MODIFY TPA/ENGINE

SUBCOMPONENT DEVELOPMENT PROGRAM

TURBINE INLET MANIFOLD STRUCTURAL TESTS

OBJECTIVES

CALIBRATE HOUSING STRUCTURAL ANALYSIS MODEL
DEVELOP FABRICATION TECHNIQUE AND QUALIFY TOOLING
PROVIDE TEST DATA FOR RELIABILITY ANALYSIS
ESTABLISH PROOF TEST TECHNIQUES AND QUALIFY PROOF
TOOLING
CONFIRM ASSUMED STEADY STATE INTERFACE LOAD
CAPABILITY

STATUS

DESIGN IN PROCESS

TEST SCHEDULE

OCTOBER 1971

SUBCOMPONENT DEVELOPMENT PROGRAM

ROTOR ASSEMBLY ADEQUACY

PROBLEM: CONFIRM ADEQUACY OF ROTOR ASSEMBLY RELATIVE
TO BEARING LOADS AND SHAFT DYNAMICS

SOLUTION APPROACH: HIGH SPEED BALANCE

ROTOR JOINT FRICTION TESTS

TIE BOLT TESTS

DISPLACEMENT INSTRUMENTATION

SUBCOMPONENT DEVELOPMENT PROGRAM

ROTOR JOINT FRICTION TESTS

OBJECTIVES

VERIFY JOINT ASSUMPTIONS USED IN ROTOR TIE BOLT DESIGN

DEVELOP DATA FOR JOINT RELIABILITY ANALYSIS

ESTABLISH FITS AND TIE BOLT PRE-LOAD FOR TURBOPUMP

VERIFY CRITICAL SPEED ANALYSIS (SHAFT ELEMENT EFFECTS)

STATUS

DESIGN INITIATED

TEST SCHEDULED

AUGUST 1971

AEROJET NUCLEAR SYSTEMS COMPANY

166 +

+

JOINT FRICTION TEST SCHEMATIC ARRANGEMENTS

PURPOSE: TO DETERMINE JOINT FRICTION LOAD CHARACTERISTICS USING SIMULATED THERMAL ENVIRONMENTAL

- JOINT FRICTION LOADS DETERMINED BY SHIFTS IN STRAIN MEASUREMENTS
- CONTRIBUTIONS OF THE ELEMENTS DETERMINED BY DIFFERENTIALS BETWEEN STRAIN MEASUREMENTS

167

SUBCOMPONENT DEVELOPMENT PROGRAM

TIE BOLT STRUCTURAL TESTS

OBJECTIVES

VERIFY STRUCTURAL MODEL USED IN ROTOR TIE BOLT ANALYSIS
CONSIDERING GEOMETRY EFFECTS AND ASSEMBLY METHOD

DEVELOP DATA FOR JOINT RELIABILITY ASSESSMENT

CONFIRM ADEQUACY OF SELECTED MATERIAL

STATUS

BOLT ANALYSIS AND DESIGN INITIATED

TEST SCHEDULE

DECEMBER 1971

158 ROTOR ASSEMBLY ADEQUACY

		CONTRACT YEAR			
		1970	1971	1972	1973
ROTOR ASSEMBLY PROGRAMS	HIGH SPEED BALANCE (S/N 1) ROTOR JOINT FRICTION TESTS TIE BOLT TESTS DISPLACEMENT INSTRUMENTATION				
TURBOPUMP PROGRAM	DESIGN SELECT CONCEPT DESIGN DRAWINGS TEST DESIGN SUPPORT FIRST TURBOPUMP SECOND TURBOPUMP				
PROGRAM MILESTONES	TURBOPUMP DDR ASSEMBLE DE-1 TURBOPUMP

AEROJET NUCLEAR SYSTEMS COMPANY

SUMMARY DEVELOPMENT SCHEDULE

10

CONCLUSIONS

ANALYTICAL *

TPA WILL SATISFY PERFORMANCE REQUIREMENTS

ADEQUATE STRUCTURAL MARGINS ON ALL MAJOR
SUBCOMPONENTS

EXPERIMENTAL

BEARING CONCEPT SELECTION CONFIRMED

TURBINE INLET/EXHAUST MANIFOLD SELECTION
CONFIRMED

* BASED ON PRESENT ANALYSIS MATURITY

VALVES AND ACTUATORS

L. D. JOHNSON/E. H. HILL

VALVE/ACTUATOR STATUS REVIEW

STATUS INCLUDING REQUIREMENTS

GENERAL

SPECIFIC COMPONENTS

SUBCOMPONENTS

PLANNED ACTIVITIES THRU SEPT 1972

(BCV) BYPASS CONTROL VALVE

VALVE CONCEPT SUMMARY "E" FLOW SCHEMATIC

UPDATED 1/7/71

VALVE REQUIREMENT SUMMARY

PARAMETER	PSOV	PDKVA	PDKV	PDBV	PDCV	SSBV	SSCV	BBV	BCV	TBV	TDBV	CSOV	CSCV
PRESSURE, PSIA	30	1430	1425	1400	1400	1400	1400	1125	1120	1105	740	30	30
TEMPERATURE, °R	40	60	60	60	60	60	60	300	300	300	270	40	40
FLOW RATE, LB/SEC	46-74	46-74	46-74	32-42	32-42	3-6	3-6	4-15	4-15	42-44	42-45	0	0
FLOW PATH DIA, IN.	9.6	4.9	4.9	4.9	4.9	3.9	3.9	3.9	3.9	7.4	7.4	2.9	2.9
RESPONSE, SEC	5	3	-	3	2	1	6	4	.8	4	4	3	2
					4 Hz				4 Hz	(.05)			
LEAKAGE, SCIM	150	2×10^3	2×10^4	2×10^3	3×10^6	1×10^6	1×10^6	3×10^6	3×10^6	3×10^3	2×10^3	50	180
	230				3300				11,000 $\pm 2^0$	275		230	
LIFE, CYCLES		170	160	270		5100	50,000 $\pm 2^0$	212			275		5100
WEIGHT, LBS	100	50	25	100	100	40	30	130	140	130	130	25	25
RELIABILITY	.9 ₃ 869	.9 ₄ 72	.9 ₄ 81	.9 ₄ 76	.9 ₄ 68	.9 ₄ 46	.9 ₃ 5	.9 ₄ 72	.9 ₄ 44	.9 ₄ 52	.9 ₄ 61	.9 ₄ 61	.9 ₄ 46

NOMINAL PARAMETERS - UPDATED FROM JULY SPECS

OVERALL VALVE STATUS

ACCOMPLISHMENT	VALVE ASSEMBLY											
	PSOV	PDKV/PDKVA	PDBV	PDCV	SSBV	SSCV	BBV	BCV	TBV	TDBV	CSOV	CSCV
CONCEPT LAYOUTS PREPARED	10	7	1	6	7	10	4	8	6	4	5	7
CONCEPT SELECTION COMPLETE	POPPET	FLAPPER	BALL (SSBV)	VISOR	BALL	VISOR	BALL (SSBV)	VISOR	POPPET	POPPET	POPPET	POPPET
MODULE ELEMENT DEFINED		X	X ONE MODULE X		X ONE MODULE X		X ONE MODULE X				X ONE MODULE X	
VALVE/ACTUATOR TORQUE REQTS DETERMINED	X	X	X	X	X	X VALVE ONLY	X	X	X	X	X	X
MAIN SEAL LEAK & LIFE ANALYZED	X	X	X	X	X	X	X	X	X	X	X	X
PRELIM STRESS & THERMAL COMPLETE					X	X			POPPET CLOSURE			
DETAIL DESIGN LAYOUT INITIATED					X	X						
FMA INITIATED					X	X						
DESIGN LOGIC STEP COMPLETED	3	4	2	2	12	9	9	9	9	3	16	16

COMPONENT STATUS AT 2-1-71
(REFERENCED TO PLAN TO COMPONENT DDR)

ACTIVITY	
DETAIL DESIGN PHASE	
1. DETAIL LAYOUT OF SELECTED CONCEPT
2. MAJOR PART SIZING	PDBV, PDCV
3. FLOW PATH CONTOUR	TDBV, PSOV
4. TYPE OF SEAL	PDKV, PDKVA
5. DETAIL FAILURE MODE ANALYSIS
6. SELECT BEARING TYPES
7. DETERMINE VALVE PART FORCES
8. DETERMINE VALVE MOVING ELEMENT INERTIAS
9. DETERMINE VALVE TORQUE PROFILE
10. SIZE MOTOR FOR PRELIMINARY TRANSIENT ANALYSIS	BBV, BCV, TBV, SSCV
11. DETERMINE RATIO AND SIZE GEARS IN TRANSMISSION
12. SELECT PRELIMINARY MATERIALS & LUBRICANTS FOR VALVE AND ACTUATOR COMPONENTS	SSBV
13. DETERMINE INDIVIDUAL GEAR AND BEARING LOADS
14. DETERMINE PRELIMINARY BEARING DESIGN
15. DEFINE POTS, SWITCHES, CLUTCHES, BRAKES & CONNECTORS REQUIRED
16. DETERMINE PRELIMINARY ACTUATOR CONFIGURATION	CSOV, CSCV
17. DETERMINE ACTUATOR MOVING ELEMENT INERTIAS

VALVE ASSEMBLY PART - MATERIAL MATRIX

PART	MATERIAL	CRES 347	CRES 440C	A286	6061-T6	5Al-2.5Sn ELI TITANIUM	CARBURIZED 9310	PHOSPHOR BRONZE	BeCu	COPPER	COPPER-ZINC ALLOY	ELECTROLYZE	GOLD PLATE	LEAD PLATE	M ₀ S ₂	ALNICO V	PBI REINFORCED GRAPHITE FABRIC	VESPEL SP-3	PYRE-ML POLYIMIDE	KAPTON POLYIMIDE FILM	FEURALON AW	FIBERGLASS TYPE E	M-19 SILICON STEEL
1. VALVE BODIES 2. ACTUATOR HOUSINGS 3. VALVING UNITS - SEAT - POPPET - BALL		2 1a 1 1		3 1a 2	1 2	1 2						1a 2											
4. SHUTOFF SEAL 5. VALVE SHAFT & LINKAGE 6. ACTUATOR SHAFT 7. FRICTION PLATES 8. MOUNTING PLATES		2 2		1a 1 2 2		1 1	1	1				1a	1b										
9. CARRIER PLATES 10. GEARS 11. BEARINGS - BALL - ROLLER - GUIDE			1 1	3 2		1	2 1		2								1	1					
12. COMPRESSION SPRINGS 13. BELLEVILLE SPRINGS 14. BELLOWS 15. BOLTS & NUTS 16. STATIC SEALS		1 2 1		1 1	1			1					2	1									
17. LUBRICANTS 18. MOTOR HOUSING 19. MOTOR SHAFT 20. MAGNETIC LAMINATIONS 21. STATOR CONDUCTORS		1 1									1				1								1
22. ROTOR CONDUCTORS 23. INSULATION - VARNISH - FIBERGLASS TAPE - MAGNET WIRE - SLOT LINERS									1	1									1 1			1 2	
- SEPARATORS - HOOK-UP WIRE 24. BEARING RETAINERS 25. MAGNETS																1				1 1	1	2	

NOTE: NUMBERS INDICATE ORDER OF PREFERENCE

AEROJET NUCLEAR SYSTEMS COMPANY

VALVE ASSEMBLY PROBLEM AREAS

PROBLEM AREA	APPLICABILITY	PROBLEM CATEGORY	
		FEASIBILITY (1)	DESIGN SUPPORT (2)
1. SHUTOFF SEAL LIFE VS LEAK	ALL VALVES	●	
2. STATIC SEAL LEAK VS THERMAL CYCLES	ALL VALVES		●
3. BEARING LIFE	ALL VALVES	●	
4. PREDICTED VS ACTUAL ΔP	ALL VALVES		●
5. VALVE/ACTUATOR COUPLING T AND LIFE	ALL VALVES		●
6. PREDICTED VS ACTUAL RESPONSE	ALL EXCEPT SSCV		●
7. GEAR WEAR & LIFE	ALL EXCEPT SSCV	●	
8. PREDICTED VS ACTUAL GEAR EFFICIENCY	ALL EXCEPT SSCV		●
9. BRAKE & SLIP CLUTCH T, WEAR & LIFE	ALL EXCEPT SSCV		●
10. POT & SWITCH RESOLUTION, REPEATABILITY & LIFE	ALL EXCEPT SSCV		●
11. PREDICTED VS ACTUAL VALVE & ACTUATOR T	ALL VALVES	●	
12. EFFECT OF CONTAMINATION	ALL VALVES	●	
13. EFFECT OF SPACE STORAGE	ALL VALVES	●	
14. VALVE/ACTUATOR REMOTE INTERFACE	PSOV, CSOV		●
15. A286 SPRING PERFORMANCE	PSOV, PDKV, CSOV, CSCV, TBV, TDBV, BBV		●
16. CLOSURE/SEAT IMPACT LOADING	PDKV, TBV		●
17. TRANSIENT DYNAMIC CLOSURE STABILITY	PDKV, TBV		●
18. PREDICTED VS ACTUAL MOTOR PERFORMANCE	ALL EXCEPT SSCV		●
19. QUICK RELEASE MECHANISM PERFORMANCE	TBV, BBV		●
20. BALL SCREW PERFORMANCE	TBV, TDBV		●

(1) BASIC DATA REQUIRED TO SUPPORT DDR - ASSUMES NO SIGNIFICANT CHANGE IN REQUIREMENTS

(2) TEST DATA REQUIRED PRIOR TO FIRST ASSEMBLY DEVELOPMENT TEST

AL-111

SIGNIFICANT ACCOMPLISHMENTS

**PREPARED OVER 75 CONCEPT DRAWINGS, 12 REPRESENT
SELECTED CONCEPTS**

**DEMONSTRATED DIGITAL STATIC INVERTER FOR CONSTANT
SLIP AC MOTOR DRIVE**

AMBIENT DEMONSTRATION OF 560:1 CRYOGENIC TRANSMISSION

**ELECTRONIC DEVICE (PMOS-FET) SELECTED FOR RADIATION
HARDENED INVERTER DESIGN**

RADIATION OF AC MOTOR AND POTENTIOMETERS COMPLETED

**ALL VALVE ASSEMBLY DESIGN CONCEPTS SELECTED AND
DETAIL DESIGN INITIATED**

VALVE/ACTUATOR DESIGN & DEVELOPMENT PHILOSOPHY

BEFORE...

AEROJET NUCLEAR SYSTEMS COMPANY

VALVE/ACTUATOR DESIGN & DEVELOPMENT PHILOSOPHY

NOW -
EITHER THIS...

VALVE/ACTUATOR DESIGN & DEVELOPMENT PHILOSOPHY

- OR THIS...

11

TBV (7.5" DIA)	BCV (4" DIA)	OTHER VALVES
ANGLE POPPET TYPE	VISOR TYPE (BALL)	FLAPPER TYPE (PDKV)
NEAR PSOV SIZE (9.5")	NEAR 3,4 & 5" SIZE	-
LINEAR MOTION (BALL SCREW)	ROTARY MOTION	CAM (CSOV), RACK & PINION (PSOV)
NO EXTERNAL ACTUATOR HOUSING	EXTERNAL ACTUATOR HOUSING	-
QUICK RELEASE MECHANISM	-	-
IMPACT & POPPET TYPE SEAL	SLIDING SEAL	-
BALANCED POPPET	AREA-POSITION CUT	-
BINARY ACTUATION	ANALOG ACTUATION	-
EMERGENCY OVERRIDE SIGNAL	-	-
LINEAR POTENTIOMETER	ROTARY POTENTIOMETER	-
LINEAR POPPET GUIDES	ROTARY SHAFT BEARINGS	-
ACTUATOR BRAKE	-	-
GH ₂	GH ₂	LH ₂ (PSOV, CSOV, PDKV, SSCV)
ALUMINUM BODY	ALUMINUM BODY	347 BODY (CSOV)
TITANIUM POPPET	A-286 VISOR	-
~ .15 HP MOTOR	~ 0.3 HP MOTOR	~ 0.5 HP MOTOR (PSOV, PDCV)
-	LOW INERTIA ACTUATOR	-

DESIGN FEATURES RELATED TO VALVE ASSEMBLY PROBLEM AREAS (CONT)

TBV (7.5" DIA)	BCV (4" DIA)	OTHER VALVES
HELICAL & BELLEVILLE SPRINGS	BELLEVILLE SPRINGS	TORSION SPRINGS (PDKV)
750 IN-LB ACTUATOR	750 IN-LB ACTUATOR	1700 IN-LB ACTUATOR (PDKV, PDCV)
		3500 IN-LB ACTUATOR (PSOV)
15 RPM VALVE	25 RPM VALVE	5 RPM VALVE (PDKV, PDBV)
~ 400:1 GEARS	~ 50:1 GEARS	~ 2000:1 GEARS (PSOV)
CONNECTORS	CONNECTORS	-
SWITCHES	SWITCHES	-
RAD HARD ELECTRONICS	RAD HARD ELECTRONICS	-
BINARY CIRCUIT	ANALOG CIRCUIT	-
-	-	SHAFT DAMPER (PDKV)
-	-	LOST MOTION COUPLING (PDKV, PSOV)
-	-	REMOTE ACTUATOR INTERFACE (PSOV)
-	-	LOW LEAK LH ₂ SEAL (PSOV, CSOV)

13

CONCLUSION

SELECT BCV AND TBV FOR CONTINUED LOW LEVEL
PROGRAM TO COVER MAXIMUM NUMBER OF DESIGN
FEATURES RELATED TO VALVE ASSEMBLY
PROBLEM AREAS

14

STATUS OF CONTINUING COMPONENTS

BYPASS CONTROL VALVE (BCV)

TURBINE BLOCK VALVE (TBV)

BCV REQUIREMENTS SUMMARY

3.625 IN. DIA INLET, VISOR VALVE

PARAMETER	REQUIREMENT
INLET PRESSURE, PSIA	1121
INLET TEMPERATURE, °R	276
FLOW RATE, LB/SEC	3.7-29.1
MAXIMUM ΔP, PSID	374
FULL OPEN LOSS COEFFICIENT, K	2.5
INTERNAL LEAKAGE, SCIM	3.4×10^6
LIFE - CYCLES	10,275
RESPONSE, SEC	$\frac{1}{4}$ Hz
RELIABILITY	.9 ₄ ⁴⁴
WEIGHT, LBS	140 TARGET

BCV VALVE ASSEMBLY

BCV ACTUATOR ASSEMBLY

SOLENOID BRAKE

AC INDUCTION MOTOR

OVERALL GEAR
REDUCTION 50:1

OVERLOAD SLIP BRAKE

AEROJET NUCLEAR SYSTEMS COMPANY

16
BCV MODULE SUBASSEMBLY

19

BYPASS CONTROL VALVE (BCV)

SIGNIFICANT ACCOMPLISHMENTS

EIGHT CONCEPT LAYOUTS PREPARED

CONCEPT SELECTION COMPLETE (VISOR)

BCV/BBV MODULE ELEMENT DEFINED

VALVE/ACTUATOR TORQUE REQUIREMENTS DETERMINED

AEROJET NUCLEAR SYSTEMS COMPANY

BCV STRESS ANALYSIS SUMMARY

PART	MATERIAL	ROOM TEMP DESIGN STR, KSI	MAX STRESS, KSI	RELIA- BILITY	CONDITION
VISOR	A-286	80.8	55.0	$.9^{+}_{15}$	374 PSID
DRIVE COUPLING	A-286	80.8	18.0	$.9^{+}_{15}$	330 LBF-IN
VALVE BODY	6061-T6	28.9	24.0	$.9_{12}$	1121 PSIA
SUPPORT PLATE	6061-T6	28.9	25.0	$.9_{11}$	374 PSID
BELLOWS	PHOSPHOR BRONZE 95 Cu, 5 Sn	33.0	20.0	$.9^{+}_{15}$	374 PSID

BCV LEAKAGE VS SEAL LOAD *

AA SURFACE FINISH = 3.5

SPECIFICATION LIMIT 3.4×10^6 SCIM

HYDROGEN LEAKAGE, SCIM

* AT START OF DUTY CYCLE

BCV STEADY STATE LEAKAGE RELIABILITY USING J CURVE

BCV STEADY STATE LEAKAGE HISTOGRAM

- $\sigma = 0.211 \times 10^6$ SCIM
- RELIABILITY BASED ON SPECIFICATION LIMIT OF 3.4×10^6 SCIM MAX
- $R = 0.96$ FOR 1ST CYCLE USING LOG NORMAL DISTRIBUTION

LEAKAGE IS A FUNCTION OF: $P_1, P_2, D, \mu, h, T, A, \lambda$

- MIN LIFE REQ:
10275 CYCLES

SEAL LIFE, CYCLES

BCV LIFE CYCLE VS SEAL LOAD

AEROJET NUCLEAR SYSTEMS COMPANY

12/

BCV CYCLE LIFE HISTOGRAM

RELIABILITY BASED ON
SPECIFICATION LIMIT OF
10275 CYCLES IS
 $R = 0.9_{15}$ + USING LOG
NORMAL DISTRIBUTION

% RANDOM SOLUTION

BCV OPENING TORQUE VS POSITION

PART FAILURE PROBABILITY RANKING - BCV

* RESULTS ARE FOR QUALITATIVE INDICATION ONLY

BCV REQUIREMENTS SUMMARY

3.625 IN. DIA INLET, VISOR VALVE

PARAMETER	REQUIREMENT	CALCULATED PERFORMANCE
INLET PRESSURE, PSIA	1121	2000
INLET TEMPERATURE, °R	276	40°
FLOW RATE, LB/SEC	3.7-29.1	MEETS REQUIREMENT
MAXIMUM ΔP , PSID	374	600
FULL OPEN LOSS COEFFICIENT, K	2.5	1.9
INTERNAL LEAKAGE, SCIM	3.4×10^6	$.377 \times 10^6$
LIFE - CYCLES	10,275	724,000
RESPONSE - SEC	1 4 Hz	TBD TBD
RELIABILITY	.9 ₄ 44	TBD
WEIGHT	140 TARGET	68

TBV REQUIREMENTS SUMMARY
6.9 IN. DIA INLET ANGLE POPPET VALVE

PARAMETER	REQUIREMENT
INLET PRESSURE - PSIA	1110
INLET TEMPERATURE - °R	300
FLOW RATE - LB/SEC	42
MAXIMUM ΔP - PSID	1050
FULL OPEN LOSS COEFF. - K	2.5
INTERNAL LEAKAGE - SCIM	5.2 x 10 ⁵ FORWARD 2.6 x 10 ³ REVERSE
LIFE - CYCLES	272 NORMAL 34 EMERG. CLOSE
RESPONSE - SEC	4 NORMAL .05 EMERG. CLOSE
RELIABILITY	.9 ₄ ⁵²
WEIGHT - LBS	130 TARGET 160 MAX

TBV VALVE

TBV ACTUATOR

TURBINE BLOCK VALVE (TBV)

SIGNIFICANT ACCOMPLISHMENTS

SIX CONCEPT LAYOUTS PREPARED

CONCEPT SELECTION COMPLETE (RIGHT ANGLE POPPET)

VALVE/ACTUATOR TORQUE REQUIREMENTS DETERMINED

TBV STRESS ANALYSIS

PART	MATERIAL	ROOM TEMPERATURE DESIGN STRENGTH	MAXIMUM STRESS (STEADY STATE)	CONDITION
MAIN SEAL	A-286	$F_{ty} = 80.8 \text{ KSI}$	$\sigma_T = 26.0 \text{ KSI}$	1050 PSI PLUS 1000 LB AXIAL LOAD
BALANCE SEAL	A-286	$F_{ty} = 80.8 \text{ KSI}$	$\sigma_T = 25.0 \text{ KSI}$	1050 PSI PLUS 1000 LB AXIAL LOAD
MAIN SPRING	A-286	$F_{sy} = 87.5 \text{ KSI}$	$\sigma_S = 66.4 \text{ KSI}$	WORKING HEIGHT
BODY	Al 6061-T6	$F_{ty} = 28.9 \text{ KSI}$	$\sigma_T = 16.8 \text{ KSI}$	2070 PSI
POPPET	TITANIUM	$F_{cy} = 79.0 \text{ KSI}$	$\sigma_C = 42.0 \text{ KSI}$	2070 PSI

TBV LEAKAGE VARIATION WITH SEAL LOAD & SEAL WIDTH
(AT START OF DUTY CYCLE)

<u> </u>	<u>LEAKAGE CRITERIA</u>	<u>SPEC LEAK. LIMIT (SCIMS)</u>
	TPA "NO SPIN"	5.2×10^5
<u> </u>	PSOV BACKUP	2.6×10^3

SEAL WIDTH, INCHES: 1 - .010, 2 - .0075, 3 - .005

TBV (PSOV BACKUP CRITERIA) LEAKAGE RELIABILITY USING J CURVE

TBV (PSOV BACKUP CRITERIA) LEAKAGE HISTOGRAM

$$\sigma = 25.2 \text{ SCIM}$$

RELIABILITY, BASED ON SPECIFICATION LIMIT OF $2.6 (10)^3 \text{ SCIM MAX}$

$R = 0.9_{14} + \text{FOR 1ST CYCLE (LEAKAGE IS FOR 2 SEALS)}$

* LEAKAGE IS A FUNCTION OF:

P1, P2, D1, μ , T1, L1, P, S1, PTV, MFP

AEROJET NUCLEAR SYSTEMS COMPANY

TDV (TPA "NO SPIN" CRITERIA) LEAKAGE HISTOGRAM

$$\sigma = 5.215 (10)^3 \text{ SCIM}$$

RELIABILITY BASED ON SPECIFICATION LIMIT OF $5.2 (10)^5 \text{ SCIM MAX}$

$R = 0.9_{15}^+$ FOR 1ST CYCLE (LEAKAGE IS FOR 2 SEALS)

* LEAKAGE IS A FUNCTION OF:

P1, P2, D1, μ , T1, L1, P, S1, PTV, MFP

TBV POPPET DISPLACEMENT LIMITS REQUIRED TO PREVENT TURBINE ROTATION

TEV CYCLE LIFE VS LOAD & WIDTH

 

TBV SEAL WEAR HISTOGRAM

RELIABILITY BASED ON SPEC
LIMIT OF 272 CYCLES MIN. IS
.90 USING LOG NORMAL DISTRIB.

% RANDOM SOLUTIONS

SEAL WEAR IS A FUNCTION OF:
UT, T2, B, P, A, E, ν , W

TBV FORCE VARIATION WITH STROKE (FOR CLOSING)

MAX STROKE:
3.0 INCHES

FORCE TO
CLOSE VALVE,
 LB_f

TBV PART FAILURE PROBABILITY RANKING

*RESULTS ARE FOR QUALITATIVE INDICATION ONLY

TBV REQUIREMENTS AND PERFORMANCE SUMMARY

6.9 IN. DIA INLET ANGLE POPPET VALVE

PARAMETER	REQUIREMENT	CALCULATED PERFORMANCE
INLET PRESSURE - PSIA	1110	2070 (AMB PROOF)
INLET TEMPERATURE - °R	300	MEETS REQUIREMENTS
FLOW RATE - LBS/SEC	42	MEETS REQUIREMENTS
MAXIMUM ΔP - PSID	1050	1050
FULL OPEN LOSS COEFF. - K	2.5	2.0
INTERNAL LEAKAGE - SCIM	5.2 X 10 ⁵ FORWARD 2.6 X 10 ³ REVERSE	8.8 X 10 ³ 65
LIFE - CYCLES	272 NORMAL 34 EMERG. CLOSE	MEET REQUIREMENTS MEET REQUIREMENTS
RESPONSE - SEC.	4 NORMAL .05 EMERG. CLOSE	MEET REQUIREMENTS .030
RELIABILITY	.9452	TBD
WEIGHT - LBS	130 TARGET 160 MAX	140

5

45

DESIGN AND DEVELOPMENT STATUS OF SUBCOMPONENTS

- . AC MOTORS
- . ELECTRONIC MODULE
 - . DEVICES
- . CONTROL VALVE ACTUATORS
 - . STEPPING MOTOR AND CONTROL CONCEPT
 - . AC MOTOR CONTROL CONCEPT
- . TRANSMISSION
- . ACCESSORIES
- . SHUTOFF SEAL LEAKAGE AND CONTAMINATION

ELECTROMECHANICAL ACTUATOR

47

ELECTRONIC SEMICONDUCTOR DEVICE TECHNOLOGIES CONSIDERED FOR NERVA

BIPOLAR

JFET

MOSFET

HOT CARRIER DIODES

SOLID STATE INTEGRATED VACUUM TUBES

OVONIC DEVICES

ION IMPLANTED DEVICES

GROUP III/V SEMICONDUCTOR DEVICES

BIPOLAR SEMICONDUCTOR DEVICES

BASIC "NPN" BIPOLAR TRANSISTOR STRUCTURE

SCHEMATIC REPRESENTATION

BIPOLAR TRANSISTOR CURRENT FLOW

BIAS ARRANGEMENT

① BACK INJECTION

② SURFACE RECOMBINATION

— ELECTRON FLOW

③ BULK BASE RECOMBINATION

④ SPACE-CHARGE REGION RECOMBINATION

- - - HOLE FLOW

AEROJET NUCLEAR SYSTEMS COMPANY

RADIATION EFFECTS IN BIPOLAR TRANSISTORS

RADIATION		PHYSICAL DAMAGE	EFFECT
NEUTRON	THERMAL (E<10 KeV)	ATOMIC TRANSMUTATIONS SIMPLE DEFECTS	RELATIVELY SLIGHT
	FAST (E>10 KeV)	BULK DAMAGE - DEFECT CLUSTERS INTRODUCTION OF RECOMBINATION CENTERS CARRIER REMOVAL INTRODUCTION OF SCATTERING CENTERS	REDUCTION OF MINORITY CARRIER LIFETIME REDUCTION OF CARRIER MOBILITY INCREASED BASE CURRENT DECREASED COLLECTOR CURRENT INCREASED SATURATION RESISTANCE DECREASED CURRENT GAIN INCREASED BREAKDOWN VOLTAGE INCREASED LEAKAGE CURRENTS
GAMMA	DOSE RATE	BULK IONIZATION	PRIMARY AND SECONDARY PHOTOCURRENT GENERATION DEVICE "LATCH-UP" DEVICE "FAILURE"
	TOTAL DOSE	SPACE-CHARGE BUILD-UP INTERFACE STATE INTRODUCTION	AT Si/SiO ₂ INTERFACE INCREASED SURFACE RECOMBIN- ATION VELOCITY INVERSION LAYER FORMATION (CHANNELING) INCREASED BASE CURRENT DECREASED CURRENT GAIN INCREASED LEAKAGE CURRENTS DECREASED BREAKDOWN VOLTAGE INCREASED JUNCTION CAPACITANCE

BIPOLAR TRANSISTOR PARAMETER DEGRADATION

BIPOLAR POWER TRANSISTOR GAIN
 (I_C/I_B) AS A FUNCTION OF COLLECTOR
 CURRENT WITH NEUTRON FLUENCE
 AS A PARAMETER

$V_{CE} = 5$ VOLTS, $BV_{CEO} = 45$ VOLTS

SATURATION VOLTAGE ($V_{CE(SAT)}$) AS
 A FUNCTION OF NEUTRON FLUENCE
 WITH COLLECTOR CURRENT AS A
 PARAMETER

$I_C/I_B = 5$

JFET SEMICONDUCTOR DEVICES

BASIC "N" CHANNEL
JFET TRANSISTOR STRUCTURE

JFET CURRENT FLOW
(AT "PINCH OFF")

SCHEMATIC REPRESENTATION
(BOTH GATES CONNECTED)

BIAS ARRANGEMENT
(BOTH GATES CONNECTED)

RADIATION EFFECTS IN JFET DEVICES

RADIATION		PHYSICAL DAMAGE	EFFECT
NEUTRON	THERMAL ($E < 10 \text{ KeV}$)	ATOMIC TRANSMUTATIONS SIMPLE DEFECTS	RELATIVELY SLIGHT
	FAST ($E > 10 \text{ KeV}$)	BULK DAMAGE - DEFECT CLUSTERS INTRODUCTION OF RECOMBINATION CENTERS <u>CARRIER REMOVAL</u> <u>INTRODUCTION OF SCATTERING CENTERS</u>	DECREASED CHANNEL MOBILITY <u>INCREASED CHANNEL RESISTANCE</u> <u>DECREASED DRAIN CURRENT AND GAIN</u> INCREASED LEAKAGE CURRENTS INCREASED BREAKDOWN VOLTAGE
GAMMA	DOSE RATE	BULK IONIZATION	PHOTOCURRENT GENERATION CHANGED "Q" POINT OR STATE
	TOTAL DOSE	SPACE-CHARGE BUILD-UP INTERFACE STATE INTRODUCTION	INCREASED LEAKAGE CURRENTS

JFET DEVICE PARAMETER DEGRADATION

JFET GAIN (DRAIN CURRENT) AS A FUNCTION OF INITIAL CHANNEL DOPING (BREAKDOWN VOLTAGE) WITH NEUTRON FLUENCE AS A PARAMETER

$$\frac{I_D(\phi, \gamma)}{I_D(0)}$$

OR

$$\frac{G_m(\phi, \gamma)}{G_m(0)}$$

MOSFET SEMICONDUCTOR DEVICES

BASIC "P" CHANNEL "ENHANCEMENT MODE"
MOSFET STRUCTURE (PMOS)

SCHEMATIC
REPRESENTATION

PMOS CURRENT FLOW

BIAS ARRANGEMENT

COMPARISON OF POWER SWITCHING DEVICES

TECHNOLOGY	NEUTRON HARDNESS $n\text{-cm}^{-2}$ $E > 1.0 \text{ MeV}$		GAMMA HARDNESS RADS Si		PRIMARY DAMAGE MECHANISM	TEMP RANGE °C	OPTIMUM OPERATING TEMP, °C	CURRENT HANDLING CAPACITY, AMP	"ON" RESISTANCE OHMS	BREAKDOWN VOLTAGE, V	% GAIN DEGRADATION	DEVELOPMENT	
	TYPICAL	DEV	TYPICAL	DEV								TIME	COST, \$K
BIPOLAR	5×10^{14}	10^{15}	10^6	10^7	NEUTRON	- 55 TO +125	+ 25	<10 (SCR's FOR >10)	PRE 0.1 - 0.5 POST 2 - 10	< 40 SECONDARY BREAKDOWN	90	1 YR	50-100
JFET	3×10^{15}	10^{16}	$> 10^8$	$> 10^8$	NEUTRON	-200 TO +150	-100	1 - 10	PRE 0.5 - 3 POST 2 - 10	< 45 NO S.B.	40	1 YR	30-50
PMOS	3×10^{15}	5×10^{16}	10^7	$> 10^8$	GAMMA	-270 TO +150	-200	5 - 20	PRE 0.25 - 1 POST 0.75 - 3	> 70 NO S.B.	20	1 YR	30-50

NERVA LEVELS	
3×10^{16}	7×10^7

COMPARISON OF INTEGRATED CIRCUITS

TECHNOLOGY	NEUTRON HARDNESS $n\text{-cm}^{-2} E > 1.0 \text{ Mev}$		GAMMA HARDNESS RADS Si		PRIMARY DAMAGE MECHANISM	TEMP RANGE $^{\circ}\text{C}$	OPTIMUM OPERATING TEMP, $^{\circ}\text{C}$	OPERATING BREAKDOWN VOLTAGE V	FAN "IN"-"OUT" LIMITATIONS	LEVEL OF COMPLEXITY	DEVELOPMENT	
	TYPICAL	DEV	TYPICAL	DEV							TIME	COST, \$K
BIPOLAR	10^{15}	7×10^{15}	10^6	10^7	NEUTRON AND GAMMA	- 55 TO +125	+ 25	3 - 7	SEVERE	COMPLEX MSI	1 YR	50-100
JFET	3×10^{15}	3×10^{16}	$> 10^7$	$> 10^8$	NEUTRON	-200 TO +150	-100	5-10	MILD	SIMPLE MSI	1-2 YR	100-500
PMOS	3×10^{15}	5×10^{16}	$> 10^7$	$> 10^8$	GAMMA	-270 TO +150	-200	30-40	NONE	COMPLEX MSI & LSI	1 YR	10-25

NERVA LEVELS	
3×10^{16}	7×10^7

RAD HARDENED ACTUATOR ELECTRONIC PROGRAM

	1971											1972					
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
1. COMPLETE BINARY VALVE ACTUATOR CONTROLLER ELECTRONIC MODULE FUNCTIONAL BLOCK DIAGRAM		△															
2. ESTABLISH DESIGN PARAMETERS FOR PMOS POWER SWITCHING DEVICES		△															
3. PLACE P.O. FOR FAB AND TEST OF PROTOTYPE POWER SWITCHING DEVICES			△														
4. BREADBOARD NON-HARDENED PMOS CIRCUIT & DETERMINE CONTROLLER/MOTOR CHARACTERISTICS				△													
5. CLASSIFY LOGIC ELEMENTS INTO "BUILDING BLOCKS" AND ESTABLISH DESIGN PARAMETERS					△												
6. PROCURE "SEPTRE" ANALYSIS PROGRAM			△														
7. PREPARE AND UPDATE PMOS DEVICE CHARACTERISTICS FROM RADIATION TEST DATA							△										
8. REVIEW VENDOR TESTING AND DATA OF POWER SWITCH										△							
9. BREADBOARD PMOS POWER SWITCH FOR MOTOR TESTING											△						
10. CONDUCT GAMMA AND REACTOR TEST ON POWER SWITCH																△	
11. PLACE P.O. FOR RAD HARD LOW LEVEL LOGIC IC'S							△										
12. COMPLETE PRELIMINARY WORST CASE ANALYSIS OF ELECTRONIC MODULE										△							
13. BREADBOARD ELECTRONIC MODULE FOR GAMMA AND REACTOR TESTS																△	
14. PREPARE INTERMEDIATE ELECTRONIC DESIGN BASED ON WORST CASE ANALYSIS USING IC'S																△	
15. PREPARE DESIGN AND INITIATE FABRICATION OF PRELIMINARY FLIGHT PACKAGE USING DISCRETE IC LOGIC																	△

RAD HARDENED ACTUATOR ELECTRONIC PROGRAM (CONT)

[illegible]

ELECTRONIC MODULE RADIATION TESTS

MONTHS (4/71)				1	3	5	7	9	11	13	15	17	19	21	23	25
PMOS DEVICES	STATIC TESTS	AMBIENT TEMP	REACTOR (NEUTRON) Co 60 (GAMMA)													
		OPERATING TEMP	REACTOR Co 60													
	DYNAMIC TESTS	AMBIENT TEMP	REACTOR Co 60													
		OPERATING TEMP	REACTOR Co 60													
		AMBIENT TEMP	REACTOR Co 60													
		OPERATING TEMP	REACTOR Co 60													
SUE CIRCUITS	STATIC TESTS	AMBIENT TEMP	REACTOR Co 60													
		OPERATING TEMP	REACTOR Co 60													
	DYNAMIC TESTS	AMBIENT TEMP	REACTOR Co 60													
		OPERATING TEMP	REACTOR Co 60													
		AMBIENT TEMP	REACTOR Co 60													
		OPERATING TEMP	REACTOR Co 60													
SUE ASSEMBLIES	STATIC TESTS	AMBIENT TEMP	REACTOR Co 60													
		OPERATING TEMP	REACTOR Co 60													
	DYNAMIC TESTS	AMBIENT TEMP	REACTOR Co 60													
		OPERATING TEMP	REACTOR Co 60													
		AMBIENT TEMP	REACTOR Co 60													
		OPERATING TEMP	REACTOR Co 60													

CHRONOLOGICAL DEVELOPMENT OF RADIATION HARDENED SEMICONDUCTOR DEVICES

61

A.C. MOTOR STATUS

- (1) SIX 1/4 HORSEPOWER, CYROGENIC, RADIATION HARDENED MOTORS PROCURED.
- (2) MOTOR RADIATION TESTED IN GTR-22.
- (3) PERFORMANCE CHARACTERISTICS DETERMINED FOR AMBIENT AND LN² TEMPERATURES.
- (4) PERFORMANCE CHARACTERISTICS DETERMINED FOR 3 WIRE, 3 PHASE AND 6 WIRE, 3 PHASE DRIVE MODE.
- (5) TWELVE 1/4 H.P. 4, 6, AND 8 POLE AMBIENT MOTORS PROCURED FOR DEVELOPMENT TESTS.
- (6) FOUR LOW RESISTANCE, LOW SLIP ROTORS PROCURED.
- (7) MOTOR DESIGN PROGRAM COMPLETED AND IN USE.
- (8) TWO SURPLUS MOTORS BEING REWOUND TO DESIGN PROGRAM CALCULATIONS.

INDUCTION MOTOR

3 PHASE, 4 POLE, 1/4 H.P.

3 PHASE INDUCTION MOTOR

AEROJET NUCLEAR SYSTEMS COMPANY

WESTERN GEAR MOTOR PERFORMANCE CURVES

PESCO MOTOR PERFORMANCE
CONSTANT SLIP

AEROJET NUCLEAR SYSTEMS COMPANY

PESCO MOTOR PERFORMANCE CURVES

63

VALVE REQUIREMENTS: TORQUE, SPEED, H.P.

MOTOR DESIGN PROGRAM

DESIGN INPUTS

ROTOR AND STATOR DIAMETERS

NUMBER OF POLES

AIR GAP DIMENSIONS

NUMBER OF CONDUCTORS

CURRENT LIMIT

FLUX DENSITIES FROM MATERIAL PROPERTIES

LOSS FACTORS

CALCULATIONS

ROTOR AND STATOR GEOMETRY

WINDING DESIGN

PERMEANCES AND REACTANCES

CURRENT AND FLUX DENSITIES

WINDING FACTORS - ROTOR RING AND BAR DESIGN

PERFORMANCE FOR CONSTANT FREQUENCY AND
CONSTANT SLIP

74 69

A.C. MOTOR DESIGN PARAMETRIC STUDY

10

ELECTRONIC MODULE STATUS

- (1) MOTOR DRIVE MODULE DESIGNED AND TESTED USING TTL DIGITAL COMPONENTS AND OPERATIONAL AMPLIFIERS FOR THE ANALOG CIRCUITS.
- (2) MOTOR DRIVE MODULE DESIGNED AND TESTED USING COMPLETE DIGITAL CIRCUITS AND TTL COMPONENTS.
- (3) MOTOR DRIVE MODULE DESIGNED USING COMPLETE DIGITAL CIRCUITS AND MOSFET COMPONENTS.
- (4) MOTOR DRIVE MODULE FABRICATED WITH LOW LEVEL MOSFET LOGIC
- (5) DESIGN COMPLETED ON SIMULATOR FOR MOSFET POWER SWITCH USING BIPOLAR POWER TRANSISTORS, ZENER DIODES AND SERIES RESISTORS TO BE USED IN MOSFET MODULE MOTOR TESTS.
- (6) PROCUREMENT INITIATED FOR POWER MOSFET DEVICES.

BINARY VALVE ELECTRONICS MODULE

3 Ø SYNTHESIZER SEQUENCE & SLIP CONTROL

72

HILL

3 Ø SYNTHESIZER SEQUENCE & SLIP CONTROL

AEROJET NUCLEAR SYSTEMS COMPANY

TACHOMETER DERIVED FIELD FREQUENCY

SIX PHASE QUASI-SQUARE WAVE INVERTER

A.C. MOTOR INVERTER - 6 PHASE LOGIC

RING COUNTER SEQUENCE

COUNT	FF1	FF2	FF3
1	1	0	0
2	1	1	0
3	1	1	1
4	0	1	1
5	0	0	1
6	0	0	0
1	1	0	0

COUNT IS 6 TIMES
MOTOR FREQUENCY

OUTPUTS SEQUENCE

BIFILAR SIX PHASE SEQUENCE

LINE-TO-LINE RESISTIVE PHASE CURRENTS

- CURRENT LIMITED WAVE SHAPE
- CURRENT LIMITING AT 24 TIMES FREQUENCY

76

NERVA ELECTRONICS MODULE COMPONENT BREAKDOWN

COMPONENT	DRAWING NUMBER & DESCRIPTION		
	1138171 SCHEMATIC DIAGRAM DC TO AC INVERTER	1139048 MODULE, ELECTRONIC NERVA VALVE ACTUATOR (FULL DIGITAL IMPLEMENTATION)	1139199 MODULE, ELECTRONIC NERVA VALVE ACTUATOR (MOS DIGITAL IMPLEMENTATION)
INTEGRATED CIRCUITS (DIGITAL)	28	12	12
INTEGRATED CIRCUITS (ANALOG)	5	0	0
TRANSISTORS	51	18	6
DIODES	18	6	6
RESISTORS	87	14	9
CAPACITORS	22	4	4
HARD WIRE CONNECTIONS	875	200	200

VALVE TIMING & MOTOR CURRENT FOR ALTERNATE MOTOR INPUT CONDITIONS

(A) 60 Hz CONSTANT SLIP

(B) SLIPS $\leq$ 60 Hz; 100 Hz STATOR LIMIT

76

CONTROL VALVE ACTUATOR STATUS

- (1) COMMERCIAL VARIABLE RELUCTANCE STEPPING MOTOR PROCURED AND MAJOR PERFORMANCE CHARACTERISTICS DETERMINED.
- (2) PRELIMINARY CONTROL CONCEPTS FOR STEPPING MOTOR DETERMINED AND ANALYTICAL PROGRAM PREPARED.
- (3) PERFORMANCE CHARACTERISTICS OF BCV DETERMINED FOR "400 D" ENGINE USING STEPPING MOTOR CONTROL.
- (4) PRELIMINARY CONTROL CONCEPTS FOR A.C. MOTOR SERVO CONTROL DETERMINED.
- (5) ANALYTICAL SERVO RESPONSE PROGRAM IN DEVELOPMENT FOR A.C. MOTOR SERVO.
- (6) A.C. MOTOR RESPONSE CHARACTERISTICS BEING DETERMINED USING DIGITAL CONVERTER DESIGN.

79

TORQUE VS SPEED
WARNER STEPPING MOTOR
SM 048-0170 AB S/N 5730

5

49

SM-048-0170-AB STEP
MOTOR OPERATED WITH
MCS-1000 CONTROLLER
8-28-70

PEAK CURRENT, AMPS

CURRENT HEIGHT, PEAK-TO-PEAK

DRIVING INPUT FREQUENCY
FOR STEP START FROM
DETENT POSITION VS
LOAD TORQUE

AEROJET NUCLEAR SYSTEMS COMPANY

PHASE PLANE STEPPING MOTOR CONTROL

PHASE PLANE - A.C. MOTOR CONTROL

AEROJET NUCLEAR SYSTEMS COMPANY

4 POLE WESTERN GEAR MOTOR - 6V L-N

QUASI-SQUARE WAVE EXCITATION

85
PESCO MOTOR CONSTANT SLIP MODE - TRANSIENT RESPONSE

CONTROL VALVE ACTUATOR POSITION SERVO

CONTROL VALVE SERVO

ROTARY ACTUATOR PROTOTYPE GEAR BOX

ESTIMATED EFFICIENCY:

STALL - 67% MIN

RUNNING - 75% MIN

STALL DESIGN TORQUE - 1500 IN-LB

SIMPLE
PLANETARY
RATIO = 8.25:1 *

DIFFERENTIAL
PLANETARY
RATIO = 61.2:1 *

* TOTAL REDUCTION 505:1

MOTOR AND TRANSMISSION HOUSING

An exploded view diagram of a mechanical assembly. At the top is a small black pin. Below it is a small black gear. In the center is a triangular metal housing with a central bore and three mounting holes. To the left and right of the housing are two small black gears. Below the housing are two small black fasteners. At the bottom is a large black gear. The components are arranged in a symmetrical pattern around the central housing.

COMPOUND DIFFERENTIAL PLANETARY GEARS

AEROJET NUCLEAR SYSTEMS COMPANY

92

TRANSMISSION TORQUE CURVE

$$\text{RATE} = \frac{\Delta \text{ INPUT}}{\Delta \text{ OUTPUT}}$$

THE UNIVERSITY OF CHICAGO

- (1) ACTUATOR HAD JUST COMPLETED A 15 MINUTE RUN
- (2) AFTER 2 MINUTES OF OPERATIONS. INPUT TORQUE WITH NO LOAD VARIED FROM 0.24 UP TO 0.65 IN #.
- (3) NO LOAD ON SLIP BRAKE AFTER BUILDUP NO. 3 (ONE WAVY SPRING TO LOAD THRUST BEARINGS)
- (4) THE TRANSMISSION HAD LOCKED AND WOULD NOT ROTATE CCW.

ACTUATOR DESIGN COMPARISON

COMPARISON OF VALVE ASSEMBLY ENVELOPES

ACTUATOR ACCESSORY SUBCOMPONENT STATUS

POTENTIOMETERS

- (A) POTENTIOMETERS PROCURED FROM THREE VENDORS AND RADIATION TESTED IN GTR-22
- (B) DEVELOPMENT SPECIFICATIONS HAVE BEEN PREPARED
- (C) ENVELOPE DRAWING FOR SSBV POTENTIOMETERS HAS BEEN PREPARED

CONNECTORS

- (A) SIX SIZE 20, 1200 PSI, RADIATION HARD CRYOGENIC CONNECTORS HAVE BEEN PREPARED
- (B) PURCHASE REQUISITION FOR TWELVE, 14 SHELL SIZE, 2250 PSI, CONNECTORS HAS BEEN INITIATED

SPEED SENSORS

- (A) TWENTY-EIGHT SPEED SENSORS WERE PROCURED FOR MOTOR TESTING AND ARE BEING EVALUATED.

MAGNETIC BRAKE DETENT

- (A) A MAGNETIC DETENT WITH 1-INCH-POUND TORQUE HAS BEEN DESIGNED AND PROCURED.

SUMMARY OF COMPUTER DESIGN PROGRAMS

1. TEST DATA CONVERSION TO A.C. MOTOR EQUIVALENT CIRCUIT PARAMETERS
2. A.C. MOTOR PERFORMANCE CHARACTERISTICS FROM EQUIVALENT CIRCUITS
3. A.C. MOTOR DESIGN PROGRAMS
4. VALVE TRANSIENT ANALYSIS WITH MOTOR DRIVEN AT CONSTANT FREQUENCY OR CONSTANT SLIP WITH CURRENT OR FREQUENCY LIMIT
5. VALVE TRANSIENT ANALYSIS WITH MOTOR TORQUE SPEED AS INPUT
6. ACTUATOR GEAR RATIO CALCULATED ON MAXIMUM POWER RATE TRANSFER
7. CALCULATION OF EPICYCLIC TRANSMISSION RATIOS, EFFICIENCIES, TOOTH STRESS AND WEAR FACTOR
8. CALCULATE SPECIAL PARAMETERS REQUIRED FOR DETAIL DESIGN OF MESHING GEARS WITHIN AN EPICYCLIC TRANSMISSION

5/98

VALVE SHUTOFF SEAL AND CONTAMINATION TEST PROGRAM

- . OBJECTIVE
 - . DESIGN A POPPET TYPE SHUTOFF SEAL
 - . DEFINE VALVE FUNCTIONAL AND LEAKAGE PROBLEMS AS A RESULT OF IMPOSED ENGINE CLEANLINESS LEVEL.
- . REQUIREMENT

NPRD - 220 GRAMS OF 600 AL PARTICLES OVER OPERATING LIFE.
- . SIGNIFICANCE

EARLY DEFINITION OF CONTAMINATION RELATED PROBLEMS REQUIRED FOR VALVE DESIGN.

TEST APPROACH

1. CONDUCT GO-NO GO TEST USING WORST CASE CONDITIONS
 - 12.6 GMS/600/³AL. PARTICLES
 - 100 CYCLES AT MAX FLOW RATE
2. IF: NO PROBLEM DURING "GO - NO GO" TEST
THEN: PRESENT VALVE DESIGN APPROACH IS SATISFACTORY
3. IF: PROBLEMS ARE EXPERIENCED DURING "GO-NO GO" TEST
THEN: STATISTICAL TEST PROGRAM REQUIRED TO GUIDE NEW DESIGN APPROACH.

CSCV CONTAMINATION TEST FIXTURE

AEROJET NUCLEAR SYSTEMS COMPANY

CSCV SHUTOFF SEAL LEAK TEST DATA

AEROJET NUCLEAR SYSTEMS COMPANY

CSCV SHUTOFF SEAL TEST HISTORY

TEST	TEMP	NO. OF CYCLES	LEAKAGE AT 30 PSIG (SCC/SEC)			
			PRE-TEST		POST-TEST	
			AMB GHe	GHe/GH ₂ AT °R	AMB GHe	GHe/GH ₂ AT °R
DEVELOPMENT	AMB	1000	0.27	-	0.096	-
DEVELOPMENT	LN ₂	1000	-	0.44 AFTER 175 CYCLES AT 160°R	0.076	0.68 AT 160°R
BASELINE	LH ₂	100	<0.1	11.9 GH ₂ AT 45°R	0.1	9.8 GH ₂ AT 45°R
"GO-NO GO"	LH ₂	102	<0.1	0.1 GH ₂ AT 45°R	0.1	0.1 GH ₂ AT 45°R

CONCLUSIONS

PRESENT CSOV DESIGN APPROACH IS SATISFACTORY
FOR REQUIRED NPRD CONTAMINATION LEVEL

OTHER VALVES WILL REQUIRE ADDITIONAL TESTS TO
CONFIRM DESIGN APPROACH

PLANNED ACTIVITIES THROUGH SEPTEMBER 1972

BYPASS CONTROL VALVE (BCV)

TURBINE BLOCK VALVE (TBV)

RADIATION-HARDENED ELECTRONICS

BYPASS CONTROL VALVE (BCV)

TURBINE BLOCK VALVE (TBV)

1971		1972	
TBV ASSEMBLY	A		B
DESIGN LAYOUT AND ANALYSIS			DESIGN REPORT

RAD HARD ELECTRONICS

CONCLUSION

NOT ALL SIGNIFICANT DESIGN FEATURES OF NERVA
VALVE ASSEMBLIES ARE COVERED IN PLAN

USEFUL EFFORT WILL BE ACCOMPLISHED ON TBV
AND BCV DESIGN IN ADDITION TO MAJOR BCV
SUBCOMPONENT DEVELOPMENT.

NOZZLE EXTENSION

ACTION ITEMS

1. EVALUATE THE EFFECT OF THE FOLLOWING ON EXTENSION PERFORMANCE, STRUCTURAL INTEGRITY, AND LIFE:
 - NEUTRON EFFECTS
 - DISCONTINUITIES
 - EXTRAPOLATION OF EROSION RATE TO 10 HOURS
 - "BOOTSTRAP" EFFECTS
 - MATERIAL APPLICABILITY (AGCarb VS INTREMOLD III)
 - (KLEIN, GAVIGAN, MEDEIROS, GERSTEIN)
2. ANSC TO DEFINE MATERIAL PROPERTIES TO BE USED FOR STRUCTURAL DESIGN (BASED ON FMA AND RELIABILITY MODELING) AND REVIEW WITH SNSO-C. (LOMBARDO)
3. PROVIDE BRIEF REPORT ON EROSION TEST DATA TO M. KLEIN. (KLEIN)

NOZZLE EXTENSION (CONT)

ACTION ITEMS

4. BRIEF SNSO-C ON RELATIVE CONTRIBUTION TO TOTAL STRESS OF METAL FLANGE INDUCED STRESS AND GRAPHITE FLANGE INTERNAL THERMAL GRADIENT STRESSES. EVALUATE CONCEPTS TO REDUCE TOTAL STRESS TO ELIMINATE NEED FOR FLANGE STRENGTH HIGHER THAN SHELL STRENGTH. (SCHROEDER)
5. DEFINE NDT TECHNIQUE FOR CONTROL OF EXTENSION "QUALITY". PROCESS CONTROL ONLY IS NOT CONSIDERED ADEQUATE. (SLIVKA)
6. INVESTIGATE FUEL MATERIALS (WHOSE PROPERTIES ARE KNOWN) FOR POSSIBLE USE. (SLIVKA)

TURBOPUMP ASSEMBLY

ACTION ITEMS

1. BRIEF SNSO-C (CORRINGTON) ON RESULTS OF EVALUATION OF LABYRINTH-TYPE THRUST BALANCER LANDS TO REDUCE FLOW RATE. (CORRINGTON)
2. REVIEW HIGH-SPEED VS LOW-SPEED BALANCE BEARING LOAD PREDICTIONS WITH GERSTEIN. (GERSTEIN)
3. EVALUATE POSSIBILITY OF CONDUCTING INDUCER BLADE VIBRATION TESTS IN GASEOUS HELIUM. (LOMBARDO)
4. ESTABLISH NUMBER OF TESTS REQUIRED TO VALIDATE BEARING WEAR TEST RELIABILITY MODEL. (SLIVKA)
5. EVALUATE DESIRABILITY OF HIGH-SPEED BALANCE OF LH₂ PUMP TEST RIG. (SLIVKA)

TURBOPUMP ASSEMBLY (CONT)

ACTION ITEMS

6. CONDUCT SEPARATE MEETING WITH SNSO AND SNSO-C TO REVIEW BEARING PROGRAM TECHNICAL PROGRESS - WEDNESDAY, 14 APRIL, CLEVELAND. (CORRINGTON)
7. SNSO-C AND ANSC EVOLVE STRUCTURAL DESIGN CRITERIA, APPROACH, AND TESTING PROCEDURE FOR TURBOPUMP BLADING HIGH CYCLE FATIGUE CONDITIONS (INDUCER AND TURBINE BLADING). (LOMBARDO/RICHARDSON)
8. ESTABLISH PLAN FOR ACCOMPLISHMENT OF TPA ACTION ITEM 7. (CAMPBELL)

VALVES AND ACTUATORS

1a. PROCEED AS PROPOSED;
REQUIRES SUPPLEMENTAL
PROPOSAL; DECIDE ACTION
AT NEGOTIATIONS

2a. EVALUATE IMPACT TO
PROJECT 110

3a. PROVIDE CURRENT DATA
TO WANL

4a. PROVIDE ROM ESTIMATE
FOR ACTION AT
NEGOTIATIONS.

1. ~~NEITHER SELECTED VALVE HAS LOW LEAKAGE REQUIREMENT.
THIS MAY BE A SIGNIFICANT PROBLEM AREA IN PSOV.
EVALUATE WHETHER THIS SHOULD BE INCORPORATED IN
VALVE PROGRAM. (CORRINGTON)~~

2. JUSTIFY LEAK RATE FOR BCV AND SEAL REQUIREMENT. (SLIVKA)

3. ~~EVALUATE CONTROL DRUM ACTUATOR ELECTRONIC DESIGN AND
LOCATION. ANSC TECHNOLOGY TO BE USED FOR NSS DRUM
ACTUATOR ELECTRONIC DESIGN AND PACKAGING. (CORRINGTON)~~

4. ~~EXAMINE FEASIBILITY/DESIRABILITY OF INCORPORATING
INTEGRATED LSI MODULE IN CURRENT PROGRAM. (SLIVKA)~~

5. EXPAND DEFINITION OF DESIRED ACTION FOR 4 (ANSC).

GENERAL ACTION ITEMS

1. AT ENGINE REVIEW, COMMENT ON POWERED CHILL COMPATIBILITY WITH NSS. COVER SYSTEM ASPECTS OF CHILLDOWN. (SCHEIB)
2. REVIEW THE BASIS AND ADEQUACY OF THE OF THE 2% BYPASS FLOW ALLOCATION FOR PARA-EQUILIBRIUM EFFECTS CONSIDERING CONANT'S DATA. (SLIVKA)

OVERALL

1. PROVIDE COMPLETION DATES FOR NOZZLE EXTENSION AND TPA ACTION ITEMS TO SNSO-C. (CAMPBELL)
2. PROVIDE ACTION AS DEFINED BY VALVE/ACTUATORS OVERLAY (ITEMS 1a THRU 4a).

SNSO ACTION

**DEFINE CONTAMINATION CRITERIA RELATIVE
TO DISTRIBUTION OF PARTICLE SIZE**