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MASTER

DATA ITEM S-54

NUCLEAR SUBSYSTEM
INSTRUMENTATION

TRADE STUDY NO. 792

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DATA ITEM S-54

NUCLEAR SUBSYSTEM INSTRUMENTATION

TRADE STUDY NO. 792

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1.0 INTRODUCTION

1.1 SCOPE

This trade study evaluates candidate transducer and support equipment design concepts and makes a preliminary selection of the candidate or candidates which appear to be the most promising for further development to meet the flight measurement requirements for the NERVA Program.

1.2 INSTRUMENT CLASSIFICATION AND LISTING OF MEASUREMENTS

Candidate transducers are classified into three types which are dependent on the relationship of measurement requirements to transducer performance as presently known.

- Type A - The device selection has been made with expectation of performance within the given requirements; therefore, no development effort is required. This type includes low temperature resistance temperature transducers (RTT) and thermocouples, medium temperature thermocouples, and demodulators.
- Type B - The basic device concept has been selected with actual design to be determined from results of the development effort. This group includes only the cluster exit gas high temperature thermocouple.
- Type C - Various basic device concepts have been identified which show promise of meeting the desired requirements. The development testing effort will lead to final selection with confirmation resulting from prequalification testing.

This type includes the core material high temperature thermocouples, support stem load transducers, in-vessel pressure transducers, vibration transducers, neutronic instrumentation, displacement transducers, acoustical transducers, and strain gages.

A listing of the maximum flight-required measurements and descriptions of their intended use is contained in Table 1-1. Measurement information is transferred from the requirements of the reactor engineer to the instrument designer/specifier by the use of Instrumentation Design Criteria (I. D. C.) sheets. These sheets are serialized and kept on record in the WANL Instrumentation group. References to these sheets appear in Table 1-1. The sheets referenced by numbers 040, 041, 061, 081, 084, 086-088, 095-097, 099-101, and 103 are new requirements and little information is shown in this report. No design work has yet started on a means to satisfy these new requirements.

1.3 INSTRUMENT STATUS

A summary of the present status of instruments for flight measurements by parameter is presented here.

Low Temperature RTT - The platinum resistive wire element has been selected as the candidate design with expectation of performance within the requirements.

Low Temperature Thermocouples - Three candidate designs with copper-constantan wires have been selected for the various measurements with expectation of performance within the requirements. The candidates are .020 and .045 inch diameter grounded junction and .065 diameter exposed junction thermocouples.

Medium Temperature Thermocouples - Two candidate designs with chromel-alumel wires have been selected for the various measurements with expectation of performance within the requirements. The candidates are .020 and .045 inch diameter grounded junction thermocouples.

Cluster Exit Gas High Temperature Thermocouples - A basic design concept has been established. Primary and back-up material candidates for

the sheath, insulators, and thermoelements to be used with the design concept have also been established. These primary candidates are tungsten-2% thoria sheath, beryllium oxide insulators, and tungsten/tungsten 26% rhenium thermoelements.

Core Material High Temperature Thermocouple - Two candidate thermocouple design concepts have been established. Primary and back-up material candidates for the sheath, insulators, and thermoelements to be used with these design concepts have also been established. Primary material candidates are tungsten-2% thoria sheath, beryllium oxide insulator, and tungsten 5% rhenium/tungsten 26% rhenium thermoelements.

Support Stem Load Transducer - Four candidate design concepts have been established utilizing a full bridge configuration for measuring the axial loading of the support stems. These candidates are iron-chromium-aluminum free grid foil, a platinum-tungsten free grid foil, a nickel-chromium free grid foil, and modified Microdot platinum-tungsten wire strain gages.

In-Vessel Pressure Transducers - Primary and back-up candidate design concepts have been established for both absolute and differential type measurements. These design concepts include variable reluctance, variable permeance, thin film strain gage, and linear variable differential transformer (LVDT) devices.

Vibration Transducers - Three candidate design concepts have been established. These design concepts include variable reluctance, variable permeance and thin film strain gage devices.

Neutronic Instrumentation - Primary and back-up candidate design approaches have been established for the source, intermediate, and power range measurements. The primary candidate for all ranges is U-238 fast fission chambers. In the power range, the chamber is used in the d. c. current mode. Source range back-up candidates are a boron trifluoride proportional counter, a boron-10 lined proportional counter, and a U-235 fission counter. Boron-10 lined compensated ion chambers or fast fission chambers, both d. c. current and Campbell, serve as backup for the intermediate range. A boron-10 lined uncompensated ion chamber, a Co-60 self-powered detector, and a fast fission chamber (Campbell) are backup candidates for the power range.

Displacement Transducers - Primary and back-up candidate design approaches have been established for all the displacement measurements. The primary candidate for all measurements uses the variable permeance technique. Transducing mechanisms for the back-up candidates are the LVDT for the Core/Core Support Plate Axial and Core/Reflector Radial-Forward measurements and the strain gage beam (full bridge) for the Core/Reflector Radial-Forward and Aft measurements. Recently-added requirements for core displacement and reactor to pressure vessel measurements will use either the LVDT or the strain gage beam.

Demodulators - A digital demodulator has been selected as the prime design candidate with the analog design recommended only as a potential back-up concept.

Others -

Two acoustic measurements in the plena, plus one in the turbine inlet have recently been included in the measurement list. Also added were two gamma dose rate measurement requirements, four neutron flux measurement requirements, and two strain measurement requirements. Transducers have not been selected, nor has design begun on these requirements.

TABLE 1-1

MEASUREMENT REQUIREMENTS

<u>Measurement Description</u>	<u>Transducer Sta*</u>	<u>Location R</u>	<u>θ</u>	<u>Measurement Justification</u>	<u>Measurement Intended Use</u>	<u>Instrumentation Design Criteria Sheet No.</u>
Reflector Inlet	-31.0	TBD	0	Monitor absolute pressure in the inlet plenum for detecting unsafe operating conditions or incipient failure and thermal power.	Control Performance Evaluation	050
Plenum	-31.0	TBD	120			
Pressure-Abs.	-31.0	TBD	240			
NSS Inlet from Turbine	-28.0	TBD	0	Monitor absolute pressure exhausting from turbine to the NSS, determine gas pressure at central shield forward end, and state point verification.	Performance Evaluation Emergency Detection	051
Pressure-Abs.	-28.0	TBD	120			
	-28.0	TBD	240			
Structural Support (SS) Supply Plenum	-31.5	12.3	0	Monitor absolute pressure in the supply plenum for determination of H ₂ inventory for reactivity calculations and control. Also to detect unsafe operating conditions and incipient failures.	Performance Evaluation Control	052
Pressure-Abs.	-31.5	12.3	90			
	-31.5	12.3	180			
	-31.5	12.3	240			
NSS Outlet to Turbine	-31.0	TBD	0	Monitor absolute pressure for state point verification	Performance Evaluation Emergency Detection	048
Pressure-Abs.	-31.0	TBD	120			
	-31.0	TBD	240			
SSBL Inlet	TBD	15.0	105	State point verification	Performance Evaluation Emergency Detection	045
Pressure-Abs.	TBD	15.0	105			

* This is reactor station. Reactor Station 0.0 is equivalent to engine station + 131.73

TABLE 1-1 (CONTINUED)

<u>Measurement Description</u>	<u>Transducer Sta*</u>	<u>Location R</u>	<u>θ</u>	<u>Measurement Justification</u>	<u>Measurement Intended Use</u>	<u>Instrumentation Design Criteria Sheet No.</u>
Reflector Inlet to NSS Outlet to Turbine Pressure-Differential	-31.0 -31.0 -31.0	TBD TBD TBD	0 120 240	To detect unsafe operating conditions and/or incipient failures and provide state point verification.	Control Performance Evaluation	004
NSS Inlet from Turbine to Core Inlet Pressure-Differential	-25.5 -25.5 -25.5	TBD TBD TBD	0 120 240	To detect unsafe operating conditions and/or incipient failures.	Control	005
Core Axial Pressure-Differential	-25.5 -25.5 -25.5 -25.5	TBD TBD TBD TBD	0 90 180 270	To detect unsafe operating conditions and/or incipient failures.	Control	053
Reflector Inlet to Core Exit Pressure-Differential	-25.5 -25.5 -25.5 -25.5	TBD TBD TBD TBD	0 90 180 270	Determine pressure drop between the reflector inlet and core exit, and measure structural loads on reflector structure.	Control Performance Evaluation	054
Final Seal Chamber Pressure-Differential	-25.5 -25.5 -25.5	TBD TBD TBD	0 120 240	Determine effectiveness of lateral support seals between core inlet and core exit for detecting unsafe operating conditions.	Control Performance Evaluation	057
S.S. System Inlet Plenum to Exhaust Plenum Pressure-Differential	-25.5 -25.5 -25.5 -25.5	TBD TBD TBD TBD	0 90 180 270	Evaluate SS coolant flow, and determine H ₂ inventory and reactivity for detecting unsafe operating conditions.	Control Performance Evaluation	060

* This is reactor station. Reactor Station 0.0 is equivalent to engine station + 131.73.

TABLE 1-1 (CONTINUED)

<u>Measurement Description</u>	<u>Transducer Sta*</u>	<u>Location R</u>	<u>θ</u>	<u>Measurement Justification</u>	<u>Measurement Intended Use</u>	<u>Instrumentation Design Criteria Sheet No.</u>
Reflector Material Temperature (Low)	26.0 26.0 52.0	22.1 22.1 22.1	0 120 240	Evaluate thermal margin in critical area and reactivity calculations and cooldown control.	Control Performance Evaluation	074
Structural Support Supply Plenum Temperature (Low)	-8.6 -8.6 -8.6 -8.6	0.0 4.0 8.0 16.0	TBD TBD TBD TBD	Calculate thermal power and detect unsafe operating conditions.	Control Performance Evaluation	075
NSS Outlet to Turbine Temperature (Low)	-28.0 -28.0 -28.0	7.0 7.0 7.0	TBD TBD TBD	Evaluation of adequacy of flow in pressure vessel annulus and reflector outlets for state point verification	Control Performance Evaluation	070
NSS Inlet from Turbine Temperature (Low)	-32.5 -32.5 -32.5	3.0 3.0 3.0	0 120 240	Detect unsafe operating conditions and or incipient failure.	Control	071
Structural Support Exhaust Plenum Temperature (Low)	-7.0 -7.0 -7.0	22.0 22.0 22.0	0 120 240	Calculate heat pickup in system and detect unsafe operating conditions.	Control	077
Support Plate Material Temperature (Low)	-6.5 -6.5 -6.5	0 8.0 19.0	0 0 0	Cooldown control initiation and to detect unsafe operating conditions.	Control	079

* This is reactor station. Reactor station 0.0 is equivalent to engine station + 131.73

TABLE 1-1 (CONTINUED)

Measurement Description	Transducer Location			Measurement Justification	Measurement Intended Use	Instrumentation Design Criteria Sheet No.
	Sta*	R	θ			
Control Drum	26.0	23.0	0	Detect unsafe operating conditions.	Control	103
Vane	26.0	23.0	120			
Temperature	26.0	23.0	240			
(Low)	26.0	23.0	TBD			
Core Inlet	-3.2	0.0	0	Evaluate reactor performance and detect unsafe operating conditions and/or incipient failures.	Control Performance Evaluation	073
Plenum	-3.2	0.0	120			
Temperature	-3.2	8.0	120			
(Low)	-3.2	8.0	240			
	-3.2	19.0	240			
	-3.2	19.0	0			
Shield	-18.0	0.0	TBD	Monitor material temperatures for shutdown control, and detect unsafe operating conditions.	Control	064
Material	-18.0	10.0	TBD			
Temperature	-22.5	19.0	TBD			
(Low)						
Final Seal Exit	49.0	20.0	0	Evaluation of lateral support performance and flow effect on chamber temperature to detect unsafe operating conditions.	Control Performance Evaluation	072
Gas	49.0	20.0	120			
Temperature	49.0	20.0	240			
(Medium)						
Structural Support	8.0	0.0	0	Evaluate parameters for cooldown control, and detect unsafe operating conditions.	Control Performance Evaluation	076
Liner	50.0	16.0	300			
Temperature	(10 over above location range)					
(Medium)						
Sta. 0.2 Fuel	0.2	TBD	TBD	Detection of unsafe operating conditions for orifice braze and for pulse cooldown control.	Control	067
Element	0.2	TBD	TBD			
Temperature	0.2	TBD	TBD			
(Medium)	0.2	TBD	TBD			
Core Unfueled	26.0	0	TBD	Startup reactor control and detect unsafe operating conditions and/or incipient failures.	Control	068
Element	26.0	18.0	TBD			
Temperature	(21 over above location range)					
(High)						

TABLE 1-1 (CONTINUED)

Measurement Description	Transducer Sta*	Location R	θ	Measurement Justification	Measurement Intended Use	Instrumentation Design Criteria Sheet No.
Cluster Exit Gas Temperature (High)	55.0 55.0 (21 over above location range)	0.0 16.0	TBD TBD	Monitor cluster exit gas tempera- ture for control purposes and detect unsafe operating conditions and/or incipient failures.	Control	063
Reflector Inlet Plenum Temperature (RTT)	58.0 58.0 58.0	25.0 25.0 25.0	0 120 240	Control of pre-start progress, evaluate reactor performance, and detect assymetry in nozzle tubes effluent to verify state point.	Control Performance Evaluation	104
Core Nuclear Power (Low Range) Neutronic	26.0 26.0 26.0 26.0	28.0 28.0 28.0 28.0	TBD TBD TBD TBD	Monitor core nuclear power from subcritical source level to approx. 5 decades above source power.	Control	037
Core Nuclear Power (Inter- mediate Range) Neutronic	26.0 26.0 26.0 26.0	28.0 28.0 28.0 28.0	TBD TBD TBD TBD	Monitor core nuclear power over approx. 5 decades with 1 decade overlap of low range detector.	Control	038
Core Nuclear Power (High Range) Neutronic	26.0 26.0 26.0 26.0	28.0 28.0 28.0 28.0	TBD TBD TBD TBD	Monitor core nuclear power from 1 decade overlap of intermediate range to 0.5 decade beyond normal full power.	Control Failure Mode Evaluation	039
Structural Support System Load	-8.0 -8.0 -8.0 -8.0	0 TBD TBD TBD 15.75	TBD TBD TBD TBD	Monitor core axial cluster load for detecting unsafe operating conditions.	Control	062

* This is reactor station. Reactor station 0.0 is equivalent to engine station + 131.73.

TABLE 1-1 (CONTINUED)

<u>Measurement Description</u>	<u>Transducer Sta*</u>	<u>Location</u>		<u>Measurement Justification</u>	<u>Measurement Intended Use</u>	<u>Instrumentation Design Criteria Sheet No.</u>
Core Support Plate	-7.0	22.0	TBD	Detect unsafe operating conditions.	Control	080
Vibration	-7.0	22.0	TBD			
	-7.0	22.0	TBD			
Reflector Material	48.0	22.2	TBD	Detect unsafe operating conditions.	Control	061
Strain	48.0	22.2	TBD			
	48.0	22.2	TBD			
	48.0	22.2	TBD			
	48.0	22.2	TBD			
	48.0	22.2	TBD			
Reflector Standoff Bolts	57.7	23.0	17	Detect unsafe operating conditions.	Control	084
Strain	57.7	23.3	137			
	57.7	23.3	259			
Core Inlet Plenum	-1.8	0	0	Monitor noise level in plenum	Performance Evaluation Incipient Failure Detection	086
Acoustical	-1.8	15.0	120			
	-1.8	17.0	240			
Reflector Inlet Plenum	54.6	25.7	0	Monitor noise level in plenum	Performance Evaluation Incipient Failure Detection	088
Acoustical	54.6	25.7	120			
	54.6	25.7	240			
NSS Outlet to Turbine	-31.0	8.0	0	Monitor noise level at NSS Outlet	Performance Evaluation Incipient Failure Detection	087
Acoustical	-30.0	14.0	120			
	-29.0	20.0	240			
Reactor to PVCS Displacement	-30.5	9.0	0	Monitor axial motion of reactor in pressure vessel.	Performance Evaluation Incipient Failure Detection	081
	-30.5	9.0	120			
	-30.5	9.0	240			

* This is reactor station. Reactor station 0.0 is equivalent to engine station + 131.73.

TABLE 1-1 (CONTINUED)

<u>Measurement Description</u>	<u>Transducer Location</u>			<u>Measurement Justification</u>	<u>Measurement Intended Use</u>	<u>Instrumentation Design Criteria Sheet No.</u>
	<u>Sta*</u>	<u>R</u>	<u>θ</u>			
Core Radial Displacement	1.2 48.3 (9 over above location range)	23.4 23.4	0 300	Monitor core radial motion.	Performance Evaluation Incipient Failure Detection	041
Core Axial Displacement	-10.0 -10.0 -10.0	0.0 12.0 18.0	TBD TBD TBD	Monitor core axial motion.	Performance Evaluation Incipient Failure Detection	040
Central Shield, Flux (Fast Neutron)	-25.5 -25.5 -25.5	0.0 10.0 21.5	0 20 40	To detect unsafe operating conditions and/or incipient failures.	Control Performance Evaluation	096
Reflector, Flux (Fast Neutron)	26.0 26.0 12.0	28.0 28.0 28.0	120 140 160	Monitor fast neutron flux external to reflector.	Performance Evaluation Incipient Failure Detection	100
Shield, Flux (Thermal Neutron)	-25.5 -25.5 -25.5	0.0 10.0 21.5	0 20 40	Monitor thermal neutron flux forward of shield.	Performance Evaluation Incipient Failure Detection	097
Reflector, Flux (Thermal Neutron)	26.0 26.0 12.0	28.0 28.0 28.0	60 80 100	Monitor thermal neutron flux external to reflector.	Performance Evaluation Incipient Failure Detection	101
Reflector, Dose Rate (Gamma)	26.0 26.0 12.0	28.0 28.0 28.0	0 20 40	Monitor gamma dose rate external to reflector.	Performance Evaluation Incipient Failure Detection	099
Central Shield Dose Rate (Gamma)	-25.5 -25.5 -25.5	0.0 10.0 21.5	0 20 40	To detect unsafe operating conditions and/or incipient failures.	Control Performance Evaluation	095

* This is reactor station. Reactor station 0.0 is equivalent to engine station + 131.73.

2.0 LOW TEMPERATURE RESISTANCE TEMPERATURE TRANSDUCER (RTT)

2.1 REQUIREMENTS

Resistance temperature transducers (RTT's) must be capable of sensing the reflector inlet plenum temperatures during normal and emergency operating modes within the performance requirements stated in Table 2-1. Table 2-1 shows the various requirements and the traceability of these requirements.

2.2 DESIGN APPROACH CHARACTERISTICS

The RTT accuracy performance characteristic was derived from WANL-TME-1876, "Error Band Limits for WANL Measurements on XE-2 . "

The RTT temperature range performance and frequency response characteristics were taken from DRM 51912, "Instrumentation Comparison Matrix - Low Temperature Measurements . "

The ambient pressure range known to date is that experienced in the previous technology testing program which was 0.5 to 900 psig.

2.3 DESIGN APPROACH DESCRIPTION

There are two design approaches considered for RTT's. These are WANL P/N 979D161H01, Temtech Model Number X1137-2, and WANL P/N 979D162G02, Rosemount Model Number 134EB1.86. Both of these units have a platinum resistance element and are the identical size and configuration, including the integral metal sheathed four-conductor cable, except for the sensing tip. The Temtech Model has a 0.250 inch diameter sensing tip while the Rosemount unit is 0.350 inch in diameter. Both units were tested extensively in the Technology Development Program by WANL and AGC and were used by WANL in the NRX testing series. During those testing programs the platinum resistance element type RTT showed good accuracy at low temperatures; however, a constant drift attributed to fast neutron damage above 5×10^{14} nvt does exist. The characteristics of the drift and annealing effects due to radiation are not yet well known; it may appear after testing that correction of data to compensate these effects will provide the required accuracy for the data. Documentation of testing and analytical results is given in References 1 through 4. These units require a 2 milliampere constant current power supply working into a 1200 ohm load. There will be one four-conductor cable of 0.090 inch diameter for each of the three required measurements.

2.4 DESIGN APPROACH SELECTION

The selected design approach is the Rosemount Model No. 134EB1.86 and is shown by WANL P/N 979D162G02.

Both candidate design approaches performed equally well in the technology development and NRX testing series programs. All of the requirement characteristics tested to date, as shown in Table 2-2, are met or exceeded by both designs. Both are platinum resistance wire types, capable of measuring temperatures over a range of 35 to 850°R with a $\pm 5^\circ\text{R}$ accuracy when supplied with a constant current source. The design selection was made on the basis that Temtech, Inc. is no longer in business.

2.5 REFERENCES

1. NERVA Program Instrumentation Data Book, AGC Serial 7168.04 (0716) Volume III, Book III, Pages RT-51.1 to RT-51-SD.3.
2. "NRX-A5 Temperature Sensor Evaluation, "WANL Report No. EI-8325, October 19, 1967.
3. "NRX-A6 Transducer Evaluation Report, "WANL-TME-1863, December 1968.
4. "Radiation Effects Testing GTR-18, "AGC-RN-S-0370.

TABLE 2-1
LOW TEMPERATURE RTT REQUIREMENTS

<u>Characteristic</u>	<u>Requirements</u>	<u>Traceability</u>
Range	60-700°R	IDC-104
Accuracy	+ 5°R	EC6775 65-Table 1
Response Time	80 msec	6775 65-Table 1
Frequency Response	2.0 Hz	IDC-104
Reliability	0.999900	EC 6775 65-3.1.2.1
Maintainability	N/A	EC 6775 65-3.1.2.2
Useful Life		EC 6775 65-3.1.2.3
Operating Lifetime	600 minutes	
Operating Life - Cycles	60 max.	
Space Lifetime	3 years	
Ground Storage Time	5 years	
Environment		EC 6775 65-3.1.2.4
Natural	Inert-Except during operation	
Induced		
Nuclear		IDC-104
Gamma Dose Rate	5.06(8) R(c)/Hr.	
Fast Neutron Flux (E>1 MeV)	5.14(13) nv	
Fast Neutron Fluence (E>1 MeV)	1.85(18) nvt	
Loads		
Shock	N/A	
Vibration	(TBD)	
Thermal	60-700°R	IDC-104
Pressure Range	10(-9) Torr to 1200 Psia	IDC-104
Transportability	N/A	EC 6775 65-3.1.2.5
Human Performance	Operation simple as possible	EC 6775 65-3.1.2.6
Safety	Normal	EC 6775 65-3.1.2.7
Fluid Compatibility	LH ₂ , GH ₂ , GN ₂ , GHe, Air	EC 6775 65-3.3.1.9
Design - Low Temperature	Platinum wire resistance element	EC 6775 65-3.3.1.15
Electromagnetic Interference	MIL-E-6051	EC 6775 65-3.3.9
Installation	DRM 52033	939J723

TABLE 2-2
DESIGN APPROACH CHARACTERISTICS - LOW TEMPERATURE RTT

<u>Characteristic</u>	<u>Requirement</u>	<u>Design Selection</u>
Range	60-700°R	35-850°R
Accuracy	$\pm 5^{\circ}\text{R}$	$\pm 5^{\circ}\text{R}$
Response Time	80 msec.	64 msec.
Frequency Response	2.0 Hz	2.5 Hz
Reliability	0.999900	(TBD)
Maintainability	N/A	N/A
Useful Life		
Operating Lifetime	600 minutes	(TBD)
Operating Life - Cycles	60 max.	(TBD)
Space Lifetime	3 years	(TBD)
Ground Storage Time	5 years	(TBD)
Environment		
Natural	Inert - Except during operation	By Design
Induced		
Nuclear		
Gamma Dose Rate	5.06(8) R(c)/Hr	(TBD)
Fast Neutron Flux (E>1 Mev)	5.14(13) nv	(TBD)
Fast Neutron Fluence (E > 1 Mev)	1.85(18) nvt	(TBD)
Loads		
Shock	N/A	N/A
Vibration	(TBD)	(TBD)
Thermal	60-700°R	35-850°R
Pressure Range	10(-9) Torr to 1200 Psia	(TBD)
Transportability	N/A	N/A
Human Performance	Operation simple as possible	Compatible
Safety	Normal	Compatible
Fluid Compatibility	LH ₂ , GH ₂ , GN ₂ , GHe, Air	By Design
Design - Low Temperature	Platinum wire element	Platinum wire element
Electromagnetic Interference	MIL-E-6051	(TBD)
Installation	DRM 52033	Compatible

3.0 LOW TEMPERATURE THERMOCOUPLE (T/C)

3.1 REQUIREMENTS

The low temperature thermocouples must be capable of sensing the required measurements as shown in Table 1-1 during the normal and emergency operating modes within the performance requirements stated in Table 3-1. Table 3-1 shows the maximum characteristic requirements for all low temperature thermocouple measurements and the traceability of these requirements.

3.2 DESIGN APPROACH CHARACTERISTICS

The requirements (see Table 3-2) for possible trade-off were established to be those design approach characteristics that present a distinct advantage or disadvantage to the requested measurement requirement.⁽¹⁾ These characteristics have been established to be frequency response, system accuracy, and routing/configuration requirements. The operating temperature range is a basic requirement and, hence, not a trade-off requirement. The type of thermocouples considered for the low temperature measurements are metal sheathed copper-constantan exposed and grounded junctions with varying sensing end diameters.

3.2.1 Frequency Response

This trade-off requirement is compared with the response characteristics of each design approach and evaluated in a comparison matrix (see Table 3-3). The response time (τ) is proportional to frequency response (in Hertz) for an ideal transducer in the relationship⁽²⁾ $(\tau) = 1/2\pi f_{3db}$. The response time of thermocouples is dependent on the configuration and type of the sensing end. The time response increases with the larger mass of the sensing end. A sensor which exhibits a frequency response slower than the measurement requirement will not permit its use for that application. Frequency response for the design approaches being considered is tabulated below:

- Exposed Junction T/C's - 10 Hz
- Grounded Junction, 0.020" diameter - 2.5 Hz
- Grounded Junction, 0.045" diameter - 2.2 Hz
- Grounded Junction, 0.065" diameter - 1.1 Hz

3.2.2 Systems Accuracy

The accuracy requirement covers the measurement system, not just the sensor accuracy; sensor accuracy is a portion of the measurement data accuracy. Accuracy limits for each design approach were established using the nominal expected temperature.⁽³⁾

Since the flight data system accuracies have not yet been established in the system specifications, the system accuracy requirement is compared with the design approach accuracies⁽⁴⁾ as experienced in the technology testing program.

The system accuracies established for the various design approaches are tabulated below:

Exposed Junction T/C's $\pm 6^{\circ}\text{R}$

Grounded Junction Copper-Constantan (C/C) (0.020") $\pm 6^{\circ}\text{R}$

Grounded Junction Copper-Constantan (C/C) (0.045") $\pm 6^{\circ}\text{R}$

Grounded Junction Copper-Constantan (C/C) (0.065") $\pm 6^{\circ}\text{R}$

The capabilities do not meet the accuracy requirements in all applications; further development might improve the accuracy of the devices.

3.2.3 Routing Configuration

The routing and configuration trade-off requirements were derived from the instrumentation application studies that were performed for each measurement and reported in the referenced DRM's. These studies indicated the problem and requirements of cable routing, including the necessary bend radii and the hole pass-through sizes dictated by the NSS reference design. These studies also indicated the available space for sensor mounting and the limiting sensing tip size. These design approach characteristics were related to the routing and configuration requirements and rated according to performance. Some of the design approaches could not be used for certain applications that require small bend radii or small clearances for installation without major design changes in the NSS mechanical components. Other design approaches could not be used with the NSS reference design because of a lack of available mounting space or due to the type of measurement. For example, to measure material temperature, a grounded junction is needed, eliminating the use of an exposed junction thermocouple (Reference 5, 6, 7, and 8).

3.3 DESIGN APPROACH DESCRIPTION

There were four design approaches considered for C/C thermocouples. These consisted of

- (1) an exposed junction device, 0.065" sheath diameter
- (2) a grounded junction device, .020" diameter
- (3) a grounded junction device, .045" diameter
- (4) a grounded junction device, .065" diameter

Exposed junction devices were considered where dynamic temperature response was required. The sheath size of the grounded junction devices satisfy the time response and/or routing configuration requirements. The designs of these T/C's are shown on WANL drawing 945C906, 963B363, 964B039, and sketch SK-I-391. Within their design temperature range all units have operated satisfactory during the development and NRX testing series. (Refer to References 9, 10, 11, and 12.)

3.4 COMPARISON MATRIX

The low temperature measurement applications have been combined into thirteen categories. The applications of each category contain the same trade-off requirements. These application categories are compared with their trade-off requirements of frequency response, system accuracy, and routing/configuration for each design approach. This composite matrix is shown in Table 3-3.

3.5 DESIGN APPROACH SELECTION

The selected designs are as follows:

C/C - Grounded (0.020"): A copper-constantan metal sheathed thermocouple with a grounded junction of 0.020 inch diameter.
WANL-P/N SK-I-391. (Refer to Figure 3-1.)

C/C - Exposed (0.065"): A copper-constantan metal sheathed thermocouple with an exposed junction of 0.065 inch diameter.
WANL P/N 945C906H01. (Refer to Figure 3-2.)

C/C - Grounded (0.045"): A copper-constantan metal sheathed thermocouple with a grounded junction of 0.045 inch diameter.

WANL P/N 964B039. (Refer to Figure 3-3.)

The exposed junction device is selected for the Core Inlet Plenum as it is superior to the others for the routing and configuration requirement and will permit staking of the device for proper positioning although it does not meet the accuracy requirement. The accuracy capability of all the design approaches is the same (about $\pm 6^{\circ}\text{R}$) at the normal operating temperature of approximately 300°R . Only a platinum resistance RTT could meet the $\pm 5^{\circ}\text{R}$ accuracy requirement but it cannot be mounted in the plenum area because of its larger size.

The grounded junction, .020" diameter device is selected for the Support Stem Supply Plenum, Support Stem Exhaust Plenum, NSS Inlet from Turbine, NSS Outlet to Turbine, and the Reflector Material measurements. This unit is superior in system accuracy, routing and configuration, and frequency response. A grounded junction is less fragile than an exposed junction and the frequency response of the smaller diameter unit greater than for the larger diameter.

The grounded junction, .045" diameter device is selected for the Core Support Plate, Control Drum Vane, and Central Shield material measurements as it combines the ruggedness of the larger diameter thermocouples for installation with the smaller mass required to meet the frequency response requirements. While the 0.065" unit would be easier to mount, the frequency response would prohibit its use.

3.6 REFERENCES

1. WANL DRM 51912, "Instrumentation Comparison Matrix, Low Temperature Measurements. "
2. H. N. Norton, "Handbook of Transducers for Electronic Measuring Systems, " page 44., Prentice-Hall, Inc.
3. EG677565, NSS Instrumentation Specification, Table 1.

4. WANL-TME-1876, "Error Band Limits for WANL Measurements on XE-1," January 1968.
5. WANL DRM 51903, "Installation - Control Shield and Cluster Plate. "
6. WANL DRM 52021, "Installation - Cluster Support Stem. "
7. WANL DRM 52033, "Installation - Reflector. "
8. WANL DRM 52036, "Installation - Support Plate and Plena. "
9. WANL-TME-907, "Calibration Specifications for Thermocouples, " August 1964.
10. WANL-TME-481, Addendum 1 "Bending Test of Thermocouples, " September, 1963
11. WANL-TME-700, "Test Report on WANL Radiation Test at GTR of NERVA Components, " March 1964.
12. WANL-TME-1863, "NRX-A6 Transducer Evaluation Report, " December, 1968.

TABLE 3-1
LOW TEMPERATURE THERMOCOUPLE REQUIREMENTS

<u>Characteristics</u>	<u>Requirements</u>	<u>Traceability</u>
Range	40 - 1000° R	IDC-064, 070, 071, 073, 074, 075, 077, 079, 103
Accuracy	+5° R -	EC677565-Table 1
Response Time	0.075 sec.	EC677565-Table 1
Frequency Response	2.0 Hz	IDC-070, 072, 073, 075, 077
Reliability	0.999900	EC677565-3.1.2.1
Maintainability	N/A	EC677565-3.1.2.2
Useful Life		EC677565-3.1.2.3
Operating Life - Time	600 minutes	
Operating Life - Cycles	60 max.	
Space Lifetime	3 years	
Ground Storage - Time	5 years	
Environment		EC677565-3.1.2.4
Natural	Inert - Except during operation	
Induced		
Nuclear		IDC-073, 074
Gamma Dose Rate	5.65(9) R(c)/Hr	
Fast Neutron Flux (E>1 MeV)	7.14(14) nv	
Fast Neutron Fluence (E>1 MeV)	2.57(19) nvt	
Loads		
Shock	N/A	
Vibration	(TBD)	
Thermal	40 - 1000° R	IDC-(ALL)
Pressure Range	10(-9) Torr to 1200 Psia	IDC-(ALL)

TABLE 3-1 CONT' D

<u>Characteristics</u>	<u>Requirements</u>	<u>Traceability</u>
Transportability	N/A	EC677565-3. 1. 2. 5
Human Performance	Operation simple as possible	EC677565-3. 1. 2. 6
Safety	Normal	EC677565-3. 1. 2. 7
Fluid Compatibility	LH ₂ , GH ₂ , GN ₂ , GHe, Air	EC677565-3. 3. 1.9
Design - Low Temperature	Copper-Constantan Thermoelements, Exposed or Grounded Junctions	EC677565-3. 3. 1.15
Electromagnetic Interference	Mil-E-6051	EC677565-3. 3. 9
Installation	DRM 51903 DRM 52031 DRM 52033 DRM 52036	939J723

TABLE 3-2

DESIGN APPROACH CHARACTERISTICS - LOW TEMPERATURE THERMOCOUPLES

<u>Characteristics</u>	<u>Requirements</u>	<u>Design Selection</u>
Range	40-1000 ^o R	35-1210 ^o R
Accuracy	+5 ^o R	+20 - 25 ^o R
Response Time	(TBD)	(TBD)
Frequency Response	2.0 Hz	2.5 Hz
Reliability	0.999900	(TBD)
Maintainability	N/A	N/A
Useful Life		
Operating Lifetime	600 minutes	(TBD)
Operating Life - Cycles	60 max.	(TBD)
Space Lifetime	3 years	(TBD)
Ground Storage - Time	5 years	(TBD)
Environment		
Natural		
Induced	Inert - Except During Operation	By Design
Nuclear		
Nuclear		
Gamma Dose Rate	5.65(9) R(c)/Hr	(TBD)
Fast Neutron Flux (E>1 MeV)	7.14(14) nv	(TBD)
Fast Neutron Fluence (E>1 MeV)	2.57(19) nvt	(TBD)
Loads		
Shock	N/A	N/A
Vibration	(TBD)	(TBD)
Thermal	40-1000 ^o R	35-1210 ^o R
Pressure Range	10(-9) Torr to 1200 Psia	(TBD)

TABLE 3-2 CONT'D

<u>Characteristics</u>	<u>Requirements</u>	<u>Design Selection</u>
Transportability	N/A	N/A
Human Performance	Operation Simple as Possible	Compatible
Safety	Normal	Compatible
Fluid Compatibility	LH ₂ , GH ₂ , GN ₂ , GHe, Air	By Design
Design - Low Temperature	Copper-Constantan Thermo- elements, exposed or grounded junctions.	By Design
Electromagnetic Interference	Mil-E-6051	(TBD)
Installation	DRM 51903 DRM 52021 DRM 52033 DRM 52036	Compatible

TABLE 3-3
COMPOSITE COMPARISON MATRIX

Measurement			Design Approach	C/C-Exposed (0.065)-Gas			C/C-Grounded (0.020)-Gas & Mat'l.			C/C-Grounded (0.045)-Gas & Mat'l.			C/C-Grounded (0.065)-Mat'l.			Selection
Application	Type	Trade-Off Requirement	Characteristics	10 Hz	+6°R	Fragile Large Rad.	2.5 Hz	+6°R	Fragile Small Rad.	2.2 Hz	+6°R	Med. Rad.	1.1 Hz	+6°R	Large Rad.	
Support Stem Supply Plenum	Gas	Frequency Response-2 Hz System Accuracy-+5°R Rout/Conf. -Small Install		1	B	3	1	B	1	2	B	2	C	B	3	C/C-Grounded (0.020)
NSS Inlet from Turbine	Gas	Frequency Response-2 Hz System Accuracy-+5°R Rout/Conf. -Small Size		1	B	3	1	B	1	2	B	2	C	B	3	C/C-Grounded (0.020)
Core Support Plate	Mat'l.	Frequency Response-1 Hz System Accuracy-+20°R Rout/Conf. -Normal		1	1	C	1	1	3	1	1	2	2	1	1	C/C-Grounded (0.045)
Control Drum Vane	Mat'l.	Frequency Response-1 Hz System Accuracy-+10°R Rout/Conf. -Med. Size		1	1	C	1	1	2	1	1	1	2	1	3	C/C-Grounded (0.045)
Refl. Mat'l.	Mat'l.	Frequency Response-1 Hz System Accuracy-+20°R Rout/Conf. -Small Size		1	1	C	1	1	1	1	1	2	2	1	3	C/C-Grounded (0.020)
NSS Outlet to Turbine	Gas	Frequency Response-2 Hz System Accuracy-+10°R Rout/Conf. -Small Size		1	1	3	1	1	1	2	1	2	C	1	3	C/C-Grounded (0.020)
Support Stem Exhaust Plenum	Gas	Frequency Response-2 Hz System Accuracy-+10°R Rout/Conf. -Small Rad.		1	1	C	1	1	1	2	1	C	C	1	C	C/C-Grounded (0.020)
Core Inlet Plenum	Gas	Frequency Response-2 Hz System Accuracy-+5°R Rout/Conf. -Normal		1	B	1	1	B	3	2	B	2	C	B	1	C/C-Exposed (0.065)
Central Shield	Mat'l.	Frequency Response-1 Hz System Accuracy-+20°R Rout/Conf. -Med. Size		1	1	C	1	1	2	1	1	1	2	1	3	C/C-Grounded (0.045)

NOTES "1" - Requirements - First Choice
"2" & "3" - Also Meets Requirements

"A" - Require System Design Changes to Meet Requirements
"B" - Will not Meet Accuracy Requirement, Best Approximation

"C" - Sensor/NSS Basic Design will not Permit use

NOTES

1. MANUFACTURE TO E 675503 SPECIFICATION
2. COMPLETED T/C INSULATION RESISTANCE TO BE 100 MEGOHMS @ 50 VDC MINIMUM
3. THERMOCOUPLE WIRES (COPPER-CONSTANTAN) TO BE CONTINUOUS ENTIRE LENGTH
4. LENGTHS A AND B TO BE DETERMINED PER EACH APPLICATION
5. SHEATH IS TO BE CONTINUOUS ENTIRE LENGTH

— REFERENCE SKETCH SK I 391 1-29-70 —

Figure 3-1. Thermocouple - Copper-Constantan, Grounded Junction

Figure 3-2. Exposed Junction Thermocouple, Part Number 945C906

Figure 3-3. Copper-Constantan Thermocouple, Part Number 964B039

4.0 MEDIUM TEMPERATURE THERMOCOUPLE (T/C)

4.1 REQUIREMENTS

The medium temperature thermocouples must be capable of sensing the required measurements as shown in Table 1-1 during the normal and emergency operating modes within the performance requirements stated in Table 4-1. This table shows the maximum characteristic requirements for all medium temperature measurements and the traceability of these requirements.

4.2 DESIGN APPROACH CHARACTERISTICS

The requirements for possible trade-off were selected as those design approach characteristics that present a distinct advantage or disadvantage to the requested measurement requirement.⁽¹⁾ These characteristics are frequency response, system accuracy, and routing/configuration requirements. They are shown in Table 4-2. The operating temperature range is a basic requirement and, hence not a trade-off requirement. The type of thermocouples considered for the medium temperature measurements are metal sheathed chromel-alumel (Ch/Al) grounded junction devices with varying sensing end diameters. Exposed junction thermocouples are not considered for these applications since their inherently better frequency response is not required and their lack of ruggedness is detrimental in routing.

4.2.1 Frequency Response

This trade-off requirement is compared with the response characteristics of each design approach and evaluated in a comparison matrix. The response time of each design approach is dependent on the sensor configuration and type. A sensor which exhibits a frequency response lower than the measurement requirement will obviate its use for that application.

The relationship between response time and frequency response is presented in Section 3.2.1, Low Temperature Thermocouples.⁽²⁾

Frequency responses for the design approaches being considered are:

Grounded Junction, 0.020" diameter - 2.5 Hz

Grounded Junction, 0.045" diameter - 2.2 Hz

4.2.2 System Accuracy

The accuracy requirement is total measurement uncertainty and not merely sensor accuracy; sensor accuracy is a portion of the measurement data accuracy. Accuracy limits for each design approach were established using the nominal expected temperature.⁽³⁾ Since the flight data system accuracies have not yet been established in the system specifications, the system accuracy requirement is compared with the design approach accuracies as experienced in the technology testing program.⁽⁴⁾ The system accuracy for the chromel-alumel grounded junction thermocouples is $\pm 30^{\circ}\text{R}$.

4.2.2 Routing/Configuration

The routing and configuration trade-off requirements were derived from the instrumentation application studies that were performed for each measurement and reported in the referenced DRM's. These studies indicated the requirements for cable routing such as the necessary bend radii and the hole pass-through sizes to concur with the NSS reference design. These studies also indicated the available space for sensor mounting and configuration requirements and rated according to performance. Some of the design approaches could not be used for certain applications that require small bend radii or which have small clearances for installation. Other design approaches could not be used with the NSS reference design because of a lack of available mounting space. (See References 5, 6 and 7.)

4.3 DESIGN APPROACH DESCRIPTIONS

There were two design approaches considered for Ch/Al thermocouples. Both were grounded junction devices, one with an 0.045" diameter sheath and the other with an 0.020" diameter. The sheath size of the T/C's were considered in order to satisfy the time response and/or routing configuration requirements. The designs of these T/C's are shown on WANL drawings 963B361 and 978D186. Within their design temperature range both units operated satisfactorily during the development and NRX testing series. (Refer to References 8, 9, 10, and 11.)

4.4 COMPARISON MATRIX

The medium temperature measurement applications have been combined into three categories. These categories (by application) are compared with their trade-off requirements of frequency response, system accuracy, and routing/configuration for each design approach. This composite comparison matrix is shown in Table 4-3.

4.5 DESIGN APPROACH SELECTION

The designs selected are:

CH/AL - GRD (0.020"): A chromel-alumel metal sheathed thermocouple with a grounded junction of 0.020 inch diameter.

WANL P/N 978D186.

CH/AL - GRD (0.045"): A chromel-alumel metal sheathed thermocouple with a grounded junction of 0.065 inch diameter.

WANL P/N 963B361.

The grounded junction, 0.020" diameter thermocouple is selected for the station 0.2 Fuel Element and the Support StemLiner Measurements because it best meets the intricate routing requirements of these applications. The accuracy of both design approaches is the same or about $\pm 12^{\circ}\text{R}$ at the normal operating temperatures. The frequency response is met almost equally well by both designs.

The grounded junction, 0.045" diameter thermocouple is selected for the final seal exit gas measurement since the larger diameter instrument is more rugged and best facilitates the recommended mode of installation. The accuracy and frequency response performances are essentially the same in both designs.

4.6 REFERENCES

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TABLE 4-1
MEDIUM TEMPERATURE REQUIREMENTS

<u>Characteristics</u>	<u>Requirements</u>	<u>Traceability</u>
Range	200-2000° R	IDC-067, 072, 076
Accuracy	+20° R	EC677565-Table 1
Response Time	80 msec.	EC677565-Table 1
Frequency Response	2.0 Hz	IDC-(ALL)
Reliability	0.999900	EC677565-3.1.2.1
Maintainability	N/A	EC677565-3.1.2.2
Useful Life		EC677565-3.1.2.3
Operating Lifetime	600 minutes	
Operating Life - Cycles	60 max.	
Space Lifetime	3 years	
Ground Storage Time	5 years	
Environment		EC677565-3.1.2.4
Natural		
Induced	Inert - Except During Operation	
Nuclear		IDC- (ALL)
Gamma Dose Rate	1.90(10) R(C)/Hr	
Fast Neutron Flux (E>1 MeV)	3.361(15) nv	
Fast Neutron Fluence (E>1 MeV)	1.21(20) nvt	
Loads		
Shock	N/A	
Vibration	(TBD)	
Thermal	700-2000° R	IDC-(ALL)
Pressure Range	10(-9) Torr to 1200 Psia	IDC-(ALL)
Transportability	N/A	EC677565-3.1.2.5

TABLE 4-1 (CON'D)
MEDIUM TEMPERATURE REQUIREMENTS

<u>Characteristics</u>	<u>Requirements</u>	<u>Traceability</u>
Human Performance	Operation Simple as Possible	EC677565-3. 1. 2. 6
Safety	Normal	EC677565-3. 1. 2. 7
Fluid Compatibility	LH ₂ , GH ₂ , GN ₂ , GHe, Air	EC677565-3. 3. 1.9
Design - Low Temperature	Chromel-Alumel Thermoelements, exposed or grounded junctions	EC677565-3. 3. 1.15
Electromagnetic Interference	MIL-E-6051	EC677565-3. 3. 9
Installation	DRM 52021 DRM 52034 DRM 52038	939J723

TABLE 4-2
DESIGN APPROACH CHARACTERISTICS

<u>Characteristics</u>	<u>Requirement</u>	<u>Design Selection</u>
Range	200-2000° R	140-2200° R
Accuracy	+20° R	+12° R
Response Time	80 msec.	64 msec.
Frequency Response	2.0 Hz	2.5 Hz
Reliability	0.999900	(TBD)
Maintainability	N/A	N/A
Useful Life		
Operating Lifetime	600 minutes	(TBD)
Operating Life - Cycles	60 max.	(TBD)
Space Lifetime	3 years	(TBD)
Ground Storage Time	5 years	(TBD)
Environment		
Natural		
Induced	Inert - Except During Operation	By Design
Nuclear		
Gamma Dose Rate	1.90(10) R(C)/Hr	(TBD)
Fast Neutron Flux (E > 1 Mev)	3.36(15) nv	(TBD)
Fast Neutron Fluence (E > 1 Mev)	1.21(20) nvt	(TBD)
Loads		
Shock	N/A	N/A
Vibration	(TBD)	(TBD)
Thermal	200-2000° R	140-2200° R
Pressure Range	10(-9) Torr to 1200 Psia	(TBD)
Transportability	N/A	N/A
Human Performance	Operation Simple as Possible	Compatibility

TABLE 4-2 (CON'D)
DESIGN APPROACH CHARACTERISTICS

<u>Characteristics</u>	<u>Requirement</u>	<u>Design Selection</u>
Safety	Normal	Compatibility
Fluid Compatibility	LH ₂ , GH ₂ , GN ₂ , GHe, Air	By Design
Design - Low Temperature	Chromel-Alumel Thermoelements, exposed or grounded junction	By Design
Electronic Interference	MIL-E-6051	(TBD)
Installation	DRM 52021 DRM 52034 DRM 52038	Compatible

TABLE 4-3
COMPARISON MATRIX

Application	Measurement		Design Approach 0.020 Dia.		0.045 Dia.		<u>Selection</u>
	Type	Trade-Off Reqmt.	2.5 Hz	Fragile Small Rad	2.2 Hz	Large Rad	
Station 0.2 Fuel Element	Mat'l.	Freq. Response-2.0 Hz Rout/Config. -Small	1	1	1	2	0.020 Dia.
Final Seal Exit Gas	Gas	Freq. Response-2.0 Hz Rout/Config. -Rugged	1	2	1	1	0.045 Dia.
Support Stem Liner	Mat'l.	Freq. Response-1 Hz Rout/Config. -Small	1	1	2	2	0.020 Dia.

NOTES: "1" - Meets requirements - first choice
"2" - Also meets requirements

5.0 CLUSTER EXIT GAS HIGH TEMPERATURE T/C

5.1 REQUIREMENTS

The cluster exit gas thermocouples must be designed to meet the requirements outlined in Table 5-1 for normal and emergency operating modes. The units will provide both diagnostic and control input measurements. Traceability of requirements is contained in Table 5-1.

5.2 DESIGN APPROACH CHARACTERISTICS

Because of the severe environments to which the cluster exit gas thermocouples are subjected, there are no well-defined candidate transducers available at this time. There are a number of basic material compatibility and survivability problems that must be evaluated before a valid design approach can be made. Some of these problem areas are:

- a) Structural integrity affected by the high temperature tensile strength and creep rupture strength of candidate tubing materials (i.e., thoriated tungsten, tungsten, tungsten/26% rhenium, doped tungsten).
- b) The tendency of thermocouple element wires to break when subjected to repeated thermal shocks.
- c) The reduction in insulation resistance of ceramic insulators with increased temperature, resulting in reduced device output due to shunting effects.
- d) The penetration of carbon into the sheath materials at high temperature, resulting in contamination of the insulation, as well as reaction with the sheath to form tungsten carbide, thereby reducing its structural integrity.

Design approach characteristics during development will be limited to material comparisons only. Trade-off characteristics are categorized as insulator, sheath, and T/C wire considerations.

5.2.1 Insulator Considerations

- 1) Electrical resistivity at 4600°R (ohm-cm).
- 2) Average linear coefficient of thermal expansion (440°R to 4600°R) (in./in./°R)

- 3) Melting point ($^{\circ}\text{R}$)
- 4) Material compatibility with sheath and T/C wires in helium atmosphere.
- 5) Temperature shock resistance based on $150^{\circ} \pm 25^{\circ}\text{R}/\text{sec}$ temperature change from 440°R to 4600°R .
- 6) Radiation effects on insulation characteristics.

5.2.2 Sheath Considerations

- 1) Melting point ($^{\circ}\text{R}$)
- 2) Yield strength (Psi)
- 3) Creep-rupture strength (Psi)
- 4) Material compatibility with insulators and T/C wire elements.
- 5) Environmental compatibility from 440°R to 4600°R in conjunction with H_2 and graphite.
- 6) Resistance to carbon penetration vs exposure time and temperature.
- 7) Temperature shock resistance based on $150^{\circ} \pm 25^{\circ}\text{R}/\text{sec}$ temperature change from 440°R to 4600°R .
- 8) Crystalline grain growth vs time and temperature.
- 9) Fabricability (i.e., capability of tubing to be bent at radius of 0.5 to 1" over a 90 degree arc and welded.

5.2.3 T/C Wire Considerations

- 1) Output repeatability.
- 2) Resistance to thermal shock.
- 3) Crystalline grain growth vs time and temperature (embrittlement).
- 4) Melting point ($^{\circ}\text{R}$).
- 5) Material compatibility.
- 6) Availability as calibrated thermoelements.

5.3 DESIGN APPROACH DESCRIPTION

The basic cluster exit gas design concept is dictated by the design of the reactor cluster end hardware so that cooling flow and basic mechanical structure are not affected. The concept is shown in Figure 5-7; however, specific dimensions, material, bend radii, etc., are yet to be determined. The details of this design will be generated based on evaluation of the candidate materials covered in this trade study, future testing, and trade-offs among the various measurement and structural requirements.

Calculations show that for minimum error the thermocouple should be positioned at 90 degrees to the gas stream⁽¹⁾. The curved configuration results from a desire to bring the thermocouple out of the cluster end and direct the sensing end perpendicular to the gas stream. The wall thickness of the sheath tubing is the limiting constraint on this configuration. The sheath for this configuration must have a tensile and creep-rupture strength of at least 8000 psi at 4600°R for 10 hours in order to qualify for use. Thoriated tungsten tubing may meet these requirements. A small junction mass must be used, since a large mass will degrade the response time of the instrument. These two conflicting requirements must be satisfied to use this configuration:

- 1) Small mass at the junction to insure fast response time.
- 2) Thick enough sheath wall to insure thermocouple strength at 4600°R.

Final dimensions on the instrument outside diameter and wall thickness will be determined after the results of the sheath tubing study are known.

Three other factors present problems when looking at the candidate design. One is the ability to bend the thoriated tungsten tubing (which is brittle at room temperature). Second is the possible weakening of the tubing where it is electron beam welded at the end cap screw. Third, obtaining a one-piece curved insulator made of BeO is difficult. A technique for bending the thoriated tungsten tubing at room temperature was developed by WANL. When the tubing is being drawn down to the specified sizes, it has a molybdenum insert inside. The usual practice is to etch this insert out of the tungsten tube after drawing. It was found that the tubing could be bent prior to removal of the insert without damage.

The second problem area, that of weakening during welding, is being worked on at this time. Several sample units have been welded, but some difficulty was experienced in obtaining a satisfactory joint.

The third problem area, that of obtaining a one-piece curved BeO insulator, is being investigated. The thermocouple design would ideally be constructed with a one-piece curved insulator at the sensing end. However, problems arise when trying to fire the BeO in the curved shape and hold tight tolerances both on the curved radius and in-line flatness. The material shrinks during firing, and it is difficult to control shrinkage. WANL has obtained some curved BeO insulators from Brush Beryllia Corporation but their radii were all different and they were wavy to varying degrees rather than flat. If these procurement problems cannot be overcome, an insulator made of BeO sections mated together to form the curve will be used.

Other modifications or designs for the cluster exit gas thermocouple have not been completely ruled out. For instance, the above thermocouple could be strengthened by a brace hanging down from the cluster end assembly. Los Alamos uses a bare wire approach which was evaluated but discarded because it would require some unacceptable cluster end redesign. At this time, the primary candidate for the cluster exit gas thermocouple is shown on Figure 5-7. None of the problem areas yet appear insurmountable and no large scale development of material is anticipated.

A summary of design description information based on the present maturity of development is given below:

- 1) Peripheral equipment requirements - Reference junctions.
- 2) Power requirements - None (self-powered).
- 3) Types of leads - sheathed (stainless steel) MgO insulated cable with two leads (tungsten and tungsten - 26% rhenium) to reference junction.
- 4) Outline configuration - Details TBD.
- 5) Unit weight - TBD.
- 6) Unit cost \$500 to \$1000 each (estimated).
- 7) Construction material - TBD.
- 8) Development status - Material testing initiated.

5.4 COMPARISON MATRIX

The comparison studies at this stage of development are centered around materials to be used for the sheath, insulation, and T/C element wires.

5.4.1 Sheath Materials Matrix

The first matrix is for the sheath materials. Because of the extreme temperature environment there are a very limited number of candidates. Tantalum was eliminated because of its incompatibility with hydrogen at temperatures to which it would be subjected during operation (hydriding).

Tungsten itself is one of the few elements that can be used in a graphite-hydrogen atmosphere at these high temperatures and still maintain some strength characteristics. The addition of thoria further increases the high temperature strength of the tungsten; therefore, tungsten-2% thoria is a prime candidate for the thermocouple sheath. With the maximum temperature of 4600°R, the use of a tungsten-26% rhenium sheath similar to that used on NRX-A6 is a possibility. The tubing study, therefore, includes an investigation into the characteristics of these three materials: thoriated tungsten, tungsten (pure), and tungsten-26% rhenium.

The primary purpose of the outer sheath of the thermocouple is to protect the thermocouple insulators and wires from the ambient environment and impart the mechanical strength required to hold the thermocouple in position.

Analysis has been performed based on use of a 10-mil wall, 0.090 inch diameter thoriated tungsten sheath. The results of these calculations are reported in DRM 51877,⁽²⁾ "Analysis of Proposed R-1 Exit Gas Thermocouple." A bending stress due to gas flow across the T/C tip of approximately 5000 psi was reported for rated conditions. For purposes of the material comparison matrices in TS 792, a 1.6 safety factor was applied to this figure to obtain

a material yield strength requirement of 8000 psi for a design employing the 10-mil wall, 0.090 inch diameter tubing. This was done to account for possible degradation due to carbiding, recrystallization of the material at the point of welding, and reduction in cross section due to forming the thermocouple curvature. The adequacy of this safety margin will be determined in later testing.

The properties that become important in the sheath material to be used are tabulated in the comparison matrix of Table 5-2. There is no material readily available that meets all these requirements. To obtain these properties will require testing of the basic materials and development work to obtain the required properties in the finished thermocouple sheath. For example, thoriated tungsten theoretically has the yield strength capability at 4600°R to meet the sheath 8000 psi requirements⁽²⁾. However, the off-the-shelf tubing tested by WANL had a yield strength of 6500 psi⁽³⁾. With the proper metallurgical techniques in forming the basic material and with control of the extrusion process, the desired strength properties are obtainable. Two other important limiting properties in the selection of the sheath material are the carbon penetration rate into the sheath at 4600°R, and the high temperature creep rate. These two properties have become extremely important since the reactor operating lifetime requirement has been extended to 10 hours duration. The comparison matrix on Table 5-2 indicates the status of candidate materials at this time.

The tabulated information on the tungsten-26% rhenium sheath is based on the results of its successful use in NRX-A6⁽⁴⁾ and XE-Prime and also on information supplied by LASL⁽⁵⁾ where more extensive testing on this material has been done. Its selection is doubtful, however because of its low carbon eutectic temperature. Post calibration testing of the NRX-A6 cluster exit gas thermocouples reported in WANL-TME-1925 shows evidence of sheath deterioration with only a short duration overshoot above 4600°R⁽⁶⁾.

Since the tungsten-2% thoria material appears the most promising at this time, the sheath development effort is concerned primarily with studying the preparation of the base material and upgrading the tubing fabrication techniques to obtain the tubing material strength characteristics required. The possibility of firing the tungsten tubing in the "green" form to obtain the required strength characteristics is being studied; the resultant product would be

available at a low cost by eliminating the drawing and/or extrusion process. Another advantage of working the tubing in a "green" form before firing is that it can be formed into almost any shape easily. A study of the present tubing fabrication techniques is planned. What effect different drawing and/or extrusion and annealing schedules have on the tubing characteristics must be investigated. Tubing manufacturers, such as Nuclear Metals, have indicated that the tubing characteristics could be improved if the buyer is willing to pay an increased cost covering the development of an optimized material working and annealing schedule.

A study is beginning on obtaining carbon penetration rates through the thoriated tungsten tubing at various temperatures to 4600°R . This study will determine what tubing thickness is required and/or what protective coatings may be required for a 10-hour run at 4600°R . LASL has performed substantial testing along these lines and much information is being obtained from them; however, LASL has not tested thoriated tungsten material. It remains to be shown whether the addition of thoria to the tungsten has any effect on the carbon penetration rate. Once this rate has been established, the required tubing wall thickness and/or protective coating can be established. The testing schedule to obtain this information is currently being written.

Several samples of high temperature thermocouples using thoriated tungsten sheaths have been tested for 60 cycles from 1000°R to 4780°R at transient rates of $180^{\circ}\text{R}/\text{sec}$ without failure. Data are available from previous reactor qualification tests and actual NERVA reactor tests for a much smaller number of cycles. These data are for devices with tungsten-26% rhenium tubing and CVD tungsten-coated molybdenum tubing. It is anticipated that further temperature shock data needed to prove the thoriated tungsten capability will be obtained during the carbon penetration rate studies mentioned above.

5.4.2 Insulator Materials Matrix

The second comparison matrix (Table 5-3) is for the thermocouple insulators. As was the case with the sheath material, the high temperature extremes reduce the number of candidate insulators to a bare minimum.

The basic problems involved in using sheathed thermocouples to 4600°R is obtaining an insulator material that will maintain adequate insulating properties, will not deteriorate

mechanically in the environment, and will not melt or react with the materials in contact with it at these temperatures. The list of useable materials narrows rather rapidly above 4000°R . The materials that were given consideration were beryllia (BeO), hafnia (HfO_2), thoria (ThO_2), and magnesia (MgO). Table 5-3 and Figures 5-1 and 5-2⁽⁹⁾ give pertinent characteristics of these materials. The melting points are shown to be well above the required maximum temperature of 4600°R . The thermal expansion ratios of these materials are compared with the expansion ratios of various wire and sheathing materials of Figure 5-1⁽⁷⁾. The expansion of the insulating materials is, on the average, about twice that of the tungsten rhenium and hence must be taken into account in the design of the thermocouple. The compatibility of the insulating materials with the various thermocouple and sheathing materials is an important criteria in its selection. Testing⁽⁸⁾ has shown that there is no damaging reaction up to 4300°F on tungsten and tungsten rhenium metals in contact with hafnia, thoria or beryllia, in a helium or hydrogen atmosphere. Two things preclude MgO for further consideration in thermocouple applications to 4600°R : its high vapor pressure, and the ease with which the MgO vapors diffuse inside the sheath from the hot end of a thermocouple probe to the cold end⁽⁹⁾. The insulation resistance properties of beryllia, hafnia, and thoria have been tested and are generally well known as a function of temperature; they are plotted along with those of other oxide materials on Figure 5-2 for reference. The data show that HfO_2 and ThO_2 are not suitable for insulation above 4300°R . An insulation resistance comparison test of these materials with solid (one-piece) insulators and insulator beads was performed up to 5000°R in a helium graphite atmosphere. The results were as predicted by the curves in Figure 5-2, with BeO maintaining the highest insulation resistance of all the materials tested. In addition, solid insulators in all cases maintained a more stable and reliable indication than beaded insulators. This suggests that the insulator shaping of the insulators could aid in improving their use in high temperature thermocouples.

Present efforts on high temperature thermocouple insulators are centered on refining the fabrication technique for enclosing the high purity ($>99\%$ pure) BeO with a minimum amount of contamination present. This will involve not only insuring that BeO insulators are

kept clean and dry at all times, but also refining techniques for cleaning the inner wall of the sheath tubing. A glove box is now being prepared that will maintain a dry inert atmosphere at all times, giving the capability to weld and braze the sheath material for test sample and thermocouple fabrication; further, it is large enough to store the BeO and sheath tubing under controlled conditions.

5.4.3 Thermoelement Matrix

The final comparison matrix, Table 5-4, reviews the various materials to be considered for the thermocouple wires (thermoelements).

The use of the tungsten/tungsten rhenium family of thermocouple wires for high temperature use ($>4000^{\circ}\text{R}$) was already an accepted fact before this study began. Numerous tests performed over the years at GE-NMPO, LASL, AGC, and WANL have established that the tungsten/tungsten rhenium thermoelement combinations give useable EMF outputs up to the melting point of the alloy leg ($>6000^{\circ}\text{R}^{(10)}$). One problem exists: the brittleness of the thermoelements. The results of past tungsten/tungsten-26% rhenium thermocouple tests at WANL were tabulated and show a large percentage of breakage in the tungsten leg after two or three cycles to $4500^{\circ}\text{R}^{(11)}$. Tungsten 3% and 5% rhenium alloy and stranded tungsten thermoelements were used in the positive leg of the thermocouple. They did not show a significant improvement in brittleness above 4400°R .

Further analysis of this problem indicated two interrelated causes: the stresses placed on the wire during thermocouple fabrication (such as bending stresses that can be imparted to the wires when the end plug is squeezed into the tube prior to welding, and recrystallization. The bending stress difficulty has been alleviated on future thermocouple designs by the use of a tungsten end plug that has two eloxed holes that the thermoelement wires slip through when the plug is inserted into the tube. The recrystallization of the tungsten wire after exposure to temperatures in excess of 4000°R is a problem. A study was performed on the possibility of using a substitute alloy for the tungsten leg that would be more resistant to recrystallization and still have good thermal EMF properties. Two types of wire were obtained: thoriated tungsten wire (W-2% Th), and a doped tungsten filament type wire. The dopants in the tungsten wire consisted of:

- 1) 80 - 110 ppm of potassium
- 2) 10 - 15 ppm of aluminum
- 3) 20 - 40 ppm of silicone

The initial testing of these wires was to determine their EMF characteristics vs that of a pure tungsten wire in a tungsten/tungsten-26% rhenium thermocouple combination. A calibration test was performed on these wires in the bell jar tungsten element furnace located in the WANL High Temperature Development Laboratory. Each test sample consisted of a pure tungsten wire with the doped tungsten or thoriated tungsten wire junctioned at the same point to a common tungsten-26% rhenium leg to insure a common junction temperature for both thermocouple combinations. At each calibration temperature stabilization point, both thermocouple outputs were measured and recorded. The test consisted of three calibration runs from 2000°R to 4600°R in a helium atmosphere. The calibration test temperatures were determined by comparison to an L&N Automatic Optical Pyrometer (Model 8641) that had been checked against an NBS traceable tungsten strip lamp. The accuracy of this system, with the sighting window correction factored out, was conservatively calculated to be less than 50 degrees over the temperature range of 3000°R to 4600°R.

The results of the calibration testing on three different lots of the doped tungsten wire and one lot of the thoriated tungsten wire are shown on Figures 5-3, 5-4, 5-5, and 5-6. These figures show the deviation of the test thermocouple outputs from the output indication of the thermocouple composed of the pure tungsten element. The largest deviation shown for the doped tungsten wire was -23 degrees ($\approx$ -1% of reading) while that for the thoriated tungsten wire was + 40 degrees ($\approx$ + 2% of reading). In all cases, the output indications tend to approach closer to the pure tungsten output with each succeeding run. Repeatability between runs was better than 0.2% full scale. Based on these results, the doped tungsten wire appears to have potential as the positive thermoelement in the thermocouple. Testing is now underway to determine whether its strength characteristics remain sufficiently better than pure tungsten after repeated high temperature cycling to warrant its selection for reactor high temperature application.

5.5 DESIGN APPROACH SELECTION

Based upon the results of the three comparison matrix tables, candidate materials for use in each fabrication of cluster exit gas T/C's are as follows:

a) Sheath Material - Tungsten-2% Thoria with a fine dispersion of ThO_2 was chosen primarily due to its higher yield and creep-rupture strengths along with its ability to retard recrystallization .

b) Insulators - BeO of high purity (99.9%) is the prime candidate at the temperature range specified because of its high strength, thermal shock resistance and high electrical resistivity.

c) T/C wire (Thermoelements) - W/W-26%Re is the prime candidate with doped W/W-26%Re as a backup. The pure W/W-26%Re was considered the final candidate due to its availability and our previous operating experience. The main advantage of the doped tungsten is its ability to retard recrystallization, but this capability is almost negated by the fact that the W-26%Re leg recrystallizes similar to pure tungsten. (It should be noted that if the temperature range from 500°R to 1000°R becomes a requirement for control, W5%Re/W-26%Re must be considered for greater accuracy at low temperatures.)

Further testing of these candidate materials will be done as part of the development program to verify those characteristics which are presently uncertain or unknown. Transducer designs will then be generated, evaluated, and tested.

5.6 REFERENCES

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TABLE 5-1
REQUIREMENTS, CLUSTER EXIT GAS TEMPERATURE MEASUREMENT

<u>Characteristic</u>	<u>Requirement</u>	<u>Traceability</u>
Range	1000°R - 4500°R	IDC-063
Accuracy	+50°F	677565-Table 1
Response Time	TBD	677565-Table 1
Frequency Response	TBD	IDC-063
Reliability	0.999900	677565-3.1.2.1
Useful Life		677565-3.1.2.3
Operating Lifetime	600 min	
Operating Life-Cycle	60 max	
Space Lifetime	3 years	
Ground Storage Time	5 years	
Environment	Inert except during operation	677565-3.1.2.4
Natural		677565-3.1.2.4.1
Induced		677565-3.1.2.4.2
Nuclear		IDC-063
Gamma Dose Rate	1.33×10^9 Rads r/hr	
Fast Flux (Neutron) (E<1 MeV)	3.35×10^{14} n/cm ² /sec	
Fast Neutron Fluence (E<1 MeV)	1.21×10^{19} n/cm ²	
Loads		677565-3.1.2.4.2.2
Shock	TBD	
Vibration	TBD	IDC-063
Thermal	440°R to 4500°R	IDC-063
Pressure Range	10 ⁻⁹ Torr to 470 psia	IDC-063
Fluid Compatibility	LH ₂ , GH ₂ , GN ₂ , GHe, Air	677565-3.3.1.9
Electromagnetic Interference	MIL-E-6051	677565-3.3.9
Installation	DRM 52032	939J723

TABLE 5-2
SHEATH MATERIAL COMPARISON MATRIX

<u>Characteristics</u>	<u>Requirements</u>	<u>Tungsten-(Pure)</u>	<u>Tungsten-26% Re</u>	<u>Tungsten-2% Thoria</u>	<u>Selection</u>
1. Melting Temperature	>4600°R (Carbon Eutectic)	>5000°R	4900°R $\pm$ 100°	>5000°R	Tungsten-2% Thoria and Tungsten-26%
2. Yield Strength	>8000 psi at 4600°R	4000-5000 psi at 4600°R	10,000 to 12,000 psi at 4600°R	40,000 to 20,000 psi at 4600°R	Tungsten-2% Thoria and Tungsten-26%
3. Creep-Rupture Strength	>8000 psi for 10 hr at 4600	2700 psi for 10 hr	600 psi for 11 hr at	9500 psi for 10 hr	Tungsten-2% Thoria
4. Material Compatibility	Will not adversely react with BeO or W-26%Re wires up to 4600°R	No measurable reaction	No measurable reaction	No measurable reaction	All
5. Environment Compatibility	440°R to 4600°R in a H ₂ Graphite - Radiation (10 ¹⁴ nv) Environment	Unknown	Compatible to 1 hr at 4400°R (NRX-A6) Hydro-Carbons Attack Material above 2300°R	Unknown	----
6. Resistance to Carbon Penetration	10 hr duration in Environment of item 5	Calculations Indicate Approx. 1 hr with 10 mil wall	1 hr Known Duration in Environment of Item 5	Unknown	----
7. Temperature Shock	60 Cycles from 440°R to 4600°R at a rate of 150°R/sec max.	Unknown	20 Cycles to 4300°R. Unknown Beyond This	60 Cycles to 4780°R from 1000°R in helium atmosphere at rate of >180°R/sec.	----
8. Recrystallization	Does not impair strength	Begins recrystallization above 2400°R	Similar Pure W	Depends on Dispersion of Thoria. Significant retardation can be accomplished up to >5000°R.	Tungsten 2% with fine dispersion ThO ₂ particles
9. Fabricability	Bend at 0.5" radius	Wrought W OK above Ductile/Brittle Transition Temperature (DBTT)	Can Be Formed Above Ductile/Brittle Transition Temperature (DBTT)	Same as W	All
10. Ductile Brittle Transition Temperature	<440°R for best low temperature shock and vibration resistance	850°R	360°R	830°R	Tungsten -26%Re is best Tungsten-2% Thoria is selected. (Fine dispersion of ThO ₂)

* Depends on fabrication method of tubing and time at temperature. (Figures are for 1/2 hour at 4600°R with wrought material.)

** Fineness of thoria dispersion affects strength at high temperature (course dispersion does not significantly improve characteristic).

*** Time to rupture at a specified temperature

+ Based on 0.090" diameter, 10-mil wall sheath with a 1.6 safety factor.

TABLE 5-3
COMPARISON MATRIX OF HIGH TEMPERATURE THERMOCOUPLE INSULATOR
CANDIDATE MATERIALS

<u>Characteristics</u>	<u>Requirements</u>	<u>Berylia</u>	<u>Hafnia (HfO₂) (Stabilized)</u>	<u>Thoria (ThO₂)</u>	<u>Magnesia (MgO)</u>	<u>Selection</u>
1. Electrical Resistivity	100 ohm-cm at 4600°R	10 ³ ohm-cm at 4600°R	10 ohm-cm at 4600°R	1 ohm-cm at 4600°R	1 ohm-cm at 4600°R	BeO
2. Avg. Thermal Expansion (535°R to 4900°R)	7 x 10 ⁻⁶ in./in./°F Maximum	6.1 x 10 ⁻⁶ in./in./°F	6.3 x 10 ⁻⁶ in./in./°F	6.05 x 10 ⁻⁶ in./in./°F	13.5 x 10 ⁻⁶ in./in./°F from 360°F to 1800°F	BeO, HfO ₂ and ThO ₂
3. Melting Temperature	4600°R	5,082°R	5,460°R	5,940°R	5,532°R	All
4. Material Compatibility	No adverse reaction with W or W-26%Re from 440°R to 4600°R	No adverse reaction in helium	No adverse reaction in helium	No adverse reaction in helium	Not recommended above 3500°F	BeO, HfO ₂ and ThO ₂
5. Temperature Shock	60 cycles from 440°R to 4600°R	Unknown, however, it is generally considered to be very good resistance to thermal shock	Unknown, however, generally considered poor for thermal shock	Unknown, same as Hafnia	Unknown, Generally considered fair for thermal shock	BeO
6. Radiation Effects	No significant reduction in insulating characteristics	Unknown	Unknown	Unknown	Unknown	

BeO is
selected

TABLE 5-4
THERMOCOUPLE WIRE COMPARISON MATRIX

<u>Characteristics</u>	<u>Requirements</u>	<u>Doped W/ W-26%Re</u>	<u>Thoriated W/ W-26%Re</u>	<u>W/W-26%Re</u>	<u>Selection</u>
1. Output Repeat- ability*	+10°R	10-12°R Span	20-22°R Span	(reference)	Doped W&W/W-26%Re
2. Thermal Shock Resistance	60 cycles from 440°R to 4600°R at rate of 150°R/sec	60 cycles to 4600°R from 1000°R in helium atmosphere at rate of 180° R/sec**	Same as doped W	Same	All
3. Embrittlement due to Recrystalli- tion	Does not impair strength	Recrystallization is retarded up to 4600°R	With proper dispersion of ThO ₂ retards recrystallization up to 5000°R	Begins recrystalli- zation above 2400°R	Doped W and Thoriated W
4. Melting Point, °R	>4600°R	>5000°R	>5000°R	>5000°R	All
5. Material Compatibility	Will not adversely react with BeO up to 4600°R	No measurable reaction	No measurable reaction	No measurable reaction	All
6. Availability as Calibrated thermoelements	Provided in calibrated lots	Not available	Not available	Available	W/W-26%Re

Selection - Doped W/W-26%Re
or W/W-26%Re

* Deviation from one run to the next.

** Test samples run with 10 mil wire in approx. 1.5" long T/C units.

Figure 5-1. Linear Thermal Expansion of Various Thermocouple Materials

Figure 5-2. Relative Resistance Variation with Temperature for Various Oxides

Figure 5-3. Output Deviation of Doped W/W-26% Re From Reference T/C

Figure 5-4. Output Deviation of Doped W/W-26% Re From Reference T/C

Figure 5-5. Output Deviation of Doped W/W-26% Re From Reference T/C

Figure 5-6. Output Deviation of Doped W/W-26% Re From Reference T/C

Figure 5-7. Cluster Exit Gas Candidate Thermocouple Design Concept

6.0 CORE MATERIAL HIGH TEMPERATURE THERMOCOUPLES

6.1 REQUIREMENTS

The Station 26 unfueled element temperature thermocouples are for use in start-up control and for diagnostic data. They shall be designed to meet the requirements outlined in Table 6-1 for normal and emergency operating modes. All requirements are tabulated along with traceability document identification.

6.2 DESIGN APPROACH CHARACTERISTICS

The temperature to which thermocouples are subjected for readout at Station 26 are similar in magnitude to those of the cluster exit gas thermocouples. The effects are, however, more severe due to the long lengths of the core devices which are exposed to the core temperature gradients and high carbon concentration. The basic design characteristics of initial interest at the present stage of development are material capability and survivability, as was the case for the exit gas thermocouple designs. Since the problems and candidate materials are the same for both designs, refer to Section 5.2 of this trade study for a discussion of the trade-off characteristics to be considered.

6.3 DESIGN APPROACH DESCRIPTION

The station 26 unfueled element thermocouple design itself is dependent on the insertion of the probe into an unfueled element with a minimum useable hole diameter of 0.098 inch. This diameter limits the sheath tubing diameter and the thickness of any protective coatings; it presents the design with its most serious constraint.

The most serious problem for the in-core thermocouple is carbon penetration through the sheath, which attacks the beryllium oxide (BeO) insulators. The carbon penetration of the thermocouple material is basically dependent on the total thickness of the sheath, its protective coatings and the operating time at a given temperature.

A trade-off between the minimum insulator diameter required to insure acceptable insulator shunting and the combined wall thickness for sheath tubing and protective coatings required to resist carbon penetration will have to be made in the final design approaches.

An analysis of the known data is being performed to determine what thickness of the various materials, if any, will impede the carbon for the 10 hour run. Information obtained from LASL⁽¹⁻²⁾ and the WANL Materials Group is being used to analyze the carbon penetration problem. As a case in point, previous testing has shown⁽²⁾ that carbide layer growth rates on tungsten can be decreased by factors of from two to seven when operated with a niobium carbide (NbC) coated environment in hydrogen (H_2). Therefore, installing the thermocouple in an NbC coated hole in the unfueled element may greatly improve the carbon penetration problem. If combinations of sheath tubing and protective coatings cannot be found that will impede the carbon penetration, an alternative could be to make the measurement at a lower station where the environment is not so severe; accuracy would be compromised somewhat.

A second (less serious) problem that occurs with the in-core thermocouple is that of the shunting effect of the insulator material. BeO is the only insulating material in which resistivity remains high enough to be an effective insulator to temperatures in excess of $4000^\circ R$ ⁽³⁾. Past thermocouple designs (i.e., 978D270 and 928F613) indicate that the BeO insulator should have a minimum diameter of 0.056 inch and two holes, 0.017 inch diameter, equally spaced. A nominal wire diameter of 0.014 inch would then be adequate. Testing these configurations for 10 hours is necessary, however, since all previous WANL testing has been limited to one hour or less. Also under consideration to increase the shunt resistance is an approach whereby the path between the wires is increased and reduced in cross-sectional area.

The wire breakage problem has been a recurring one with all previous in-core thermocouple designs⁽⁴⁾. Since the thermocouples tend to open up during temperature cycle testing, the stresses imposed on the wires during rapid temperature changes may cause breakage. However, a closer study must be made of a broken portion of an in-core thermocouple to fully determine the causes and the solutions. In the meantime, steps have been taken in the candidate design to relieve stresses at the junction by the use of eloxed plugs rather than squeezing the wires between the plug and sheath weld of the thermocouple tube, and by making the holes for the T/C wire slotted rather than round so that the wire can be corrugated in this plane to permit expansion and contraction.

Two candidate in-core thermocouples are shown on Figures 6-1 and 6-2. The merits of each of these thermocouples can only be suggested at this time since the results of more analysis must be known.

Figure 6-1 design is based on the 978D270 type thermocouple that has been used successfully in the NRX-6 and XE-Prime reactor tests. It is simpler to fabricate than the other candidate and its time response is faster, but its ability to withstand the temperature shock and carbon environment will have to be determined. Calculations are being performed to determine the trade-off required between the thickness of the tungsten-2% thoria sheath tubing and the NbC or zirconium carbide (ZrC) coating on the wall of the unfueled element hole.

Figure 6-1 is similar to the 928F613 type floating junction thermocouple design, although more difficult to fabricate. Previous testing of this design did show good results to 4600°R for a total time of one hour⁽⁴⁾ and four temperature cycles. This floating junction design does tend to eliminate stresses on the wires under temperature shock conditions and thus improve the wire breakage problem. However, the time response is slower and the carbon penetration problem is still significant. This change does show promise in solving the in-core thermocouple problems and is being considered as a secondary candidate to the thermocouple discussed previously.

A summary of design description information based on the present maturity of development is given below:

- 1) Peripheral Equipment Requirements - Reference Junctions
- 2) Power Requirements - None
- 3) Types of Leads - Sheathed (Stainless Steel) MgO Insulated Cable with 2 Leads (W/W-26% Re or W-5% Re/W-26% Re) to Reference Junctions
- 4) Outline Configuration - TBD
- 5) Unit Weight - TBD
- 6) Unit Cost - \$1500 to \$2000 each.
- 7) Construction Material - TBD
- 8) Development Stations - Material Testing Initiated.

6.4 COMPARISON MATRIX

Since the basic problem areas, as previously stated, are common to those of the Cluster Exit Gas thermocouples, reference is made to Section 5.4 for comparison matrix information. It should be noted, however, that in the comparison matrix for the thermoelement wire, the additional requirement to provide a useable output in the range of 500°R to 1000°R is applicable to the core material thermocouples. In order to obtain good sensitivity in this range, W-5% Re/W-26% Re, must be seriously considered as a prime candidate due to its superior performance at those temperatures.

6.5 DESIGN APPROACH SELECTION

Based upon the results of the three comparison matrix tables, candidate materials for use in the fabrication of the Station 26 unfueled element thermocouples are as follows:

- 1) Sheath Material - Tungsten-2% Thoria (finely dispersed) was chosen due to its higher strength characteristics and its ability to retard recrystallization.
- 2) Insulators - BeO of high purity (99.9%) is the prime candidate with shape as shown in Figure 6-3. This was chosen because of its high insulation resistance, high strength, and thermal shock resistance.
- 3) T/C Wire - Due to the requirement for control use in startup (500°R to 1000°R Range) W-5% Re/W-26% Re is the prime candidate due to its greater sensitivity and linearity in this range.

Additional testing of materials and configurations as well as investigation into the use of protective coatings on the inner wall surface of the unfueled element holes will be performed in our upcoming development schedule. Based on the results of this work, final transducer designs will be generated and evaluated.

6.6 REFERENCES

1. "The Chemical Diffusion of Carbon in the Group VI b Metal Carbides, " by Fries, Cummings, Hoffman & Daily of LASL; Reprint from "High Temperature Materials" - 6th Plansee Seminar, June 1968.
2. Letter from R. J. Fries - LASL to T. C. Burlas - WANL, February 1970, regarding parabolic layer growth rate constants for tantalum & W/25 at . %Re.
3. "Tungsten/Tungsten-Rhenium Thermocouple Research and Development, " by McGurty & Kuhlman; SAE National Aeronautical Meeting & Production Engineering Forum, N. Y., April 1962.
4. WANL-TME-1773, "High Temperature Thermocouple Qualification and Development Testing, " by G. Zellner; March 1969.

TABLE 6-1
REQUIREMENTS

<u>Characteristics</u>	<u>Requirement</u>	<u>Traceability</u>
Range	500°R - 4500°R	IDC-068
Accuracy	$\pm 30^{\circ}\text{R}$	677565 - Table 1
Response Time	TBD	677565 - Table 1
Frequency Response	TBD	IDC-068
Reliability	0.999900	677565-3.1.2.1
Useful Life		
Operating Lifetime	600 min.	
Operating Life - Cycles	60 Max.	
Space Lifetime	3 years	
Ground Storage Time	5 years	
Environment		677565-3.1.2.4
Natural	Inert except during operation	677565-3.1.2.4.1
Induced	Inert except during operation	677565-3.1.2.4.2
Nuclear		IDC-068
Gamma Dose Rate	$3.39 \times 10^{10} \text{ Rad-c/hr}$	
Fast Flux (Neutron (E>1 MeV)	$4.51 \times 10^{15} \text{ n/cm}^2/\text{sec}$	
Fast Neutron Fluence (E>1 MeV)	$1.62 \times 10^{20} \text{ n/c}^2$	
Loads		677565-3.1.2.4.2.2
Shock		
Vibration	TBD	
Thermal	440°R to 4500°R	IDC-068
Pressure Range	159 Torr to 630 Psia	IDC-068
Fluid Compatibility	LH ₂ , GH ₂ , GN ₂ , GHe, Air	677565-3.3.1.9
Electromagnetic Interface	MIL-E-6051	677565-3.3.9
Installation	DRM 52037	939J723

Figure 6-1. NERVA In-Core Thermocouple Primary Candidate Profile

Figure 6-2. NERVA In-Core Thermocouple Secondary Candidate Profile

Figure 6-3. Insulator Cross Section

7.0 SUPPORT STEM LOAD TRANSDUCER

7.1 REQUIREMENTS

The support stem load transducer shall be capable of measuring the axial cluster loading of the reactor core during normal and emergency operating modes within the performance requirements stated in Table 7-1.

7.2 DESIGN APPROACH CHARACTERISTICS

In order to evaluate the various design approaches in a comparison matrix, a significant number of trade-off characteristics must be established to show how well each approach fulfills the requirements and also to show the relative suitability of the approaches with respect to the application. Table 7-1 has presented specific requirements for support stem measurements. Using these requirements as a basis, the trade-off characteristics most applicable to strain gage designs have been identified and are listed below. Only those characteristics which will produce a meaningful evaluation at this time have been listed.

7.2.1 Primary Characteristics (Quantitative Evaluator)

- a) Strain Range: 3000 Microstrains - calculated (see DRM 51915)
- b) Strain Type: Static - 60 cycles at 10 min. each for 10 hrs total
- c) Size: Height < 0.125" and Length < 0.85"
- d) Contour: 0.1" R to 0.2" R
- e) Temperature Range: -210 to +740°F
- f) Neutron Radiation: 9×10^{18} nvt
- g) Pressure: 1150 Psia to 10^{-9} Torr
- h) Cabling: 0.041" diameter
- i) Accuracy: ± 150 microstrains

7.2.2 Secondary Characteristics (Narrative Evaluator)

- a) Strain Sensitivity: High
- b) Apparent Strain: Low

- c) Gage Installation Complexity: Simple
- d) Relative Cost (Gages and Equipment): Low
- e) Development Effort: Minimum
- f) Procurability: High
- g) Repeatability (Gage to Gage): High

7.3 DESIGN APPROACH DESCRIPTION

To ensure all commercially available strain gages would be initially evaluated for reactor applications, a screening process was undertaken which began with a survey of the present strain gage population along with a search for technical literature to support the findings. Sources for the information included strain gage vendors, gage users, and numerous technical papers presented on strain gages. In the interest of brevity, the survey was limited to metallic resistance gages since semiconductor-type gages will undergo severe changes in electrical characteristics at radiation levels of 10^{12} nvt. A detailed evaluation⁽⁵⁾ of past radiation testing on resistance metallic gages could not provide any predictability as to the relative degradation levels of the various types of gages or alloys. Minimal emphasis was placed on gages which are attached with organic bonding materials since irradiation has deteriorating effects on the properties of these materials. As a result of the screening process the following gage designs were found to have advantages which merit consideration for reactor applications. Each design is identified with a significant phrase which will be carried through the remainder of this section for consistency.

7.3.1 Hermetically-Sealed Weldable Wire Type Gages

Gages of this type are manufactured exclusively by Microdot, Inc. and are comprised of filamentary wire sensing elements inside a small diameter metal tube. The tube is attached to a thin metal flange for welding to the strain member. Within the tube is a half-bridge circuit consisting of both active and compensating elements insulated with magnesium oxide (MgO). A metal sheathed MgO insulated cable is provided with each gage and is attached to the strain tube through a metal transition. Application advantages for the design are (1) it is hermetically sealed in a metal container and (2) it can be rather simply installed

by spotwelding. The main application disadvantage is the relatively long length of the gage and transition. The specific types of the Microdot design that will be considered for reactor applications are as follows:

7.3.1.1 Microdot Nickel-Chromium Weldable Gages

- a) Strain Sensing Material: Evanohm Nickel-Chromium Alloy
- b) Approximate Composition: 75% Ni-20% Cr-3% Al-2% Cu
- c) Strain Range: ± 6000 Microstrains
- d) Temperature Range: -452 to $+650^{\circ}\text{F}$ (Static Strain)
- e) Size: Length: 1.88" including transition (1.10" Strain Tube)
Height: 0.040" for Strain Tube and 0.053" for Transition
- f) Strain Member Compatibility: Weldable ferrous and non-ferrous materials
- g) Minimum Applicable Contour: 0.050" Radius (Estimated)
- h) Ambient Strain Sensitivity: 1.8 Nominal
- i) Apparent Strain: Gage is heat treatable to produce relatively low apparent strain over temperature range.
- j) Installation Complexity: Rather simple welding process
- k) Procurability: Long Lead Item
- l) WANL or Vendor Identification: WANL P/N's 978D802 and 978D803
- m) Radiation Stability: This type of gage was used during past NERVA tests for tie rod, support spring, and displacement transducer measurements. Testing data indicated this design operated within tolerable errors for radiation levels up to 10^{17} nvt.

7.3.1.2 Microdot Platinum-Tungsten Weldable Gage

- a) Strain Sensing Material: Platinum Tungsten Alloy
- b) Approximate Composition: 92% Pt-8% W
- c) Strain Range: ± 6000 Microstrains

- d) Temperature Range: -452 to $+950^{\circ}\text{F}$ (Static Strain)
- e) Size: Length: 1.88" including transition (1.10" Strain Tube)
Height: 0.040" for strain tube and 0.063" for transition
- f) Strain Member Compatibility: Weldable ferrous and non-ferrous materials
- g) Minimum Applicable Contour: 0.050" Radius (Estimated)
- h) Ambient Strain Sensitivity: 4.0 Nominal
- i) Apparent Strain: Very high. Must use additional compensating means
- j) Installation Complexity: Rather simple welding process
- k) Procurability: Long lead item
- l) WANL or Vendor Identification: Microdot SG 425 Series
- m) Radiation Stability: No available data. Alloy exhibits very good thermal stability.

7.3.1.3 Modified Microdot Platinum-Tungsten Weldable Gage

- a) Strain Sensing Material: Platinum-Tungsten Alloy
- b) Approximate Composition: 92% Pt - 8% W
- c) Strain Range: $\pm 5,000$ Microstrains (Static)
- d) Temperature Range: 320 to $+750^{\circ}\text{F}$ (Static Strain)
- e) Size: Length: 0.85" max
Height: 0.040" for strain tube and 0.063" for transition
- f) Strain Member Compatibility: Weldable ferrous and non-ferrous materials
- g) Minimum Applicable Contour: 0.050" Radius (Estimated)
- h) Ambient Strain Sensitivity: >3.0 nominal
- i) Apparent Strain: Very high. Must use additional compensating means.
- j) Installation Complexity: Rather simple welding process
- k) Procurability: Long lead item
- l) WANL or Vendor Identification: WANL 928F819
- m) Radiation Stability: No available data. Alloy exhibits very good thermal stability.

7.3.2 Ceramic-Bonded Free-Grid Foil Type Gages

Gages of this type consist of a thin foil sensing element which is supplied without a backing or carrier. A ceramic cement (see Appendix A) is used to bond the gage to the member and also provide electrical insulation resistance. A polyimide varnish (see Appendix B) is used to moisture-proof the cement after installation. One of the main advantages of the foil gage is the high surface to cross-section ratio which provides excellent heat transfer characteristics. This is of particular interest for reactor applications since heating rates can be significant under a high gamma flux. Another advantage is that the foil gage can be manufactured in relatively small sizes. The main disadvantage is the high temperature required during the high curing cycles ($+600^{\circ}\text{F}$) while installing the free-grid gages. Foil gages may be manufactured by either etching or die-cutting. The die-cutting process appears to produce better uniformity from gage to gage; this would aid in minimizing variations in performance from gage to gage. Also, certain gage alloys like Pt-W cannot be suitably etched and must be die-cut. The specific types of die-cut free-grid foil gage designs that will be considered for reactor applications are as follows:

7.3.2.1 Nickel-Chromium Free-Grid Foil Gages

- a) Strain Sensing Material: Modified Karma Nickel-Chromium Alloy
- b) Approximate Composition: 73% Ni - 20% Cr plus Fe and Al
- c) Strain Range: ± 3000 Microstrains (Ceramic cement limit)
- d) Temperature Range: -452 to $+800^{\circ}\text{F}$ (Static Strain)
- e) Size: Length: Sizes down to 0.125" grid
Height: Typ. Installation 0.005"
- f) Strain Member Compatibility: Almost all metals when properly prepared.
- g) Minimum Applicable Contour: Almost unlimited (0.031" R estimated).
- h) Ambient Strain Sensitivity: 2.2 nominal
- i) Apparent Strain: Gage is partially heat-treatable to produce relatively low apparent strain over temperature range.

- j) Installation Complexity: Moderately involved process required.
- k) Procurability: Good - 90 days typical
- l) WANL or Vendor Identification: WANL P/N 914E077H03 and H06
- m) Radiation Stability: Plum Brook Reactor Tests indicated relatively good stability for similar Karma foil gages. Gages were irradiated to 2×10^{18} nvt.

7.3.2.2 Iron-Chromium-Aluminum Free-Grid Foil Gages

- a) Strain Sensing Material: Armour Iron-Chromium-Aluminum Alloy
- b) Approximate Composition: 70% Fe - 20% Cr - 10% Al
- c) Strain Range: ± 3000 Microstrains (Ceramic Cement Limit)
- d) Temperature Range: -400 to $+800^{\circ}\text{F}$ (Static Strain)
- e) Size: Length: Size down to 0.125" grid
Height: Typ. Installation 0.005"
- f) Strain Member Compatibility: Almost all metals when properly prepared
- g) Minimum Applicable Contour: Almost unlimited (0.031" R Estimated)
- h) Ambient Strain Sensitivity: 2.6 nominal
- i) Apparent Strain: Moderate - better than Pt-W but not as good as Ni-Cr gages
- j) Installation Complexity: Moderately involved process required.
- k) Procurability: Good - 90 days typical
- l) WANL or Vendor Identification: WANL P/N 914E077H01/4
- m) Radiation Stability: No data available. Alloy exhibits very good thermal stability.

7.3.2.3 Platinum-Tungsten Free-Grid Foil Gages

- a) Strain Sensing Material: S. Cohn Platinum Tungsten Alloy
- b) Approximate Composition: 92% Pt - 8% W
- c) Strain Range: ± 3000 Microstrains (Ceramic cement limit)
- d) Temperature Range: -452 to $+1200^{\circ}\text{F}$ (Static Strain)

- e) Size: Length: Sizes down to 0.125" grid
Height: Typical Installation 0.005"
- f) Strain Member Compatibility: Almost all metals when properly prepared
- g) Minimum Applicable Contour: Almost unlimited (0.031" R estimated)
- h) Ambient Strain Sensitivity: 4.5 nominal
- i) Apparent Strain: Very high. Must use additional compensating means.
- j) Installation Complexity: Moderately involved process required.
- k) Procurability: Good - 90 days typical.
- l) WANL or Vendor Identification: WANL P/N 914E077H02/5
- m) Radiation Stability: No available data. Alloy exhibits very good thermal stability.

7.3.3 Shim-Mounted Weldable Type Gages

Gages of this type are free-grid designs that are ceramic-cement bonded to a weldable shim by the manufacturer. The gage may then be directly applied to the member by spot welding. Disadvantages with this design are that it is limited to flat surfaces and is fragile. The specific types of shim-mounted gages that will be considered for reactor applications are:

7.3.3.1 Nickel-Chromium Shim-Mounted Foil Gages

- a) Strain Sensing Material: Modified Karma Nickel-Chromium Alloy
- b) Approximate Composition: 73% Ni - 20% Cr plus Fe and Al
- c) Strain Gage: ± 3000 Microstrains (Ceramic cement limit)
- d) Temperature Range: -452 to $+800^{\circ}\text{F}$ (Static Strain
- e) Size: Length: 0.50"
Height: 0.010" Typical
- f) Strain Member Compatibility: Weldable ferrous and non-ferrous materials
- g) Minimum Applicable Contour: Limited to flat surfaces
- h) Ambient Strain Sensitivity: 2.2 nominal

- i) Apparent Strain: Gage is partially heat-treatable to produce relatively low apparent strain
- j) Installation Complexity: Rather simple welding process
- k) Procurability: Long lead item
- l) WANL or Vendor Identification: Dentronics weldable base MW series
- m) Radiation Stability: Karma alloy exhibited relatively good radiation stability when tested to 2×10^{18} nvt.

7.3.4 Flame-Spray Bonded Free-Grid Wire Type Gages

Gages of this type consist of a small diameter filamentary wire sensing element which is supplied with a temporary teflon tape carrier. A flame-spray process is used to bond the gage to the member. A ceramic spray is created by atomizing directly from solid bodies. Coatings are produced by fusing the end of an alumina rod and blowing the molten particles against a cool, properly prepared surface where they solidify to form the coating. The flame-spray process is not suitable to foil gages because of filament damage and poor bond to the smooth foil surface. Since the flame-sprayed material is an absorber, a polyimide varnish (Pyre-ML) is to be used to moistureproof the cement after installation. High temperature cures are not required in order to achieve high temperature operating capability. A disadvantage is that flame-spraying must presently be considered a fairly difficult technique and it is questionable as to the control that can be maintained with this method. The specific types of flame-sprayed gages that will be considered for reactor applications are as follows:

7.3.4.1 Platinum-Tungsten Flame-Spraying Wire Gages

- a) Strain Sensing Material: Platinum Tungsten Alloy
- b) Approximate Composition: 92% Pt-8% W
- c) Strain Range: 5000 Microstrains
- d) Temperature Range: -452 to +1200°F (Static Strain)
- e) Size: Length: Down to 0.125" grid
Height: 0.005" typical

- f) Strain Member Compatibility: Almost all metals when properly prepared
- g) Minimum Applicable Contour: Spraying Process more suitable to flat and moderate contoured surfaces, although small contours of 0.125" R are possible.
- h) Ambient Strain Sensitivity: 4.0 nominal
- i) Apparent Strain: Very high. Must use additional compensating means
- j) Installation Complexity: Very complex process required
- k) Procurability: Good - 90 days typical
- l) WANL or Vendor Identification: BLH type HT1200 and Bean Series BPTH
- m) Radiation Stability: Vendor (Baldwin-Lima-Hamilton) reports good stability in tests where gages were irradiated to 2×10^{16} nvt.

7.4 COMPARISON MATRIX

Table 7-2 shows a comparison of the capabilities of the strain gages of paragraph 7.3 with respect to the requirements of paragraph 7.2. Three of the eight strain gage designs can immediately be eliminated for this application since they do not meet one or more of the primary requirements. The Microdot nickel-chromium half-bridge weldable gage is unsuitable because of its known instability in radiation levels above 10^{17} nvt, its temperature range is below the requirement, and its length is too long to fit into the available installation space. This length problem also eliminates the standard Microdot platinum-tungsten gages. The shim-mounted weldable gages are unsuitable since they cannot meet the contour requirement for this application. The remaining five gage designs appear feasible for the intended measurement, but since actual test data are not available for accuracy and radiation performance, development testing is necessary. These five designs are: 1) modified Microdot Pt-W gage, 2) Ni-Cr free-grid foil gage, 3) Fe-Cr-Al free-grid foil gage, 4) Pt-W free-grid foil gage, and 5) Pt-W flame sprayed wire gage.

7.5 DESIGN APPROACH SELECTION

In order to limit development testing to only the most promising designs, the five remaining designs have been further compared against the secondary requirements of paragraph 7.2. This comparison is shown in Table 7-3. The Ni-Cr, Fe-Cr-Al, and Pt-W free-grid foil gage designs scored best in this evaluation and should therefore be given primary attention for the support stem application. Development testing (as indicated in TIS 26)⁽⁴⁾ will reveal the specific performance characteristics of each design and thus permit a more extensive trade-off to be conducted in the future. The optimum foil gage circuit for the support stem application is a full bridge arrangement with two active gages in opposite arms of the bridge and parallel to the axial tube stresses. Two dummy gages are at right angles to the axial stresses. This network provides a transducer which is sensitive to axial stresses but not to bending and is self compensated for environmental effects.

In determining the optimum free-grid strain gage pattern for this application, three different concepts were considered. These concepts are numbered 2, 3, and 4 in Figure 7-1 and also drawing 914E078. Concept 2, with four captive grid patterns, is unsuitable because it requires the use of terminal strips. Strips presently on the market will not withstand the upper temperature limit (+740°F) for this application. Concept 3, which uses two "T" rosette patterns, appears highly suitable since only a few operations would be required for installation. Unfortunately, free-grid rosette gages are very fragile and hard to use. Due to this characteristic, a very high mortality rate would be encountered during installation. Concept 4, utilizing two "H" tab and two standard tab patterns, is less vulnerable to installation damage and is therefore considered the best choice. This concept, however, will require more installation operations and more control of gage alignment than if rosette gages were used. The strain gage to sheath cable transitions shown for Concept 4 will require effort to establish a suitable technique.

Although the modified Microdot Pt-W gage did not score as well as the free-grid gages when compared against the secondary requirements of paragraph 7.2, this design should be included in development testing because it offers distinct advantages of installation ease

and environmental protection. If testing indicates the performance of the Microdot Pt-W design is better than anticipated, the advantages of this design may be significant trade-off characteristics. The optimum circuit for the modified Microdot gage is shown in concept 1 of Figure 7-2 and also drawing 914E078. The two half-bridge gages are installed on opposite sides of the support stem and complete a bridge circuit external to the reactor.

The flame-spray gage design had a relatively poor score when compared against the secondary requirements of paragraph 7.2. It appears most advantageous at this time to no longer consider this design for the support stem application. This decision is mainly because the flame-spray design represents a considerably higher cost and greater development effort but does not indicate any greater chance of success.

In conclusion, there is no presently available strain gage design that qualifies for the support stem strain measurements. Based on the evaluations made in this report, the following strain gages show promise for the application and therefore merit development testing.

- a) Iron-Chromium-Aluminum free grid foil gage - P/N 914E077H01/4
- b) Platinum-Tungsten free grid foil gage - P/N 914E077H02/5
- c) Nickel-Chromium free-grid foil gage - P/N 914E077H03/6
- d) Modified Microdot platinum-tungsten strain gage - P/N 928F819H01

A constant current excitation source will be required for the load transducer, independent of which gages are used. The power requirements for this source will be established during development testing. Peripheral equipment for the transducer output will also be defined as development progresses. An eight-wire system for each transducer would be a worst-case condition. This case will exist if a double-shunt calibration system is selected. The worst-case condition for unit weight has not been established at this time.

7.6 REFERENCES

1. WANL-TME-1254, "Non-Nuclear Evaluation Testing of Strain Gages Bonded with Ceramic Cement," July 27, 1965.
2. WANL-TME-1366, "Weldable and Bondable Steam Gages Irradiated at PBRF," January 28, 1966.
3. DuPont Bulletin on Pyre-M-L Volume No. 1, Rev. 5 - dated November, 1968.
4. TIS-26, "Non-Nuclear Development Testing-Core Axial Cluster Load Transducer Design Approaches," February 27, 1970.
5. DRM 51904, "Preliminary Selection of Transducer Design Approaches for Reactor Strain Measurements," October 16, 1969.

TABLE 7-1
REQUIREMENTS - SUPPORT STEM LOAD

<u>Characteristics</u>	<u>Requirement</u>	<u>Traceability</u>
Range	0 to 1200 lbs.	IDC-062*
Accuracy	± 60 lbs (5% FR)	EC677565-Table 1**
Response Time	(TBD)	EC677565-Table 1
Frequency Response	1000 Hz	IDC-062
Reliability (+)	0.99990	EC677565-3. 1. 2. 1
Maintainability (+)	N/A	EC677565-3. 1. 2. 2
Useful Life (+)		EC677565-3. 1. 2. 3
Operating Lifetime	600 minutes	
Operating Life - Cycles	60 max.	
Space Lifetime	3 years	
Ground Storage Time	5 years	
Environment		EC677565-3. 1. 2. 4
Natural (+)	Inert	EC677565-3. 1. 2. 4. 1
Induced	(See Below)	EC677565-3. 1. 2. 4. 2
Nuclear		EC677565-Table 2
Gamma Dose Rate	2.5×10^9 R(c)/hr.	
Fast Neutron Flux (E>1 MeV)	2.4×10^{14} nv	
Fast Neutron Fluence (E>1 MeV)	2.5×10^{18} nvt	
Loads	(See Below)	EC677565-3. 1. 2. 4. 2. 2
Shock (+)	N/A	

* IDC - Instrumentation Design Criteria Sheet Number

** EC677565 - EC677565 NSS Instrumentation Spec. and Paragraph/Table Number

(+) These characteristics are independent of measurements.

TABLE 7-1 (CON'T)
REQUIREMENTS - SUPPORT STEM LOAD

<u>Characteristics</u>	<u>Requirement</u>	<u>Traceability</u>
Vibration	(TBD)	IDC-062
Thermal	250 to 1200° R	IDC-5/22/68
Pressure Range	10 ⁻⁹ Torr to 1150 psia	IDC-062
Transportability (+)	N/A	EC677565-3. 1. 2. 5
Human Performance (+)	Operation Simple as Possible	EC677565-3. 1. 2. 6
Safety (+)	Normal	EC677565-3. 1. 2. 7
Fluid Compatibility (+)	LH ₂ , GH ₂ , GN ₂ , GHe, Air	EC677565-3. 3. 1. 9
Design	Temperature Compensated	EC677565-3. 3. 1. 20
Installation	DRM 52022	939J723

* IDC - Instrumentation Design Criteria Sheet Number

** 65-EC677565 NSS Instrumentation Spec. and Paragraph/Table Number

+ These characteristics are independent of measurements.

TABLE 7-2
COMPARISON MATRIX - PRIMARY REQUIREMENTS - SUPPORT STEM LOAD

Characteristics	Requirements	Microdot Ni-Cr Weldable Gages	Microdot Pr-W Weldable Gages	Mod. Microdot Pr-W Weldable Gages	Ni-Cr Free- Grid Foil Gages	Fe-Cr-Al Free-Grid Foil Gages	Pr-W Free- Grid Foil Gages	Ni-Cr Shim-Mounted Foil Gages	PT-W Flame- Sprayed Wire Gages
Strain Range	3000 Microstrains	6000	6000	6000	3000	3000	3000	3000	>5000
Strain Type	Static	Static	Static	Static	Static	Static	Static	Static	Static
Size	Height <0.125" Length <0.85"	0.063" 1.10"	0.063" 1.10"	0.063" <0.85"	0.005" 0.125"	0.005" 0.125"	0.005" 0.125"	0.010" 0.500"	0.005" 0.125"
Contour	0.1" R to 0.2" R	0.1-0.2	0.1-0.2	0.1-0.2	0.1-0.2	0.1-0.2	0.1-0.2	Limited to Flat Surfaces	0.1-0.2
Temperature	-210 to +740°F	-452 to +650°F	-452 to +950°F	-452 to +750°F	-452 to +800°F	-452 to +800°F	-452 to 1200°F	-452 to +800°F	-452 to 1200°F
Radiation	9×10^{18} nvt	<10 ¹⁷	*	*	*	*	*	*	*
Pressure	10 ⁻⁹ Torr to 1150 Psia	Vacuum to 2500 Psia	Vacuum to 2500 Psi	Vacuum to 2500 Psia	*	*	*	*	*
Cabling	<0.041" Dia.	<0.041	<0.041	<0.041	<0.041	<0.041	<0.041	<0.041	<0.041
Accuracy	+150 Microstrains	*	*	*	*	*	*	*	*

* Unknown - Must Test to Application

TABLE 7-3
COMPARISON MATRIX - SECONDARY REQUIREMENTS - SUPPORT STEM LOAD

Characteristics	Requirement	Mod. Microdot Pr-W Weldable Gages *	Ni-Cr Free-Grid Foil Gages *	Fe-Cr-Al Free-Grid Foil Gages *	Pr-W Free-Grid Foil Gages *	Pt-W Flame-Sprayed Wire Gages *
Strain Sensitivity	High	2 Moderate	3 Low	2 Moderate	1 High	1 High
Apparent Strain	Low	3 High	1 Low	2 Moderate	3 High	3 High
Gage Installation Complexity	Simple	1 Simple	2 Moderate	2 Moderate	2 Moderate	3 Complex
Relative Cost (Gages plus Equip.)	Low	2 Moderate	1 Low	1 Low	1 Low	3 High
Development Effort	Minimum	1 Minimum	2 Moderate	2 Moderate	2 Moderate	3 Maximum
Procurability	High	2 Moderate	1 High	1 High	1 High	1 High
Repeatability (Gage to Gage)	High	2 Moderate	1 High	1 High	1 High	3 Low
TOTAL SCORE	--	13	11	11	11	17

* Rate Gages 1st, 2nd, 3rd --- AGAINST EACH OTHER WITH RESPECT TO SUITABILITY

Figure 7-1. Application Concepts for Free-Grid Foil Strain Gages

TWO WELDABLE HALF-BRIDGE STRAIN GAGES CONCEPT - I

HALF BRIDGE SCHEMATIC

Figure 7-2. Application Concept for Modified Microdot Strain Gages

APPENDIX 7-A

STRAIN GAGE CERAMIC CEMENT CHARACTERISTICS

1. Name: Type "H" Ceramic Cement
2. Manufacturer: W. T. Bean, Inc., 18915 Grand River Avenue, Detroit, Michigan 48223
3. General Type: Chemical setting, heat curing
4. Basic Composition
 - a. Aluminum Phosphate Binder
 - b. Al_2O_3 Filler
 - c. Silica Flour
 - d. Distilled Water
 - e. Phosphoric Acid
5. Normal Cure Temperature: 600°F
6. Maximum Operating Temperature: $>1000^\circ\text{F}$
7. Strain Limit: 1/2% (~5000 Microstrains)
8. Strain Confidence Level: 3000 Microstrains⁽¹⁾
9. Cure Time: 1 hour
10. Cure Pressure: 0 Psi
11. Humidity Resistance: Fair, is hygroscopic - generally requires moistureproofing.
12. Radiation Resistance: Gages bonded with type "H" cement were irradiated⁽²⁾ to 2×10^{18} nvt with no visible physical damage nor severe changes in electrical characteristics.

APPENDIX 7-B

STRAIN GAGE POLYIMIDE MOISTURE PROOFING MATERIAL CHARACTERISTICS

1. Name: Pyre - M. L. Varnish
2. Manufacturer: E. I. DuPont De Nemours and Co., Wilmington, Delaware 19898
3. Composition: The varnish film is chemically an aromatic polyimide polymer.
4. Temperature Range: Polyimide films exhibit excellent mechanical properties throughout a temperature range of liquid helium (-452°F) to as high as 1100°F .
5. Baking Equivalents:
 - a. 15 hrs 300°F
 - b. 20 min. 400°F
 - c. 3 min. 600°F
6. Radiation Resistance:

LASL used the "Pyre ML" varnish to provide a moisture seal coating on ceramic cemented connections and strain gage applications for service in liquid hydrogen while being subjected to radiation doses of 10^9 Rad gamma and 10^{18} nvt $E > 1$ MeV neutron doses. Tests conducted at LASL and elsewhere have shown this material and H-film to be capable of exposure to these dose levels without major physical property changes.
7. Insulation Resistance: Infinite when dry and 5×10^5 megohms after boiling 10 minutes in water.
8. Properties (Typical)⁽³⁾
 - a. Thermal Conductivity: 35×10^{-5} cal/sec(cm^2) ($^{\circ}\text{C}/\text{cm}$)
 - b. Linear Coefficient of Expansion: $4 \times 10^{-5}/^{\circ}\text{C}$
9. Health Hazards: Adequate ventilation must be provided and skin contact should be avoided.

8.0 IN-VESSEL PRESSURE TRANSDUCERS

8.1 REQUIREMENTS

The measurement requirements applicable to pressure transducers were derived from the NSS Instrumentation Specification or from the Instrumentation Design Criteria sheets. A summary of the more difficult requirements is shown in Table 8-1. A diagram of the NSS showing the various points of required measurements is shown in Figure 8-1.

8.2 DESIGN APPROACH CHARACTERISTICS

8.2.1 Design Characteristics

The following paragraphs describe the characteristics of the various concepts used for pressure transducers. A basic pressure transducer consists of a pressure sensing element, transducer mechanism for converting pressure energy into electrical energy, pressure connecting system, and an electrical connection system.

8.2.1.1 Pressure Sensing Elements

There are five basic pressure sensing elements used to convert applied pressure to a displacement. These elements are generally referred to as "force summing devices".

8.2.1.1.1 Bellows A bellows consists of a number of plates, frustums of conical shells, or the like, connected in series. One end of the bellows is fixed in position while the other end deflects where pressure is applied internally or externally to the bellows. By proper design the displacement of the free end of the bellows is proportional to the applied pressure and acts as an input to the transducer mechanism.

Errors arise from hysteresis, friction, wear in the mechanical linkages, spring rate changes due to temperature, radiation effects, and change in displacement due to vibration of the bellows and linkages. Most of these errors may be held to a minimum by proper design and compensations; usually compensating devices tend to increase the total size and mass of the transducer, thereby increasing the problem of radiation effects. For this reason, a bellows is not considered for use in a high radiation environment.

8.2.1.1.2 Capsule A capsule can be described as a two-plate bellows or a double inverted diaphragm. Hence, a capsule combines the bellow's advantages of large displacement with the diaphragm's advantage of minimum points of errors. One plate of the capsule is fixed, with the other plate permitted to expand or contract as the differential pressure internal and/or external to the capsule changes.

At present, differential pressure measurements with capsules have a relatively low (approximately 500 psi) limit to minimize the errors due to hysteresis and maintain high mechanical integrity. Vendors are working to increase the useable range to 1200 psi while maintaining the performance and reliability levels. A capsule sensing element is a NERVA candidate, especially for differential pressure sensing measurements.

8.2.1.1.3 Straight Tube The straight tube is a thin wall tube of circular cross section. Under internal pressure the walls of the tube expand with a corresponding increase in diameter. The displacement that is measured may be either the diameter increase or increase in circumference.

Temperature and radiation effects are the largest sources of error and are difficult to compensate. Therefore this pressure sensing element is not used in high temperature or radiation environments.

8.2.1.1.4 Bourdon Tube A bourdon tube, usually elliptical in cross section, has its length formed into a C-shape, helix, coiled into a spiral, or is twisted. The pressure to be measured is directed internal to one end of the tube with the other end sealed and tends to straighten the tube out. The sealed end provides a displacement input to the transducer mechanism through mechanical linkages or electrical pick-offs designed to provide resulting displacement proportional to the applied pressure.

Errors for bourdon tube sensing elements are similar to those described for the bellows. Designs to minimize or compensate for these errors have the same problem of radiation effects, except for the twisted type. The twisted bourdon tube requires fewer mechanical linkages, and less mass and therefore exhibits less temperature and radiation effects. For these reasons, the twisted type is the only type of bourdon tube that will be considered for NERVA applications.

8.2.1.1.5 Diaphragm A diaphragm is a thin plate, usually of a circular configuration, fixed in position at its outer periphery. The center of the diaphragm deflects as a function of the applied pressure. Deflections are kept to a minimum so that the middle surface does not become appreciably strained and to enable the stress/deflection relationship to remain constant.

Material property changes due to temperature and radiation effects and vibration displacement changes are the largest sources of error for diaphragm sensing elements. These sources of error can be minimized by proper design and compensation. A diaphragm pressure sensing element will be considered for these applications.

8.2.1.2 Transducer Mechanisms There are numerous types of transducing mechanisms that can be employed with the sensing elements to provide an electrical output proportional to a pressure input. Some of the more common types are: variable inductance (including variable reluctance (VR), and variable permeance (VP), linear variable differential transformer (LVDT), strain gage (including unbonded wire, bonded foil, and thin film), variable resistance (potentiometric), and variable capacitance (VC). The VR, VP, and LVDT types employ magnetic circuits and are energized by magnetomotive force (mmf) and the S/G, potentiometric, and VC types employ electric circuits and are energized by electromotive force (emf). Figure 8-2 shows the basic circuitry for these transducing mechanisms.

8.2.1.2.1 Variable Inductance A variable inductance mechanism makes use of the magnetic properties of core material and air gap to alter the self-inductance of fixed coils. Mechanisms that make use of an air gap change are commonly known as variable reluctance (VR) types and those utilizing a variable core permeability to change reluctance are referred to as variable permeance (VP) types.

Variable reluctance transducing mechanisms generally employ an "E" core with two or four coils set up in a magnetic field which has one or more air gaps in its magnetic circuit. As the position of a moveable armature is varied, the gap space and magnetic circuit reluctance change.

This results in a change of the magnetic flux density self inductance and a proportionate variation in the inductance of the coils. The change of coil inductance produces a change of the phase angle of the output voltage from a reference or null voltage. This voltage change is then proportional to the length change of the air gap. VR type mechanisms are quite rugged, require high flux densities, and are low impedance devices, thereby simplifying cable requirements. They are generally sensitive to strong magnetic fields in close proximity and must be reactively and resistively balanced.

A variable permeance transducing mechanism consist of a moveable armature in proximity to a fixed coil and core with a center-tapped winding. This creates a magnetic parallel path or shunt. As the distance between the shunt path armature and coils changes, the flux density changes because of the associated change of permeability of the magnetic path. This produces a change of inductance. The change of coil inductance produces a change of the phase angle of the output voltage from a reference or null voltage. This voltage change is then proportional to the displacement change of the armature. VP type mechanisms require lower flux densities than the VR type and generally have a higher output sensitivity per unit movement of the armature.

8.2.1.2.2 Linear Variable Differential Transformer (LVDT) An LVDT consists of a primary coil and two secondary coils with a magnetic core. The position of the core within the coils determines the mutual coupling and thus the voltage developed between the primary winding and each of the secondary or output windings. When the primary coil is energized with a.c., voltages are induced in the secondary coils. These coils are connected in series opposition so that the voltages in the secondary circuit cancel. At null position the net output voltage approaches zero. When the core is displaced from null, the voltage induced in the coil toward which the core moves will, for example, increase while the voltage induced in the opposite coil will decrease. This results in a differential voltage output from the transformer which can be designed to vary linearity with the core motion. LVDT mechanisms are relatively simple and rugged in construction, are frictionless in operation, and are low output impedance devices.

8.2.1.2.3 Strain Gage Strain gage transducing mechanism for measuring pressure are normally classified into three categories; bonded, unbonded and thin film.

In bonded devices a grid or helix of fine strain gage wire is bonded to a member which is subjected to stress or strain upon the application of the force being measured. The strain wires may be helically wound on the force summing device and then bonded to the force summing device. The strain wires or foil are usually arranged in the form of a Wheatstone bridge. The four active elements (legs on the bridge circuit) are arranged so that opposite elements increase (or decrease) their resistance at the same rate for given direction of displacement. Having four active elements provides greater sensitivity and provides a certain amount of compensation for environmental effects. The major advantages and disadvantages are outlined below.

Advantages

- Excellent linearity and hysteresis
- Low sensitivity to temperature effects
- Low sensitivity to shock and vibration
- May be excited by AC or DC
- Continuous resolution
- Static or dynamic response

Disadvantages

- Low sensitivity to unit change of displacement
- Limited temperature range
- Limited radiation resistance
- Low range limitations

The unbonded devices use a group of fine strain-sensitive filaments wired between a fixed frame and the force summing device. The filaments are arranged in the form of a Wheatstone bridge. The four active filaments (legs of the bridge circuit) are arranged to produce the same effect as the bonded strain gage. The advantages and disadvantages are about the same as outlined for the bonded strain gage, except the heat dissipation characteristics are generally worse for the unbonded gage.

The thin film device consists of a ceramic insulation film, vacuum deposited on a metal sensing element such as a diaphragm; then, a metal film is vacuum deposited to the ceramic film. The interconnecting leads are then deposited to form the bridge circuit. The strain gage bridge consists of four active legs which have the same length-to-width ratio and are balanced internally to insure electrical uniformity. Since each unit consists of four active gages, better sensitivity and compensation of certain environmental effects results. The major advantages are as follows:

- Low power consumption
- Negligible creep and hysteresis
- High power dissipation
- High natural frequency
- Low acceleration sensitivity (shock and vibration)

8.2.1.2.4 Variable Resistance (Potentiometer) A potentiometer transducing mechanism is the most common variable resistance transducer for pressure measurements. The potentiometer relies on the mechanical displacement of a sliding contact to determine the value of the resistance output. This mechanism consists of a wire-wound or deposited conductive film element on a core. A voltage impressed across the winding allows an output from the sliding contact to act as a voltage divider. The electrical circuit may also use constant current excitation to help control cable losses or a voltage excitation with the potentiometer being the active leg in a bridge circuit. This type of mechanism has disadvantages of finite resolution (wire-wound units), significant functional wear, and vibration compensation that is not compatible with a radiation hardened design. Consequently this type of transducing mechanism is not to be considered as a candidate.

8.2.1.2.5 Variable Capacitance Capacitance is a function of the effective area of conductors, separation between them, and the dielectric strength of the material in the separation. The variable capacitance transducing mechanisms most commonly used for pressure measurements utilize the change in plate (conductor) separation. The plates are diaphragms, one fixed and the other subjected to the pressure medium. The flexing of the diaphragm produces a change in plate separation that is proportional to the applied pressure.

Major shortcomings of a VC device are its sensitivity to temperature, high impedance output, a requirement for reactive as well as resistive balancing, and the comparative complexity of associated electronic circuitry. Further, this design cannot be used in a nuclear environment because of radiation charge dissipation. Long lead lengths and moving leads permit strong pickup and variation in capacitance which must be avoided. This type of mechanism is not to be considered further.

8.2.1.3 Pressure Connecting System

The most desirable pressure connecting system depends on what the transducer measures: at the point of measurement for absolute transducers or remote from the point of measurement, as required by one side of a differential unit. Since the response time is a function of the transducer cavity volume and impulse tube volume it is desirable to keep these parts as small as possible. When impulse tubes are required, they may be an integral part of the transducer or may be attached by means of pressure fittings. For long-term reliability and maintenance free operation integral tubing is generally preferred.

8.2.1.4 Electrical Connecting System

The electrical connecting system generally consists of an electrical connector or an integral metal sheathed cable. Again, for the long-term reliability and maintenance-free operation the integral sheathed cable is deemed more desirable.

8.2.2 Functional Characteristics

Functional characteristics that are considerations for trade-off are accuracy, response time, environmental effects, and size.

8.2.2.1 Accuracy

Transducer accuracies are made up of compensated and uncompensated errors.

8.2.2.1.1 Compensating Errors These are errors that are taken care of within the transducer or the signal conditioning network of the measurement channel. Inherent errors due to non-linearities and some predictable environmental effects can be compensated by individual and/or lot calibrations of the transducers.

8.2.2.1.2 Uncompensating Errors Uncompensating errors affecting the transducer accuracy are hysteresis, friction and wear of moving components, and certain kinds of linearity and environmental effects.

8.2.2.2 Response Time

As previously stated, the response time of pressure transducers is a function of the cavity and impulse tube volumes as well as the pressure sensing elements and transducing mechanisms. The cavity volume is the only volume consideration used for trade-off studies since the impulse tube volume will be identical for all pressure measuring transducers.

8.2.2.3 Environmental Effects

As stated in Section 8.2.2.1 some environmental effects can be compensated while others are unpredictable or not repeatable and result in an uncompensated error. A description of the major effects and means of compensation are described below:

<u>EFFECT</u>	<u>MEANS</u>
Temperature	May be internally compensated to a specific accuracy for a specific temperature range. Points outside this range may be predictable if temperature condition is known.
Vibration	Generally compensated by design to be within a specified error for a specific vibration range.
Radiation	Generally compensated by design to be within a specified error for a specific radiation environment. Outside this range the error may be predictable if the environment is known.

The environment effects may change the sensitivity (shift) or may produce a change in the zero output (drift), both of which may be permanent or temporary depending on the degree of the effect.

8.2.2.4 Size

The size of the unit is a consideration for trade-off since the NSS design limits the volume. The transducer when mounted in the pressure vessel may affect propellant flow and distribution. Also, size may indirectly contribute to the radiation effect errors.

8.3 DESCRIPTION OF DESIGN APPROACHES

The design approach descriptions are presented in two parts; absolute and differential. Each of these parts is categorized by the transducing mechanism as described in Section 8.2.1.2. Various pressure transducers were investigated through a literature survey and evaluated against certain additional major requirements. These additional major requirements are:

- Pressure Range Capability

- Temperature Compensation Design

- Radiation Resistant Design

- Transducer Accuracy

A summary of these design approach descriptions is presented in Table 8-2.

8.3.1 Absolute Transducers

8.3.1.1 Variable Inductance

This category of transducers includes both variable reluctance and variable permeance mechanisms. These units may be classified as open case or closed case types. An open case unit is one which the unknown pressure permeates the transducer through the case primarily to provide mass cooling to the transducer coils. By design, therefore, the open case transducer has to be mounted at the point of pressure measurement. A closed case design permits an impulse tube to direct the unknown pressure internal to the case. Its distinct advantage is it can be mounted with the transducer remote from the pressure sensing point.

8.3.1.1.1 Kaman Nuclear (Model K-1700 Series) This transducer is a variable inductance closed case device within the required pressure ranges and has operated satisfactorily up to 10^{14} nvt. Vendor data indicate a constant drift results when it is exposed to fast neutron fluence above this level. These transducers do not meet the required temperature compensation range as related to accuracy and require a one megahertz carrier frequency with an individual linearizer to meet other aspects of accuracy. Hence, this transducer type is not being considered as a candidate for the NERVA pressure measurements.

8.3.1.1.2 Tavis Engineering Co. (Model P-104 and P-106) These transducers are closed-case diaphragm-operated variable reluctance instruments with built-in electronic circuitry. Although the desired pressure ranges can be accomplished, these units are not of a radiation hardened design, cannot meet the accuracy requirements, and have a low range of temperature compensation. This transducer type is not being considered further for NERVA pressure measurement requirements.

8.3.1.1.3 Wiancko (Model 54726) This pressure transducer is represented by WANL P/N 945C923. It is a variable reluctance closed case type with the unknown pressure being directed into a twisted bourdon tube. The rotation of the tube changes the magnetic field and results in a change of output voltage. A cutaway view of this transducer is shown in Figure 8-3. These units have been used in the technology reactor testing series and exhibited output shunting in high radiation environments. The radiation requirements for these units when mounted above the internal shield are lower than the environment in which they have been previously tested. It is felt that some minor design changes (as yet unspecified) can be made to make these units more radiation resistant. These changes will be identified in a radiation effects analysis, yet to be performed. This transducer type, with the minor changes incorporated, is to be considered as an alternate candidate for the NERVA pressure measurement requirements.

8.3.1.1.4 Wiancko (Model 600755) This absolute pressure transducer is represented by WANL P/N 979D717, Equipment Specification 675576. It is an open-case variable reluctance type unit where the measured pressure is the plenum pressure at the point of mounting. Figure 8-4 is a cutaway view of this transducer. This unit was evaluated during the NRX-A6 testing series; output shunting due to the radiation environment was experienced. This transducer cannot physically be mounted at the desired point of measurement for all absolute pressure requirements; it is too large. Units providing the capability of remote sensing will have to be qualified. Therefore, for standardization, this type of pressure transducer is not being considered further for the NERVA pressure measurement requirements.

8.3.1.1.5 Schaevitz Engineering (Model PTA-10) This unit is a variable permeance, closed-case type transducer. It used a metallic capsule to move a core within fixed coils. Since the magnetic flux path is a constant, the relative movement of the core to the coils effectively varies the permeance of the magnetic circuit. Although the VP type pressure transducer has not previously been used in the NERVA program, LASL has used successfully the VP principle in a displacement-type transducer. A cutaway view of the transducer is shown in Figure 8-5. This unit is to be considered a candidate for the NERVA in-vessel flight requirements.

8.3.1.2 Linear Variable Differential Transformer (LVDT)

An LVDT transducing mechanism when coupled with a diaphragm or capsule, the most common type pressure sensing elements, produces a pressure transducer design. A relatively large displacement is required by an LVDT for good sensitivity and accuracy. The capsule generates larger displacements per unit area for a given force than does a diaphragm. Two manufacturer's models were investigated and evaluated. The results indicated an LVDT type of pressure transducer has no distinct advantage over the variable inductance units and the disadvantage of being a 4 or 6 wire system versus a 3 wire system. The two manufacturers surveyed were Consolidated Controls Corp. (CCC), and Schaevitz Engineering.

8.3.1.2.1 Consolidated Controls Corp. - CCC A CCC unit (Model No. 413 M37) was used early in the technology program. Although this particular model is a differential-type transducer (WANL P/N 945C934), it can easily be made to measure absolute pressures. The unit has very little radiation test data; it is not being considered further for NERVA pressure measurements.

8.3.1.2.2 Schaevitz Engineering (Model PTA-11) This unit utilizes an Inconel X-750 capsule with a 300 series stainless steel body. The vendor literature indicates the performance of this unit is as good or better than all other models investigated. It is comparable to the Schaevitz variable permeance type (Model PTA-10) transducer except it is a 4 or 6 wire system instead of the 3 wire system. A cutaway view of this transducer is shown in Figure 8-6. This unit is to be considered further for NERVA pressure measurements.

8.3.1.3 Strain Gage

This category of transducers includes the bonded foil, unbonded wire, and thin film type of transducing mechanisms. Basic advantages of strain gage type transducers are:

- Excellent frequency response for dynamic measurements

- Good linearity and hysteresis characteristics

- Ease of temperature compensation

The basic disadvantages are:

- Low output and sensitivity

- Difficult radiation effects compensation

8.3.1.3.1 MB Electronics - Alnico (Model 172-BAA-1)

The Alnico pressure transducer is a rugged design with a sensitive cantilever-beam sensing element using a bonded foil strain gage in a four-active-arm Wheatstone bridge. These transducers have excellent pressure ranges, good temperature compensation, and good accuracy for the pressure and temperature range requirements. However, their rugged design is detrimental to radiation environment performance. The basic design construction will not permit a good radiation resistance modification since the mass of the cantilever-beam is large and any effort to reduce the beam size will greatly affect the accuracy and performance of the instrument.

This transducer type will not be considered further for the NERVA pressure measurement requirements.

8.3.1.3.2 BLH Electronics (Model DFHM) This type of BLH pressure transducer is a stiff diaphragm sensing element in a closed case design using a bonded foil strain gage in a four-active-arm Wheatstone bridge. It is similar to the Alnico type described above except the means of temperature compensation and the resultant overall accuracy are not as good. This type of transducer will not be considered further for the NERVA pressure measurement requirements.

8.3.1.3.3 Dynisco (Model PT119H)

The Dynisco pressure transducers consist of a diaphragm sensing element in a closed case using a four-active-arm bonded strain gage bridge which is compensated and balanced. Although the pressure ranges and basic accuracies are satisfactory, their temperature compensation and radiation resistant designs are considered insufficient. This transducer type will not be considered further for the NERVA pressure measurements.

8.3.1.3.4 Consolidated Electrodynamic Corp. - CEC (Model 4-350-0002)

The CEC pressure transducer sensing element is an unbonded strain gage composed of a four-active-arm, spring-type sensor, and a diaphragm force-summing area within a closed case. This transducer has been used successfully in the technology program as a pressure sensing device mounted in a radiation-shield environment. It is represented by WANL P/N 980D603. The temperature compensating range and radiation hardened design do not meet the requirements for in-vessel mounting. This transducer type will not be considered further for the flight NERVA pressure measurements but will be a candidate for ground test measurements until an in-vessel design has been qualified.

8.3.1.3.5 Statham (Model PA 732) This Statham-type transducer is exactly the same as the CEC model described above. It also was used in the technology program in a radiation shielded environment but exhibited more drifting with temperature and small excitation voltage changes. It is represented by WANL P/N 978D255.

This type of transducer will not be considered further for the flight in-vessel NERVA pressure measurement requirements nor in the ground test series.

8.3.1.3.6 Statham (Model RPH-034, Basic PA 822) This pressure transducer model is represented by WANL P/N 979D718, Equipment Specification 675529. This transducer is a thin film strain gage design employing a diaphragm sensing element with a ceramic insulated, vacuum-deposited, four-active-arm bridge. This unit is a flush-mounted diaphragm design and can only sense the pressure of the plenum in which it is mounted. A cutaway view of this design is shown in Figure 8-7. The WANL P/N 979D718 was evaluated during the NRX-A6 testing series and showed only a slight shunting of output; this was attributed to radiation effects. Since this transducer cannot sense pressures remotely it is not being considered further for the NERVA pressure measurement requirements.

8.3.1.3.7 Statham (Model 50927) This pressure transducer is represented by WANL P/N 980D619. This transducer is also a thin film strain gage design and the configuration will permit remote pressure sensing. A cutaway view is shown in Figure 8-8. The radiation requirements for these units are lower than for the environment in which the thin film design was previously tested. This design is to be considered the prime candidate for the NERVA pressure measurement requirements, from WANL, LASL, and Aerojet results with similar devices.

8.3.1.4 Variable Resistance (Potentiometer)

A variable resistance pressure transducer is a potentiometer device using a wire wound core and wiper and is generally employed as a voltage divider. The basic advantages of this type of transducer are:

- High output
- High electrical efficiency
- Impedance matching not necessary

The basic disadvantages are:

- Finite resolution in most cases
- Limited life
- High noise level with wear

- Low frequency response
- Large displacement required
- Difficult temperature compensations
- Not generally of a radiation hardened design

Bourns, Edcliff, and other manufacturers of potentiometric-type pressure transducers are not being considered further for the NERVA pressure measurement requirements because of the disadvantages listed above.

8.3.1.5 Others

Other types of pressure transducers which exist and were briefly surveyed include variable capacitance, piezoelectric, and variable frequency (vibrating wire). These transducer types offer no distinct advantage and are not being considered further for the NERVA pressure measurement requirements because of the following disadvantages:

Variable Capacitance

- High impedance output
- Must be reactively and resistively balanced
- Require complex signal conditioning systems
- Impose various cabling restraints
- Cannot be used in radiation fields

Piezoelectric

- Difficult to measure static conditions
- High impedance output
- Requires impedance matching
- Requires complex signal conditioning system
- Imposes various cabling restraints

Variable Frequency (Vibrating Wire)

- Very sensitive to thermal changes
- Very sensitive to shock and vibration
- Questionable stability

8.3.2 Differential Transducers

It is desirable to standardize the design characteristics between absolute and differential pressure transducers if this can be accomplished without compromising the functional characteristics. Hence, the only type of differential transducers here described are the types of absolute transducers which are being further considered for the NERVA pressure measurement requirements.

8.3.2.1 Variable Inductance

This category of transducer includes both variable reluctance and variable permeance transducing mechanisms. The description of this type of transducer is identical to that for the absolute transducer described in Section 8.3.1.1.

8.3.2.1.1 Wiancko (Model 54726) This pressure transducer is represented by WANL P/N 945C922. It is a variable reluctance type with the low side pressure directed into the case and the high side pressure directed into the twisted bourdon tube.

These units have been used in the technology program. The output signal exhibited marked shunting effects in the high radiation environment. A cutaway view of this transducer is shown in Figure 8-9. The same minor changes described for the absolute version of this transducer can be made to make them more radiation resistant. This transducer type, with the minor changes incorporated, is to be considered as an alternate candidate for the NERVA high differential pressure measurements.

8.3.2.1.2 Schaevitz Engineering (Similar to Model PTA-10) This differential transducer is similar to the variable permeance absolute unit. The vendor literature suggests the high pressure be applied outside the capsule and low pressure applied internal to the capsule for best operation. A cutaway view of this unit is shown in Figure 8-10.

8.3.2.2 Linear Variable Differential Transformer

The description of this type of transducer is identical to the absolute transducer described in Section 8.3.1.2.

8.3.2.2.1 Schaevitz Engineering (Similar to Model PTA-10) This differential transducer is similar to the LVDT absolute unit. The vendor literature suggests the high pressure be applied external to the capsule and the low pressure internal. A cutaway view of this unit is shown in Figure 8-11.

8.3.2.3 Strain Gage (Thin Film)

This strain gage transducer is the only strain gage type being further considered for the absolute pressure measurements. Although there has not been a thin film strain gage differential pressure transducer made, Figures 8-12 and 8-13 show cutaway views of possible constructions. It is desirable to isolate the side of the diaphragm on which the strain gage is deposited to prohibit the strain gage from being affected by the pressure medium. This configuration is depicted in Figure 8-12. An alternate to this configuration is shown in Figure 8-13 which permits the strain gage to be exposed to the pressure medium.

8.4 COMPARISON MATRIX

The Summary of Description Chart, Table 8-2, presents a screening comparison based on past test data and vendor's literature. Those design approaches selected for further consideration are compared to the considerations for trade-off as identified in Section 8.2 and the measurement requirements shown in Section 8.1.2. These data are then presented in a comparison matrix (Table 8-3).

8.5 SELECTION OF DESIGN APPROACHES

The prime candidate for the NERVA in-vessel pressure measurements are as follows:

Absolute - Statham thin film strain gage, because of the past testing results in the technology program.

Differential - Schaevitz variable permeance because of its high radiation resistance potential and the problems associated with differential thin film strain gages. Past Phoebus 2A testing indicates that this device should be superior to the Schaevitz LVDT model.

All other design approaches described in the comparison matrix will be considered as backup candidates. All candidate design approaches to be considered further in the NERVA development instrumentation program show some prospect of being capable of meeting the desired results. The variable reluctance units continuously showed output degradation due to the high radiation environment during the technology program testing and definitely require modification to perform successfully. The variable permeance units have yet to be tested in this radiation environment; however, the concept appears satisfactory as a result of LASL testing. The thin film strain gage concept was tested successfully in the technology program; however, it has not been manufactured in a design which permits remote sensing of the desired pressure.

TABLE 8-1
PRESSURE TRANSDUCER REQUIREMENTS

<u>Characteristic</u>	<u>Requirement</u>	<u>Traceability</u>
Accuracy - Abs.	+ 0.6% (Transducer)	EC677565- Table 1
-Diff.	± 0.5% (Transducer)	
Range - Abs.	0-6 to 0-1200 psia	IDC - 004, 005, 048, 050,
-Diff.	0-50 to 0-800 psid	051, 052, 053, 054,
		057, 060
Freq. Response	10 Hz	IDC - (All)
Reliability	0.999900	EC677565- 3.1.2.1
Maintainability	N/A	EC677565- 3.1.2.2
Useful Life-Space Life	3 years	EC677565- 3.1.2.3
Operating	10 hrs at 60 cycles max.	
Grd Storage	5 years	
Environmental:		EC677565- 3.1.2.4
Temperature Range	100 - 700° R	IDC - (All)
Fast Neutron (E >1MeV)	2.2×10^{12}	IDC - (All)
	7.7×10^{16} nvt	IDC - (All)
Gamma Flux	1×10^7 R (c)/hr	IDC - (All)
Heating Rate	.03 watt/gm (s.s)	IDC - (All)
Vibration	(TBD)	
Acceleration	(TBD)	
Shock	(TBD)	
Vacuum (Storage-Space)	10^{-9} Torr	
Transportability	N/A	EC677565- 3.1.2.5
Human Performance	Non-Complicated	EC677565- 3.1.2.6
Safety	N/A	EC677565- 3.1.2.7
Fluid Compatability	GH ₂ , GHe, GN ₂ , Air	EC677565- 3.3.1.9
Design Feature	Mount close to point of measurement	EC677565- 3.3.1.16
Electromagnetic Interference	MIL-E06051	EC677565- 3.3.9
Installation	DRM 52025	939J723
	DRM 52026	
	DRM 52028	

TABLE 8-2
SUMMARY OF DESCRIPTION

Transducing Mechanism	Sensing Element	Manufacturer	Vendor Model WANL P/N	Absolute/Differential	Design Appr. Candidate	Pro	Remarks	Con
V. I.	Diaphragm	Kaman	K-1700 series	Abs/Diff	No	Pressure ranges O. K. Sense remote press.	Constant drift above 10^{14} nvt Low temp. compensation Requires 1 MHz carrier frequency. Requires individual linearizer.	
V. R.	Diaphragm	Tavis Engineering Company	P-104 and P-106	Abs/Diff	No	Pressure ranges O. K. Sense remote press.	No radiation hardened design. Low accuracy Low temp. compensation	
V. R.	Twisted Bourdon Tube	Wiancko	54726/ 945C923 945C922	Abs.	Yes (with small modifications)	Sense remote press. Pressure ranges O. K. Linearity/Hysteresis - good Temp. comp - good Radiation Hardened Design - Fair (Requires changes)	Output drifts in a higher radiation environment than anticipated.	
V. R.	Twisted Bourdon Tube	Wiancko	600755/ 979D717	Abs.	No	Pressure ranges O. K. Lin/Hyst - good Temp comp - good Radiation Hardened Design - Fair	Cannot sense remote pressure, only where mounted	
V. P.	Capsule	Schaevitz Engineering	PTA-10	Abs/Diff	Yes	Transducing mechanism has shown good radiation resistance	No previous experience as a pressure transducer in a high radiation environment	
LVDT	Bellows	Consolidated Controls Corp. CCC	4L3M37/ 945C934	Diff	No	Sensor remote press. Pressure ranges O. K. Lin/Hys - Fair Temp comp - Fair	Requires 4 or 6 wire system	
LVDT	Capsule	Schavitz Engineering	PTA-11	Abs/Diff	Yes	Sense remote press. Pressure ranges O. K. Lin/Hys - Fair Temp Comp - Fair	Requires 4 or 6 wire system No advantages over V. P. type	

TABLE 8-2 (CONTINUED)

Transducing Mechanism	Sensing Element	Manufacturer	Vendor Model WANL P/N	Absolute/ Differential	Design Appr. Candidate	Pro	Remarks	Con
Bonded Foil S/G	Cantilevered Beam	MB Electronics- Alnico	172-BAA-1	Abs/Diff	No		Sense remote press. Pressure ranges O. K. Temp comp - good Accuracy - good except for radiation	Not a radiation hardened design
Bonded Foil S/G	Diaphragm	BLH Electronics	DFHM	Abs/Diff	No		Sense remote press. Pressure ranges O. K. Accuracy - good except for radiation	Not a radiation hardened design Low temp comp.
Bonded Foil S/G	Diaphragm	Dynisco	PT119H	Abs/Diff	No		Sense remote press. Pressure ranges O. K. Accuracy - Fair except for radiation	Not a radiation hardened design Low temp comp.
Unbonded S/G wire	Diaphragm	Consolidated Electro- magnetic Corp - CEC	4-350-002/ 980D603 and 980D608	Abs/Diff	No		Sense remote press. Pressure ranges O. K.	Not a radiation hardened design Low temp comp. Low accuracy
Unbonded S/G wire	Diaphragm	Statham	PA732/ 978D225	Abs/Diff	No		Sense remote press. Pressure ranges O. K.	Not a radiation hardened design Low temp comp Low accuracy Drifts with time.
Thin film S/G	Diaphragm	Statham	RPH-034/ 979D718	Abs	No		Pressure ranges O. K.	Cannot sense remote press. only where mounted.
Thin film S/G	Diaphragm	Statham	50927/ 980D619	Abs/Diff	Yes		Remote sense press. Pressure range O. K. Temp comp - good Accuracy - Fair	Slightly larger mass than 979D718 model

TABLE 8-3
COMPARISON MATRIX

Design Approach	Design Approaches (Section 8.3) Manufacture - P/N (Model)				
Characteristics (Section 8.2)	Requirements (Section 8.1)	Wiancko 945C923	Schaevitz PTA-10 945C922	Statham 980D619	Schaevitz PTA-11
Pressure Sensing Element	N/A	Twisted Bourdon Tube	Capsule	Diaphragm	Capsule
Transducer Mechanism	N N/A	V. R.	V. P.	Thin Film S/G	LVDT
Range Capability	Abs 0-1200 psia	Acceptable	500 psi-limit (can be made 1200 psi)	Acceptable	500 psi-limit (can be made 1200 psi)
Accuracy - Noncompensated	+0.55% F.S.	+1.0%	+1.5%	+1.0%	+1.5%
Resolution	+0.10% F.S.	Cont.	Cont.	Cont.	Cont.
Temperature Comp. Range	100 - 700°R	Accept.	Accept.	Accept.	Accept.
Radiation Range - Limits	2.2×10^{12} nv 7.7×10^{16} nvt 1×10^7 R(c)/hr 0.03 watts/gm(ss)	1.0×10^{13} nv 3.6×10^{16} nvt 5.5×10^7 R/hr 0.2 watts/gm	----- 1×10^{20} nvt ----- -----	1.0×10^{13} nv 3.6×10^{16} nvt 5.5×10^7 R/hr 0.2 watts/gm	----- 1×10^{20} nvt ----- -----
Size (Cu. In.)	Small as possible	1.85	0.85	1.25	0.75
Cavity Volume	Small as possible	ALL APPROXIMATELY SAME SIZE			
Testing Experience*	Much as possible	NRX-A2 to -A6	Phoebus 2A	NRX-A6	NONE
Selections Absolute Differential		Backup Backup	Backup Prime	Prime Backup	Backup Backup

* Similar units

Figure 8-1a. In-Vessel Pressure Measurements

MEASUREMENT NUMBER DESCRIPTION

Absolute Pressures:

1. Reflector Inlet Plenum
2. Core Inlet Plenum
3. Support System Bypass Line
4. NSS Outlet to Turbine
5. Structural Support Supply Plenum
6. NSS Inlet from Turbine

Differential Pressures:

7. Reflector Inlet/Turbine Inlet
8. Reflector Inlet/Core Exit
9. Core Inlet/Core Exit
10. NSS Inlet from Turbine/Core Inlet
11. Structural Support System (SSCA Inlet/Reflector Outlet)
12. Seal Chamber/Core Exit

Figure 8-1b. In-Vessel Pressure Measurements

NOMENCLATURE - MAGNETIC CIRCUITS

R = RELUCTANCE
L = INDUCTANCE
P = PERMEANCE
A = AREA, PERPENDICULAR
TO FLUX PATH

μ = PERMEABILITY, CORE MATERIAL
 Δ = CHANGE IN PARAMETER
SUBSCRIPT 1 = IRON PATH
SUBSCRIPT 2 = AIR PATH
l = TOTAL LENGTH OF PATH

Figure 8-2a. Transducing Mechanisms - Basic Circuit

NOMENCLATURE - ELECTRIC CIRCUITS

STRAIN GAGE/VARIABLE RESISTANCE

R = RESISTANCE, LEG-INITIAL
 Δr = RESISTANCE CHANGE, LEG
 α = RATIO R_t/R_c 1.0

SUBSCRIPTS: T = RESISTOR (S/G), TENSION
 C = RESISTOR (S/G), COMPRESSION
 1 + 2 = RESISTOR (S/G), COMPENSATING

VARIABLE CAPACITANCE

C = CAPACITANCE
 K = DIELECTRIC CONSTANT
 A = AREA, PLATE CROSS-SECTION
 D = DISTANCE, BETWEEN PLATES
 f = FUNCTION, CONSTANT

$$\text{STRAIN GAGE: } E_{\text{OUT}} = E_{\text{IN}} \left[\frac{\alpha}{(1+\alpha)^2} \right] \left[\frac{\Delta r_t}{R_t} - \frac{\Delta r_1}{R_1} + \frac{\Delta r_c}{R_c} - \frac{\Delta r_2}{R_2} \right]$$

$$\text{VARIABLE RESISTANCE (POTENTIOMETER): } E_{\text{OUT}} = \frac{1}{4 E_{\text{IN}}} \left[\frac{\sum \Delta R}{R} \right]$$

$$\text{VARIABLE CAPACITANCE: } C = (f) \frac{KA}{D}$$

Figure 8-2b. Transducing Mechanisms - Basic Circuits

Figure 8-3. Wiancko Model 54726. WANL P/N 945C923
VR - Closed Case X Absolute

NOTE: Not a Candidate Design

Figure 8-4. Wiancko Model 600755. WANL P/N 979D717
 VR - Open Case - Absolute

Figure 8-5. Schaevitz Model PTA-10, WANL P/N SK-I-425
VP - Capsule - Absolute

Figure 8-6. Schaevitz Model PTA-11, WANL P/N SK-I-424
LVDT - Capsule - Absolute

NOTE: Not a Candidate Design

Figure 8-7. Statham Model RPH-034 (Basic PA 822),
WANL P/N 979D718 - Strain Gage Thin
Film Diaphragm - Absolute

Figure 8-8. Statham Model 50927, WANL P/N 980D619
S/G Thin Film - Diaphragm - Absolute

Figure 8-9. Wiancko Model 54726, WANL P/N 945C922
VR - Closed Case - Differential

Figure 8-10. Schaevitz Model PTA-10, WANL P/N SK-I-421
VR - Capsule - Differential

Figure 8-11. Schaevitz Model PTA-11, WANL P/N SK-I-422
LVDT - Capsule - Differential

Figure 8-12. Design Concept - S/G Thin Film Isolated Diaphragm

Figure 8-13. Design Concept, WANL P/N SK-I-426
S/G Thin Film - Exposed Diaphragm - Differential

9.0 VIBRATION TRANSDUCERS

9.1 REQUIREMENTS

NERVA vibration transducers must be capable of measuring the axial, radial, and tangential vibration during normal and emergency operating modes within the performance requirements started in Table 9-1. This table shows the various requirements and the traceability of these requirements.

9.2 DESIGN APPROACH CHARACTERISTICS

In order to evaluate the various design approaches, a significant number of characteristics must be established to show how well each approach is suited to the application. Using the requirements in Table 9-1, the characteristics most applicable to vibration transducer designs are as follows:

1) Nuclear Environment

- Gamma Dose Rate
- Fast Neutron Flux ($E > 1\text{MeV}$)
- Fast Neutron Fluence ($E > 1\text{ MeV}$)

2) Thermal Environment

3) Accuracy

4) Frequency Response

5) Design

6) Installation

Previous use of internally-mounted vibration transducers in the technology testing program has been limited to VR types, and indicates that at reactor full power the output reduces to zero. This is a known transducer limitation and the output cannot be considered valid during this period. The transducer is not permanently damaged by this, however, and begins to operate normally again when the reactor power level is decreased. It must be noted that the VR accelerometer does survive the core support plate radiation environment and gives good internal reactor vibration data before and after full power. This information is not attainable with any other accelerometer tested to date. The NRX-A6 test indicates that future development on this transducer will be necessary so that it will operate throughout the full power test.

9.3 DESIGN APPROACH DESCRIPTION

There are numerous types of transducing devices that can be employed with the accelerators-sensing mechanisms to provide an electrical output. Some of the more common types are: variable inductance (including variable reluctance and variable permeance), linear variable differential transformer (LVDT), and strain gage (including unbonded wire, bonded foil, and thin film). The VR, VP, and LVDT types employ magnetic circuits and are energized by magnetomotive force (mmf) and the strain gage employs electric circuits and is energized by electromotive force (emf). Figure 9-1 and 9-2 show the basic circuitry for these transducing mechanisms.

9.3.1 Variable Inductance

A variable inductance mechanism makes use of the magnetic properties of core material and air gap to alter the self-inductance of fixed coils. Mechanisms that make use of an air gap change are commonly known as variable reluctance (VR) types and those utilizing a variable core permeability to change reluctance are referred to as variable permeance (VP) types.

9.3.1.1 Variable Reluctance

This transducing mechanism generally employs an "E" core with two or four coils set up in a magnetic field which has one or more air gaps in its magnetic circuit. As the position of a moveable armature is varied, the gap space and magnetic circuit reluctance change. This results in a change of the magnetic flux density self inductance and a proportionate variation in the inductance of the coils. The change of coil inductance produces a change of the phase angle of the output voltage from a reference or null voltage. The resulting output voltage change is then proportional to the length change of the air gap. VR type mechanisms are quite rugged, require high flux densities, and are low impedance devices, thereby simplifying cable requirements. They are generally sensitive to strong magnetic fields and must be reactively and resistively balanced.

9.3.1.1.1 Improved Model Wiancko AX-44 VR Accelerometer This type, which was redesigned internally by Wiancko in order to reduce the thermal sensitivity effects, was used for WANL vibration measurements in the NRX-A6 reactor tests. The accelerometer has a 347 stainless steel hexagon case measuring 1.25 inches across the flats by 1 inch high. The electrical connection is a three conductor (62 mil dia.) stainless steel sheathed magnesium oxide (MgO) insulated cable integral with the accelerometer case. The transducer excitation voltage in NRX-A6 was 3.536 v.a.c. (rms) at 5 KHz. Its operating temperature range is -320°F to $+600^{\circ}\text{F}$.

9.3.1.2 Variable Permeance

This transducing mechanism consists of a moveable armature in proximity to a fixed coil and core with a center-tapped winding. This creates a magnetic parallel path or shunt. As the distance between the shunt path armature and coils changes, the flux density changes because of the associated change of permeability of the magnetic path. This produces a change of inductance, resulting in a change of the phase angle of the output voltage from a reference or null voltage. The resulting output voltage change is then proportional to the displacement change of the armature. VP type mechanisms require lower flux densities than the VR type and generally have a higher output sensitivity per unit movement of the armature.

9.3.2 Linear Variable Differential Transformer (LVDT)

An LVDT consists of a primary coil and two secondary coils with a magnetic core. The position of the core within the coils determines the mutual coupling, and thus the voltage developed between the primary winding and each of the secondary or output windings. When the primary coil is energized with a.c., voltages are induced in the secondary coils. These coils are connected in series opposition so that the voltages in the secondary circuit cancel. At null position the output voltage approaches zero. When the core is displaced from null, the voltage induced in the coil toward which the core moves for example, increases, while the voltage induced in the opposite coil decreases. This results in a differential voltage output from the transformer which can be designed to vary linearity with the core motion. LVDT mechanisms are relatively simple and rugged in construction, are frictionless in operation, and are low output impedance devices.

9.3.3 Strain Gage

Strain gage transducing mechanisms for measuring vibration are normally classified into three categories: bonded, unbonded, and thin film.

9.3.3.1 Bonded Strain Gage

The bonded devices consist of a grid or helix of fine strain gage wire bonded to a member which is subjected to stress or strain upon the application of the force being measured. The strain wires may be helically wound on the force summing device and then bonded to it. The strain wires or foil are usually arranged in the form of a Wheatstone bridge. The four active elements (legs on the bridge circuit) are arranged so that opposite elements increase (or decrease) their resistance at the same rate for a given direction of displacement. Having four active elements provides greater sensitivity and a certain amount of compensation for environmental effects. The major advantages and disadvantages are:

Advantages

- Excellent linearity and hysteresis
- Low sensitivity to temperature effects
- Low sensitivity to shock and transverse vibration
- May be excited by a.c. or d.c.
- Continuous resolutions
- Static or dynamic response

Disadvantages

- Low sensitivity to unit change of displacement
- Limited temperature range
- Limited radiation environment
- Low range limitations

9.3.3.2 Unbonded Strain Gage

The unbonded devices use a group of five strain-sensitive filaments wired between a fixed frame and the force summing device. The filaments are arranged in the form of a Wheatstone bridge. The four active filaments (legs of the bridge circuit) are arranged to produce the same effects as the bonded strain gage.

The unbonded strain gage has a better frequency response than the bonded gage; otherwise its advantages and disadvantages are the same as outlined for the bonded strain gage.

The Statham (A-519) transducer is an unbonded strain gage accelerometer having a cylindrical case 0.88 inch in diameter, 1.52 inches high, with a 1.0 inch square mounting base. The case material is 410 stainless steel. The strain sensitive wire elements, made from a platinum alloy and connected in full bridge configuration, are electrically connected to an attached four conductor (90 mil dia.) stainless steel sheathed MgO insulated cable integral with the accelerometer core. This transducer is compensated for ambient temperature within the -65°F to $+250^{\circ}\text{F}$ range. Five volts d.c. excitation are required for a nominal sensitivity of ± 20 millivolts, full range. Details of the acceleration measurement are documented in the WANL Control Systems Engineering report for the NRX-A6 actuator side-by-side tests.

The strain gage accelerometer operated throughout the NRX-A6 test series with no apparent structural damage, although the usability of the data is subject to some disagreement^(1, 2). The temperature environment for these transducers reached as low as -200°F and as high as $+150^{\circ}\text{F}$ during the EP-III A full power test.

9.3.3.3 Thin Film

The thin film instrument consists of a ceramic insulation film being vacuum deposited on a metal sensing element, such as a diaphragm. Four strain gages are applied by the process of vacuum deposition. The interconnecting leads are then deposited to form the bridge circuit. The strain gage bridge consists of four active legs which have the same length-to-width ratio and are balanced internally to insure electrical uniformity. Using four active gages provides for better sensitivity and compensation of certain environmental effects. The major advantages are as follows:

- Low power consumption
- Negligible creep and hysteresis
- High power dissipation
- High natural frequency
- Low acceleration sensitivity (shock and vibration)

9.3.3.3.1 Trantec, Inc. Thin Film Deposited Beam Accelerometer The accelerometer has a 17-4PH stainless steel case measuring 1 inch dia. x 2 inch maximum length. The electrical connection is four stainless steel-sheathed MgO-insulated leads. The transducer excitation voltage is 15 v.d.c. or a.c.(rms) through carrier frequencies. Its operating temperature range is -65 to +250°F. There have been no WANL tests made of this accelerometer to date.

9.4 COMPARISON MATRIX

Due to the lack of both non-nuclear and nuclear testing of the various vibration transducers insufficient information exists to provide a comparison; therefore a comparison matrix table is not included.

9.5 DESIGN CONCEPT SELECTION

In reviewing the various vibration transducers covered in this document, three have been considered as the most promising candidates from a design concept approach. They are: 1) the improved Model Wianko AX-44 VR Accelerometer; 2) Variable Permeance; and 3) Trantec, Inc. Thin Film Deposited Beam Strain Gage. As described in paragraph 9.2 the AX-44 has been tested (nuclear) and shows further development needed. The VP and the Thin Film Strain Gage have not been tested. In the area of installation (DRM 51902 and 979J723) there is a definite problem: there is not enough clearance in the plenum between shield and support plate. The VR type of transducer cannot fit within the installation limitations for the axial measurement and requires a pedestal with a cutout in the central shield. It is assumed that the thin film strain gage transducer will fit within the installation limitations.

There is no available vibration transducer that qualifies for the core support plate measurements. Based on this report, the following vibration transducers may be acceptable for this application and therefore merit development testing:

- a) Wianko AX-44 Variable Reluctance
- b) Variable Permeance
- c) Trantec, Inc. Thin Film Deposited Beam Strain Gage

9.6 REFERENCES

1. WANL-TME-1863, "NRX-A6 Transducer Evaluation Report, " December 1968
2. WANL-TME-1832, "NRX-A6 Reactor Structural Performance, " March, 1969.

TABLE 9-1

REQUIREMENTS - CORE SUPPORT PLATE

<u>Characteristic</u>	<u>Requirement</u>	<u>Traceability</u>
Range	± 15 g	* IDC-080
Accuracy (System)	± 0.75 g	** EC677565-Table 1
Response Time	(TBD)	EC677565-Table 1
Frequency Response	1000Hz	IDC-080
Reliability (3)	0.999900	EC677565-3.1.2.1
Maintainability (3)	N/A	EC677565-3.1.2.2
Useful Life (3)		EC677565-3.1.2.3
Operating Lifetime	600 minutes	
Operating Life-Cycles	60 max.	
Space Lifetime	3 years	
Ground Storage Time	5 years	
Environment		EC677565-3.1.2.4
Natural +	Inert	EC677565-3.1.2.4.1
Induced		EC677565-3.1.2.4.2
Nuclear		IDC-080
Gamma Dose Rate	1.7×10^9 R(c)/hr.	
Fast Neutron Flux (E>1 MeV)	1.78×10^{14} nv	
Fast Neutron Fluence (E>1 MeV)	6.41×10^{18} nvt	
Loads		EC677565-3.1.2.4.2.2
Shock +	N/A	

TABLE 9-1 (CONT)

<u>Characteristic</u>	<u>Requirement</u>	<u>Traceability</u>
Vibration	(TBD)	IDC-080
Thermal	60-700° R	IDC-080
Pressure Range	10(-9) TDRR to 640P51A	IDC-080
Transportability +	N/A	EC677565-3.1.2.5
Human Performance +	Operation simple as possible	EC677565-3.1.2.6
Safety +	Normal	EC677565-3.1.2.7
Fluid Compatability +	LH ₂ , GH ₂ , GN ₂ , GHe, Air	EC677565-3.2.1.9
Design	As required	EC677565-3.3.1.19
Electromagnetic Interference	Mil-5-6051	EC677565-3.3.9
Installation	DRM 51902	939J723 (4)

* IDC - Instrumentation Design Criteria Sheet Number

** EC677565-NSS Instrumentation Spec. and Paragraph/Table Number

+ These characteristics are independent of measurements

NOMENCLATURE - MAGNETIC CIRCUITS

R = RELUCTANCE
 L = INDUCTANCE
 P = PERMEANCE
 A = AREA, PERPENDICULAR
 TO FLUX PATH

μ = PERMEABILITY, CORE MATERIAL
 Δ = CHANGE IN PARAMETER
 SUBSCRIPT 1 = IRON PATH
 SUBSCRIPT 2 = AIR PATH
 l = TOTAL LENGTH OF PATH

Figure 9-1. Magnetic Circuits, Transducing Mechanisms - Basic Circuits

NOMENCLATURE - ELECTRIC CIRCUIT

STRAIN GAGE/VARIABLE RESISTANCE

R=RESISTANCE= LEG-INITIAL

Δr =RESISTANCE CHANGE, LEG

α =RATIO $R_t/R_c \approx 1.0$.

SUBSCRIPTS: T = RESISTOR (S/G), TENSION

C = RESISTOR (S/G), COMPRESSION

1+2 = RESISTOR (S/G), COMPENSATING

$$\text{STRAIN GAGE: } E_{\text{OUT}} = E_{\text{IN}} \left[\frac{\alpha}{(1+\alpha)^2} \right] \left[\frac{\Delta r_t}{R_t} - \frac{\Delta r_1}{R_1} + \frac{\Delta r_c}{R_c} - \frac{\Delta r_2}{R_2} \right]$$

Figure 9-2. Electrical Circuit, Transducing
Mechanism - Basic Circuit

10.0 NEUTRONIC INSTRUMENTATION

10.1 REQUIREMENTS

The control system neutronics shall be capable of sensing the core nuclear power from subcritical source level to beyond nominal full power during normal and emergency operating modes within the performance requirements stated in Table 10-1. This table shows the various requirements and the traceability of these requirements.

10.2 DESIGN APPROACH CHARACTERISTICS

The design approach characteristics of the control system neutronics instrumentation as they relate to the traceable requirements specified in Table 10-1 are listed in Table 10-2. Items that are suitable for trade-off considerations are identified. Additional detector requirements are shown later in the comparison matrix tables.

10.3 DESIGN APPROACH DESCRIPTION

DRM 52763 presents a preliminary analysis of the startup source and in-vessel neutron detector volume requirements for future NERVA reactors. It is presently felt that a neutron source of about 30 curies of Am^{241} -Be, located in the reflector, would produce a reactor power level of approximately 25 mW. Since full power is given as about 1500 MW, the neutronics system must cover a range of approximately eleven decades. One detector is not capable of operating over such a wide range; it is necessary to use two or more different detector types. Typically, the entire range of reactor power levels is split into three overlapping sub-ranges: source range, intermediate range, and power range.

In order to monitor neutron fluxes in mixed neutron-gamma fields, it is necessary to utilize some technique for gamma compensation. This is particularly true during reactor restarts when the neutron-to-gamma ratios are at their lowest values. In the NERVA reactor, however, the reflector acts as a large neutron source during shutdown due to (γ, n) reactions in the beryllium. These photoneutrons, in turn, produce fissions in the reactor core, and

hence keep the reactor at some minimum power level. Consequently, during shutdown there is a correlation between the gamma radiation and the reactor power level. The extent of gamma compensation required will be determined for each detector type and range.

10.3.1 Source Range Detector

Three types of neutron detectors are generally used for the source range: boron trifluoride (BF_3) filled proportional counters, boron-10 lined proportional counters, and U-235 fission counters. It should be noted that all of these detectors depend primarily upon the interaction of thermal neutrons to produce output pulses which are then counted with appropriate electronic equipment.

If the detectors are covered with cadmium, their response will be largely due to the epithermal flux ($E > 0.4 \text{ ev}$).

The thermal neutron flux may be subjected to large perturbation effects during the start-up of the NERVA reactor. One of these perturbation effects is caused by the change in the hydrogen density. In DRM 51165, the neutron fluxes in the reactor are calculated for flow and no-flow conditions. For this worst case situation, thermal neutron flux changes ($E < 0.4 \text{ ev}$) as large as 100% would be seen on the pressure vessel surface at core midplane. At the aft face of the core, and at the aft and forward faces of the shield, the thermal flux perturbations are even larger. The epithermal and fast neutron fluxes, on the other hand, experience changes of less than 10%. The magnitudes of these effects for realistic start-up flow profiles have not been calculated since these profiles have not been completed, but it is clear that the problem may be a serious one.

Another perturbation to the neutron flux results from the rotation of the control drums. The importance of this effect is a strong function of instrument location. For example, in the reflector outlet plenum, experiments conducted at the WANEF facility showed no measurable effect on any of the neutron energy groups for drum rotations of 0° to 180° . On the outside of the reflector at core midplane, however, the thermal flux (as calculated by the EXTERMINATOR Code) is shown to vary by approximately a factor of two

midway between the drums, and by a factor of greater than eight at a location next to the drums. For neutrons with energies between 0.4 eV and 0.8 MeV, the flux is estimated to vary by approximately 10% midway between the drums, and by about 25% next to a drum for rotations from 0° to 180° . For fast neutrons ($E > 0.8$ MeV), these numbers are approximately 5% for both locations.

These perturbation effects on the thermal neutron flux will be superimposed on changes in the flux caused by true changes in the reactor power level. Hence, the problem becomes one of discriminating between the two effects. If the perturbation effects can be adequately modeled, the control system digital computer can make the necessary corrections to the neutronics readings. It is not clear at this time, however, that this approach is either technically or economically feasible. A fairly extensive experimental program would have to be conducted before this question can be resolved.

Another approach to the problem of perturbation effects is to use detectors that are relatively insensitive to thermal and epithermal neutrons. For example, a fast fission counter using U-238 as the neutron sensitive material has an energy threshold of approximately 1.5 MeV. The major drawback in using fast fission detectors is their relatively low sensitivity. For example, the Westinghouse WL-23076 fast fission counter has a specified sensitivity of 1×10^{-3} cps/nv. The comparable thermal fission counter (WL-23075) has a specified sensitivity of 0.35 cps/nv. This difference is due basically to the much larger cross section for the thermal fission reaction. The low sensitivity of the fast fission counter requires a detector that is relatively large in size in order to produce a usable count rate. As will be discussed in more detail later, this may create serious installation problems if detectors are located inside the reactor pressure vessel.

In addition to the problems discussed above, each of the three detector types has its own unique advantages and disadvantages:

10.3.1.1 Boron-Trifluoride (BF₃) Counter

This counter has the highest sensitivity of the three types of thermal neutron detectors. Typical sensitivities range from about 5 to 50 cps/nv, depending on the size of the detector. Burnup of the neutron sensitive material (boron) is not a problem for NERVA applications. The detector specifications state that a 10% decrease in sensitivity can be expected for a neutron fluence of 2×10^{19} n/cm². For a NERVA flux of 10^{14} n/cm² sec, this would correspond to an operating time of approximately 56 hours. The main disadvantages of a BF₃ detector are: (1) its very poor gamma discrimination ability, and (2) its limited lifetime due to disassociation of the BF₃ fill gas. It is generally agreed that BF₃ detectors cannot measure thermal neutron fluxes when the associated gamma background is 10^3 R/hr or greater. Hence, for NERVA applications this type of detector would be incapable of proper operation during restarts, and therefore is not useable unless subsequent analysis shows that monitoring gamma radiation is satisfactory for reactor control purposes. As noted earlier, fast fission counters have typical sensitivity values of approximately 10^{-3} cps/nv. Helium was used as a fill gas for fast fission counters that were developed for the XE-Prime Engine Tests. During preliminary neutron testing, however, it was observed that the pulse amplitudes were too small for satisfactory counting applications. Hence, they were refilled with Ar-N (see DRM 51905). Burn-up of the fissionable material is not a problem for NERVA applications. The detector specifications state that for U-235, a thermal neutron fluence of 3×10^{20} n/cm² is required to change the sensitivity by 10%. For U-238, of course, a much larger fluence would be required. There are some serious questions about the ability of a detector of this type to survive full power flux conditions, and then operate satisfactorily under re-start conditions. During full power operation, the rate of fission energy release may be so high as to require special electrode cooling. Furthermore, during high power reactor operation, there will be a significant buildup of fission product activity in the detector. This will limit the ability of the detector to measure low fluxes during re-start conditions. In order to obtain some information on the magnitude of these problems,

discussions were held with Westinghouse Elmira, Reuter-Stokes, and Los Alamos. Both detector manufacturers were unable to offer any quantitative data. LASL stated that they had used Reuter-Stokes fission chambers (current mode) on the nozzle throat of both the Phoebus and PEWEE reactors. Although they did not remember the exact fluxes and fluences to which these detectors were exposed it was stated that no permanent damage was observed. However, the detectors could not be used for re-start applications for about one or two days after a power run. On the nozzle throat these detectors were subjected to unrecorded cryogenic temperatures. The detectors, which were filled with helium gas, operated satisfactorily except when the temperature changes rapidly due to hydrogen flow changes. The reason for this problem was not determined.

Another possible approach to making fast neutron flux measurements is to surround a thermal neutron detector with a sufficient thickness of suitable moderating material. For example, a boron-lined detector could be enclosed in zirconium hydride as was done on a previous NRX test.

The lifetime problem caused by the BF_3 gas disassociation is one that is difficult to resolve. The high voltage must be removed from the counter when the flux exceeds 10^9 n/cm^2 sec or permanent damage may be incurred.⁽¹⁾ Other reports received from both vendors and users indicate that even with the high voltage off, BF_3 disassociation will eventually occur. Another potential problem with BF_3 detectors is the possibility that the gas would liquefy during NERVA operation, particularly at locations internal to the reactor pressure vessel.

10.3.1.2 Boron-10 Lined Counter

This type of detector employs a thin layer of boron-10 on the electrodes. Typical sensitivities range from about 1 to 30 cps/nv. The fill gas normally used for this application is an argon- CO_2 mixture which provides larger pulses at lower voltages than BF_3 counters. For this reason, boron lined counters may be operated in higher gamma fields than BF_3 counters. The detector specifications state that the upper limit is approximately 10^5 R/hr, although a fast electronic system is required to eliminate gamma pulse pile-up at this level.

The main problem with this type of detector appears to be its limited lifetime. Both Westinghouse Elmira and Reuter-Stokes report that boron lined detectors require replacement after being exposed to approximately 10^{17} n/cm². The exact damage mechanism is not well understood at this time. Also, it is highly doubtful that the argon-CO₂ fill gas would be satisfactory under cryogenic conditions.

10.3.1.3 Fission Counter

The primary advantage of a fission counter is its inherently superior gamma discrimination ability due to the much larger energy released per event for (n, fission) reactions as compared to (n, alpha) reactions. With suitable electronics to avoid gamma pulse pile-up problems, it is possible to obtain useable data from fission counters in gamma fields as high as 10^7 R/hr. The sensitivity of a thermal fission counter has a maximum value of about 1 cps/nv for an argon-nitrogen fill gas mixture.

In order to avoid the thermal neutron perturbation effects discussed earlier, a fast fission counter could be employed for the intermediate range. The required sensitivity of 10^{-5} cps/nv is well within the state-of-the art for detectors of reasonable size^{*}. Furthermore, the problems of electrode heating and fission product activity would be greatly reduced.

Another approach to making neutronic measurements in the intermediate range is to use a Campbell technique. This technique, which is also known as the mean square voltage method, uses the a.c. component of the chamber current as a measure of neutron flux rather than the d.c. component. The advantages claimed for this technique include: (1) good gamma discrimination, (2) good suppression of d.c. leakage currents in cables and insulators, and (3) good stability (since a-c amplifiers have better long-term stability than d.c. amplifiers). On the other hand, the operating range of a Campbell channel is very

* A fast fission detector built for Waltz Mill by Westinghouse Elmira Division had a sensitivity of 7×10^{-4} cps/nv. Its size was 2" dia. x 6" long.

limited by signal-to-noise ratio. This is especially true for small in-core chambers with mineral insulated cables, where the application of the Campbell technique has been very questionable or even impossible. Using a signal correlation technique, however, an improvement of the signal-to-noise ratio of two to three decades has been reported.⁽²⁾

According to Weiss, "The method is based on the following principle: Two signals are obtained from the ion chamber, one from the center electrode as usual and an additional one from the outer electrode. The signals after being separately amplified are cross-correlated by means of a simple correlator. The cross-correlation function obtained for zero delay time is a measure of the neutron flux and is independent of the channel noise." It is obvious that such a technique requires rather elaborate signal conditioning and readout equipment.

The advantages of such a technique are increased detector sensitivity, and avoidance of the fission detector problems discussed above. However, it should be noted that the overall size of the detector and moderator may create serious installation and cooling problems. Analyses of this type have not yet been made for flight reactor configurations.

One of the most important factors affecting the type of source range detector used and its location on the NERVA reactor is its sensitivity, which in turn, is related to its size. DRM 52763 presents a detailed analysis of these parameters for locations inside the reactor pressure vessel. It is concluded that three U-238 fast fission counters would require approximately one-half of the volume available below the peripheral shield (about 1500 in.³) in order to produce a count rate of 10 cps at source power level (25mW). An alternate location would be on the outside surface of the pressure vessel at about core midplane. To evaluate this option, full power flux values were obtained for this location for the latest reactor configuration. At 1515 MW, the fast neutron flux ($E > 1.0$ MeV) is given as 6.1×10^{13} n/cm² sec. Hence, at two decades above source level (2.5W), the fast flux would be approximately 10^5 n/cm² sec. In order to limit the standard error (1σ) to $\pm 10\%$, a total of 100 counts must be obtained during the sampling interval. With a specified sampling interval of 100 milliseconds, this requires a count rate of 1000 cps. Hence, the required sensitivity of the fast fission counter is 1×10^{-2} cps/nv - a factor of ten higher than the commercially available

Westinghouse model WL-23076. In discussing the possibility of increasing the detector sensitivity with the Westinghouse Elmira Division, it was learned that a factor of five increase is probably all that could reasonably be achieved. Hence, the accuracy requirements would require modification in order to use this approach.

One of the important considerations in evaluating internal versus external detector locations is radiation heating. Gamma heating of the detector materials and supporting hardware, plus heating caused by neutron interactions with the neutron sensitive material must be transferred to a suitable heat sink. At internal locations, the hydrogen gas flow should be more than adequate for this purpose. For external locations, however, the problem will be much greater, particularly for large detector sizes. A detailed heat transfer analysis of this problem must be conducted before any final conclusions can be reached.

Related to the question of what detector type to use for the source range measurements is the matter of cables and preamplifiers. Integral metal-sheathed, inorganic-dielectric cables are required for detectors located inside the NERVA reactor pressure vessel. These cables are normally restricted to a maximum outside diameter of about 1/8 inch, which means that a relatively high capacitance per foot will be encountered. Also, the fairly thin dielectric limits the high voltage that can be supplied to the detector. Outside the pressure vessel, the same type of cable will be required in order to survive the radiation doses; however, the cable diameter would not be restricted in size. Furthermore, connectors could be used between the cable and the detector in order to allow units to be replaced in the event detector problems are experienced prior to power operation. The total amount of detector and cable capacitance that can be tolerated, the type and location of the preamplifiers, and the degree of radiation hardness required for the preamps are all interrelated questions requiring resolution.

10.3.2 Intermediate Range Detector

The problems associated with making measurements in the intermediate range are very similar to those already discussed for the source range. The fact that the neutron fluxes are higher means that less sensitive detectors must be used to keep the counting rates below

10^6 cps, or alternatively, these detectors may be operated in a current mode. One of the arguments in favor of using pulse type detectors is that they are inherently compatible with the control system digital computer. On the other hand, there is a practical limit to pulse counting at higher reactor power levels. With present detector technology, pulse counter operation must be limited to gamma fields that are less than 10^7 Rads (C)/hr. At 2.5 MW the gamma dose rate would be 2.3×10^6 Rads (C)/hr. In other words, if pulse counting is used for the intermediate range, a reasonable range of reactor power level would be from 250 W to 2.5 MW. The required detector sensitivity to produce a maximum count rate of 10^6 cps at 2.5 MW is 10^{-5} cps/nv.

10.3.3 Power Range Detector

In the power range (above 10 MW) radiation creates so much ionization in the detector that pulse counting is no longer feasible. Consequently, current-type detectors are always used for this range. If the power range covers only the upper two power decades (which is often the case), the detector is normally connected to a linear data readout channel (1 to 100% of full power). A logarithmic system can be used to extend the range covered, but with some sacrifice in readout accuracy.

With regard to gamma compensation, uncompensated ion chambers are usually used for the power range. This is because the neutron/gamma ratios in the upper two decades are sufficiently large so that gamma compensation is not required, even during reactor restarts. If the power range extends beyond two decades, however, the residual gamma activity from the core will necessitate some degree of gamma compensation.

The degree of gamma compensation required for NERVA applications requires further analysis. In the meantime, however, it will be assumed that gamma compensation is required, even for the power range detector.

The Campbell technique discussed earlier is one approach to the power range measurement. A simpler and perhaps equally satisfactory approach is to measure the d.c. currents from the intermediate range detectors. It should be noted, however, that in the current mode fission chambers do not provide any inherent gamma compensation. One

approach that can be used for gamma compensation is to provide an identical detector that contains no neutron sensitive material. By subtracting the current output from this detector, fairly good gamma compensation can be obtained.

Boron-10 lined compensated ion chambers such as the Westinghouse WX-5362 used on the XE-Prime engine may also prove useful for power range measurements. The perturbation effects discussed earlier will also be occurring in the power range. To minimize these, it may prove feasible to surround the detector with cadmium. Such a technique would effectively shield the detector from the thermal neutrons, which as noted earlier undergo the largest changes.

If it is decided that thermal neutron measurements are suitable for reactor control purposes, and if it is also decided that good gamma compensation is not required, then another detector that can be considered for power range applications is the cobalt-60 self powered neutron detector. In this detector, the output current results from the flow of secondary electrons that are produced by the prompt gamma rays emitted from the nuclei upon neutron capture. Since the time for this reaction and the subsequent charge collection is approximately 10^{-14} seconds, the time constant of the circuit becomes the limiting factor in the response time of the detector system. Although the sensitivity of the detector is quite low (about 10^{-21} amps/nv), it should prove adequate for the power range on NERVA applications. The major advantages of self-powered detectors are: (1) they require no external power, (2) they are very small or about the size of a 0.062 inch thermocouple, (3) they are designed for in-core use; hence they can withstand high temperature/high pressure environments, and (4) they have a relatively long lifetime (1% loss of sensitivity at 2.8×10^{20} nvt).

10.4 COMPARISON MATRICES OF DESIGN APPROACHES

Comparison matrices of design approaches for the source range detector, the intermediate range detector, and the power range detector are presented in Table 10-3.

10.5 SELECTION OF DESIGN APPROACH

Based upon the comparison matrices of design approaches, it is concluded that the reactor control neutronic instrumentation system should consist of the following detector types and locations.

10.5.1 Source Range Detector

U-238 fast fission counters are recommended for the source range. Since these detectors will have to be quite large (520 in.³/detector) in order to have adequate neutron sensitivity (5×10^{-3} cps/nv), it is further recommended that they be circumferentially located on the outside surface of the reactor pressure vessels at approximately core midplane or be located internally in the reflector outlet plenum. These detectors should have excellent discrimination against perturbation effects and gamma radiation.

The major problems requiring experimental investigation include fission heating of the electrodes, fission product activity problems during reactor re-starts, effects of different fill gases (including helium), determining the detector gamma compensation characteristics, and developing units that can withstand the NERVA non-nuclear environments for both ground and space tests.

If further studies show that thermal neutron flux measurements are acceptable for reactor control purposes, thermal detectors would be recommended instead of fast-fission counters because of their higher sensitivity.

10.5.2 Intermediate Range Detector

A U-238 fast fission counter is also recommended for the intermediate range. For this application, however the sensitivity requirements are much lower (10^{-5} cps/nv). Hence, a smaller detector (2" outside diameter x 5" long) than that required for the source range may be used. This means that these detectors may be used inside or outside the reactor pressure vessel with little difficulty.

10.5.3 Power Range Detector

For the power range, the use of a U-238 fast fission chamber (d.c. current mode) is recommended. In order to insure an adequate signal in the lower portion of the power range, a fairly large detector is required (2" outside diameter x 11.5" long). In addition to the problems already mentioned for fission counters, measurements should be made of the

leakage and radiation - induced currents in the detector cables and insulators in order to determine the errors that will be encountered in the lower portion of the power range. A summary of typical physical and electrical characteristics of the recommended detectors is presented in Table 10-4.

10.6 REFERENCES

1. Swift, O. F. and Bayard, R. T., "A Rugged Boron Trifluoride Proportional Counter WL-6307," *Nucleonics*, 17-122 (May 1959).
2. Weiss, H., "A Correlation Method for Neutron Flux Measurement in Nuclear Reactors," *Atomkernenergie*, 1969.

TABLE 10-1
REQUIREMENTS

<u>Characteristic</u>	<u>Requirement</u>	<u>Traceability</u>
Range	<p>Low Range: Subcritical source level to five decades above source level</p> <p>Intermediate: Five decades with one decade overlap of low range unit</p> <p>High Range: One decade overlap of intermediate range to beyond nominal full power</p>	IDC 037, 038, 039
Accuracy *	<p>Low Range: (TBD)</p> <p>Intermediate: $\pm 10\%$ (at point of measurement)</p> <p>High Range: $\pm 10\%$ (at point of measurement)</p>	EC-677565

* Accuracy, as used here, refers to the ability of a detector to give repeatable readings at the lowest level of its control range at a statistical level of $\pm 1\sigma$.

TABLE 10-1 (CONT)
REQUIREMENTS

<u>Characteristic</u>	<u>Requirement</u>	<u>Traceability</u>	
Response Time	(TBD)	EC-677565	
Reliability	0.9999	6775-65-3.1.2.1	
Maintainability	N/A	6775-65-3.1.2.2	
Useful Life		6775-65-3.1.2.3	
Operating Lifetime	600 Minutes		
Operating Life Cycles	60 Max.		
Space Lifetime	3 Years		
Ground Storage Time	5 Years		
Environment		6775-65-3.1.2.4	
Natural	INERT-Except during operation	6775-65-3.1.2.4.1	
Induced		6775-65-3.1.2.4.2	
Nuclear (Full power)	Internal	External	
Gamma Dose Rate	1.7×10^9 Rads (c)/hr	1.4×10^9	IDC 037, 038, 039
Fast Neutron Flux			(for internal location
(E>1 MeV)	1.8×10^{14} n/cm ² sec	6.1×10^{13}	only)
Fast Neutron Fluence	6.5×10^{18} n/cm ²	2.2×10^{18}	
(E>1 MeV)			
(10 hour)			
Loads			6775-65-3.1.2.4.2.2
Shock	N/A		
Vibration	(TBD)		IDC-073A
Thermal	Internal	External	IDC 037, 038, 039
	200 to 700° R	(TBD)	

TABLE 10-1 (CONT)

REQUIREMENTS

<u>Characteristic</u>	<u>Requirement</u>	<u>Traceability</u>
Pressure Range	10^{-9} Torr to 1150 Psia	10^{-9} TORR to IDC 037, 038, 039 (TBD)
Transportability	N/A	6775-65-3.1.2.5
Human Performance	Operation simple as possible	6775-65-3.1.2.6
Safety	Normal	6775-65-3.1.2.7
Fluid Compatability	Internal LH_2 , GH_2 , GN_2 , GHe, Air	External 6775-65-3.3.1.9 (TBD)
Electromagnetic Interference	MIL-E-6051	6775-65-3.3.9
Installation	Internal DRM 52763	External (TBD) Dwg. No. 914E904 (Internal only)

TABLE 10-2A

DESIGN APPROACH CHARACTERISTICS SOURCE RANGE DETECTORS

<u>Characteristic</u>	<u>BF₃ Proportional Counter</u>	<u>B-10 Lined Proportional Counter</u>	<u>U-235 Fission Counter</u>	<u>U-238 Fission Counter</u>
Range	5 decades	5 decades	5 decades	5 decades
Accuracy *	$\pm 10\%$	$\pm 10\%$	$\pm 10\%$	$\pm 15\%$
Useful Life (due to nuclear environment)	May fail at thermal neutron fluence of 10^{18} n/cm^2	Presently require replacement at 10^{17} n/cm^2	10^{18} n/cm^2 Special electrode cooling may be required	10^{18} n/cm^2
Environment				
Non-Nuclear	Development required for all detector types			
Nuclear	Special cooling may be required for externally-mounted detectors			
Installation*	No problem for either internal or external locations	No problem	No problem	Large detector size may cause internal installation problem

* Trade-Off Characteristics

TABLE 10-2B

DESIGN APPROACH CHARACTERISTICS INTERMEDIATE RANGE DETECTORS

<u>Characteristic</u>	<u>B-10 Lined Compensated Ion Chamber</u>	<u>Fast Fission Counter</u>	<u>Fast Fission Chamber</u> <u>D. C. Current</u>	<u>Campbelling</u>
Range *	5 decades	5 decades	5 decades	Good for Limited range only unless signal correla- tion is used.
Accuracy *	$\pm 10\%$	$\pm 10\%$	Questionable accuracy at lower part of range.	
Useful Life * (due to nuclear environment)	Possible problem at fluences of 10^{17} n/cm^2	10^{18} n/cm^2	10^{18} n/cm^2	
Environment	Special electrode cooling may be required			
Non-Nuclear	Development required for all detector types Special cooling may be required for externally-mounted detectors			
Nuclear				
Installation *	No problem for either internal or external locations	Large size of fast fission detectors may cause internal installation problems.		

* Trade-Off Characteristic

TABLE 10-2C

DESIGN APPROACH CHARACTERISTICS HIGH RANGE DETECTORS (POWER RANGE)

Characteristic	B-10 Lined Uncompensated Ion Chamber	CO-60 Self-Powered Detector	Fast Fission Chamber D. C. Current and Campbell
Range	10^{10} to 10^{14} n/cm ² sec	10^8 to 10^{16} n/cm ² sec	10^9 to 10^{14} n/cm ² sec (fast)
Accuracy	+ 10% -	Questionable accuracy at lower part of range	+ 10% except for lowest decade of range
Useful Life * (due to nuclear environment)	Possible problem at fluences of 10^{17} n/cm ²	10^{18} n/cm ²	10^{18} n/cm ² Special electrode cooling may be required
Environment	Development required for all detector types Special cooling may be required for externally-mounted detectors		
Non-Nuclear			
Nuclear			
Installation *	No problem	No problem	

* Trade-Off Characteristics

TABLE 10-3A
LOW RANGE DETECTOR - COMPARISON MATRIX

SOURCE RANGE DETECTOR

SELECTION

COMPARISON MATRIX OF DESIGN APPROACHES

FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS		1) BF_3 Proportional Counter	2) B-10 Lined Proportional Counter	3) Fission Counter a) U-235 b) U-238	
1. Size Restrictions					
A. Internal (Reflector Outlet Plenum)	3030 in. ³ (Maximum)	2 in. ³ /detector	7 in. ³ /detector	200 in. ³ /detector 520 in. ³ /detector	1
B. External (Core Midplane Outside PV)	No practical limitation on size.	1 in. ³ /detector	3 in. ³ /detector	100 in. ³ /detector 500 in. ³ /detector	Equal
2. Accuracy					
A. Period	+ 10% at two decades above source level.	No Problem	No Problem	No Problem + 15%	Approx. Equal
B. Power	+ 50%	No Problem	No Problem	No Problem No Problem	
3. Gamma Compensation	Requirements Not Defined	Very poor (limited to fields of 10^3 R/Hr).	Fair (limited to fields of 10^5 R/Hr).	Good (can be operated in fields of 10^7 R/Hr with suitable electronics).	3
4. Sensitivity to Perturbation Effects (H_2 Flow and Drum Rotation)	Requirements Not Defined	Large	Large	Large 10%	3b
5. Environmental Survivability					
A. Nuclear	Minimum of 10^{18} n/cm^2 thermal neutron fluence.	Disassociation of BF_3 gas may be a problem.	Presently require replacement at 10^{17} n/cm^2 .	Special electrode cooling may be required to dissipate fission heating; fission product activity may be a problem.	3
B. Non-Nuclear (Temp., Shock, Vibration, etc.)	Not Defined	DEVELOPMENT REQUIRED FOR ALL DETECTOR TYPES.			

TABLE 10-3B

INTERMEDIATE RANGE DETECTOR - COMPARISON MATRIX

INTERMEDIATE RANGE DETECTOR

SELECTION

COMPARISON MATRIX OF DESIGN APPROACHES

FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS		1) B-10 Lined Compensated Ion Chamber	2) Fast Fission Counter	3) Fast Fission Chamber a) D.C. Current b) Campbelling	
1. Size		3"O.D. x 7.5"long(Based on WX-5362)	2"O.D. x 5"long(Based on WL-23073)	2.0"O.D. x 16"long (Based on WL-23071 with U-238)	2
2. Accuracy					
A. Period	+ 10%	No problem except for lowest decade of range.	No problem except for lowest decade of range.	Questionable accuracy at lower part of range.	1, 2
B. Power	+ 50%				
3. Gamma	Requirements Not Defined	5% gamma response at fixed dose rate.	Very good up to 10^7 R/Hr.	5% gamma response with compensating gamma detector. Good for limited range only unless signal correlation is used.	2
4. Sensitivity to Perturbation Effects (H_2 Flow & Drum Rotation)	Requirements Not Defined	Large	10%	10%	2, 3
5. Environmental Survivability					
A. Nuclear	10^{18} n/cm ² thermal fluence	Possible problem at fluences 10^{17}	SPECIAL ELECTRODE COOLING MAY BE REQUIRED TO DISSIPATE FISSION HEATING; FISSION PRODUCE ACTIVITY MAY BE A PROBLEM.		2, 3
B. Non-Nuclear	Not Defined	DEVELOPMENT REQUIRED FOR ALL DETECTOR TYPES.			Equal
6. Compatibility With Control Digital Computer		Poor	Good	Poor Requires elaborate signal conditioning equipment.	2

TABLE 10-3C
POWER RANGE DETECTOR - COMPARISON MATRIX

POWER RANGE DETECTOR

COMPARISON MATRIX OF DESIGN APPROACHES

SELECTION

FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS		1) B-10 Lined Uncompensated Ion Chamber	2) Co-60 Self-Powered Detector	3) Fast Fission Chamber a) D.C. Current b) Campbell	
1. Size		0.188" O.D. x 1.25" long with integral 0.125" O.D. mineral insulated cable. (Based on WL-23192)	0.062" O.D. x 34" long with integral 0.062" O.D. mineral insulated cable. (Based on WL-23283)	2.0 O.D. x 11.5" long (Based on WL-7188 with U-238)	2
2. Range		10^{10} to 10^{14} n/cm ² sec	10^8 to 10^{16} n/cm ² sec	10^9 to 10^{14} n/cm ² sec (fast)	Equal
3. Accuracy					
A. Period	+ 10%	No Problem	Questionable accuracy at lower part of range.	No problem except for lowest decade of range.	1
B. Power	+ 20%	No Problem			
4. Gamma Compensation	Requirements Not Defined	5% gamma response with compensating gamma detector.	Reportedly large response.	5% gamma response with compensating gamma detector. Good for limited range only unless signal correlation is used.	1, 3a
5. Sensitivity to Perturbation Effects (H ₂ Flow & Drum Rotation)	Requirements Not Defined	Large	Large	10%	3
6. Environmental Survivability					
A. Nuclear	10^{18} n/cm ² thermal fluence	Possible problem at fluences 10^{17} n/cm ² .	1% sensitivity loss at 2.8×10^{20} n/cm ² .	Fission product activity may be a problem.	2
B. Non-Nuclear	Not Defined	DEVELOPMENT REQUIRED FOR ALL DETECTOR TYPES			Equal

TABLE 10-4

PHYSICAL AND ELECTRICAL CHARACTERISTICS OF TYPICAL RECOMMENDED DETECTORS

<u>Detector Type</u>	<u>Sensitivity</u>	<u>Size</u>	<u>Weight</u>	<u>Materials</u>	<u>Type of Leads</u>	<u>Power Requirements</u>
Source Range: U-238 Fast Fission Counter WL-23076	5×10^{-3} cps/nv	2" O.D. x 11.5" long	1.75 lb	Al case	Coaxial Cable	200-800 v.d.c.
Intermediate Range: U-238 Fast Fission Counter	10^{-5} cps/nv	2" O.D. x 5" long	1.0 lb	Ti case	Coaxial Cable	350-650 v.d.c.
Power Range: U-238 Fast Fission Chamber (d.c.current mode)	2×10^{-17} A/nv	2" O.D. x 11.5" long	1.75 lb	Al case	Coaxial Cable	300-1000 v.d.c.

11.0 DISPLACEMENT TRANSDUCERS

11.1 REQUIREMENTS

Displacement transducers must be capable of sensing relative motion during all operating modes within the performance requirements stated in Table 11-1. This table shows the various requirements and the traceability of these requirements.

11.2 DESIGN APPROACH CHARACTERISTICS

Table 11-2 shows the performance characteristics of each design approach being considered. The transducers considered in this study had to be compatible with the displacement range and media requirements for flight reactors.

11.3 DESIGN APPROACH DESCRIPTION

The following information describes the basic construction and operation of each transducer type.

11.3.1 Linear Variable Differential Transformer (LVDT)

An LVDT consists of a primary coil and two secondary coils with a magnetic core. The position of the core within the coils determines the mutual coupling and thus voltage developed between the primary winding and each of the secondary or output windings. When the primary coil is energized with an alternating carrier signal, voltages are induced in the secondary coils. These coils are connected in series opposition so that the voltages in the secondary circuit cancel with the plunger at this center position. At null position the output voltage approaches zero. When the core is displaced from null, the voltage induced in the coil toward which the core moves, for example, increases while the voltage induced in the opposite coil decreases. This results in a differential voltage output from the transformer which can be designed to vary linearity with the core motion. LVDT mechanisms are relatively simple and rugged in construction, are frictionless in operation, and are low output impedance devices.

The LVDT requires a demodulator amplifier system capable of reconstructing the stimulus signal from the modulated carrier input signal. The LVDT carrier power requirement per unit is approximately one watt; this must be furnished by the demodulator also.

The construction of this transducer CE Electronics Model 300-5K-119 includes a 316 stainless steel outer case and a 410 stainless steel inner shell. Three coils are wound of "Ceramatemp" coated wire on a lava spool. Two of the coils, comprising the transformer secondary and wound in series opposition, bracket the third coil, which is the transformer primary. All lead terminations are insulated with "Sauereisen No. 7" ceramic potting compound and all voids are subsequently backfilled with magnesium oxide. A hole, traversing the center of the lava spool and transducer case, permits movement of the plunger through the transducer. (See Figure 11-1.)

The LVDT is relatively small (0.5 in. dia. x 2.0 in. long) but requires a holding assembly and a spring.

The plunger, fabricated to a 0.125 outer diameter from non-permeable stainless steel, contains a small 0.600 inch long (core) of "Hiperco." "Hiperco" has a high permeability and a Curie temperature of 1746°F. Movement of the core through the center of the coils changes the inductance characteristics between the coils, causing a variation in the secondary a.c. output voltage level. The a.c. output voltage level is monitored by an externally-located demodulator which reconstructs the stimulus signal.

This transducer permits plunger displacements of at least ± 0.300 inch; however, these limits establish the most linear portion of the output curve. Increasing the displacement range to 0.400 inch in either direction from null (i.e., point of zero phase shift) increases the non-linearity to 4.0 percent (FS).

The input and output voltages are supplied through a magnesium oxide insulated, 4/C stainless steel sheath cable which is permanently attached to the transducer.

The weight of each assembly including 30 feet of cable and the sensing probe is approximately 250 grams.

11.3.2 Variable Permeance (VP) Linear Displacement Transducer

Variable permeance transducing mechanisms consist of a moveable armature in proximity to a fixed coil and core having a center-tapped winding. This creates a magnetic parallel path or shunt. As the distance between the shunt path armature and coils changes, the flux density changes because of the associated change of permeability of the magnetic path. This produces a shift in inductance. The change of coil inductance produces a change of the phase angle of the output voltage from a reference or null voltage. A demodulator recovers the stimulus signal from the phase-shifted transducer output. VP-type mechanisms require lower flux densities than the VR type and generally have a higher output sensitivity per unit movement of the armature.

The VP displacement transducer requires a demodulator system capable of recovering the stimulus signal from the modulated transducer output. The carrier power requirement per unit is approximately one watt, also provided to the transducer by the demodulator.

The Schaevitz variable permeance displacement transducer is similar to the LVDT in appearance and size. The size of the present model (300 X SCTR) being considered is 0.68 inch in diameter x 1.83 inches in length. It also requires a mounting bracket and spring loading of the probe. Its construction uses a stainless steel housing and bore liner (347). Internally there are two coils wound of ceramic insulated silver wire on two lava bobbins. The coils are connected in series making up a center-tapped single coil having three leads. The three conductors of a stainless steel sheathed, magnesium oxide insulated cable are connected to the coil leads. Installed within the transducer body is a copper-constantan thermocouple, with its sensor located near the center of mass, to measure the internal temperatures. All voids and lead terminations are back filled with magnesium oxide. Encased within the housing and completely surrounding the coil bobbins is a magnetic shield of Hiperco. The core and magnetic shield are "Hiperco 27". (See Figure 11-2.)

The total weight of each transducer is unknown at present since it is still in the design development stage.

11.3.3 Strain Gage/Constant Stress Cantilever Beam (S/G Beam)

The constant stress beam is a design that permits beam stress to be at the same level at all points (at the beam surface) along the length of the beam. This is true for all deflections of the beam within its calibrated range. The relaxed position of the beam is concave down to the plunger. This condition allows the beam to provide its own spring loading for the full deflection range. (See Figure 11-3.) A strain gage is attached (welded) to this beam and is subjected to tension and compression forces at the surface of the beam as the assembly plunger deflects the beam through its full range. The strain gage consists of two resistive elements (one active and one dummy) arranged to compose one-half of a bridge network. Strain on the active element alters its resistance level which subsequently changes the gage output level.

The previous design of this transducer required a clear volume of 2.5 inch diameter x 6.5 inches, and had a resonant frequency condition in the range 360 to 400 Hz. A new design is under investigation to decrease the volume to 1.5 in. dia. x 4.5 in. This new design should also have a higher resonant frequency. This transducer includes its own holding fixture and provides its own spring loading.

The strain gage beam displacement transducer requires a highly regulated d.c. power supply and bridge completion network. A three-conductor stainless steel sheath, magnesium oxide insulated cable is used to interconnect the transducer and bridge completion network. The cable is permanently attached to the transducer assembly. The power requirement at 10 volts is approximately 1 watt.

The weight and cost per transducer assembly is unknown at this time since it is undergoing design changes. It is considerably larger and heavier than the VP or LVDT transducer.

11.3.4 Load Cell

The load cell displacement transducer would be about the same size as the LVDT; however, a very heavy spring (i.e., 30 pounds per inch spring rate) would be required for its operation. The assembly consists of a support cup, a strain gage retainer piece, a base plate,

the spring, and a plunger. The strain gage is attached on one end to the retainer. This assembly fits freely inside the support cup where the other end of the gage is attached to the forward end of the cup. The retainer piece is equipped with arms that extend through slots in the side of the support cup. In assembly the base plate holds the support cup in position and the support cup is inside the spring, allowing the spring to act directly on the extended arms of the retainer piece. The plunger acts on the spring. In this manner, plunger movement is translated into force on the extended arms of the retainer which consequently changes the strain level of the gage. The gage itself may be a quarter bridge or half bridge, and in conjunction with an externally-located bridge completion network produces a analog output signal.

11.3.5 Rolamite Transducer

The Rolamite transducer is still in the design feasibility stage and specific information on size and construction is not available. At this time the development effort has been discontinued.

11.3.6 Eddy Current Displacement Transducer

This transducer in its smallest configuration is about the same size as the LVDT. It cannot be made smaller than the LVDT or VP transducers and has no significant advantage over them; therefore, it will not be given any further consideration.

11.4 COMPARISON MATRIX

Tables 11-3, 11-4, and 11-5 are a compilation of transducer data (actual and calculated) for the various displacement measurements required. These tables rate the transducers with each other versus the specific requirements for that measurement. Consideration is given only to those characteristics that differ sufficiently. Trade-off items include accuracy, size, configuration complexity, vibration, and radiation resistance.

11.5 DESIGN APPROACH SELECTION

Transducer selections for flight measurements are based not only on the information contained herein but also on transducer installation complexities (see DRM 52031 and DRM 52035). On the basis of anticipated performance capabilities, the variable permeance (VP)

displacement transducer is selected as the prime candidate for all displacement measurements included in this report. Although the VP transducer is still in the design phase, primary selection is based on the performance in Phoebus 2A of similar transducers. LASL reported⁽¹⁾ measurement accuracies corrected to within $\pm 2\%$ (FS) which were the best made to date. The present proposed design incorporates a copper-constantan thermocouple to measure the internal temperature. By knowing this temperature, the indicated displacement can be corrected using the transducer temperature characteristics.

The LVDT (CE Electronics Model 300-5K-119) is scheduled as an alternate. This transducer is the result of previous design studies by WANL and C. E. Electronics resulting in a transducer that should function satisfactorily in a high radiation and temperature environment. Two experimental transducers were installed on PEWEE I in an attempt to determine the effects due to radiation. The test results were inconclusive due to severe drift problems in the readout equipment; however, the transducer did perform throughout the full-power periods. It is estimated that the gamma heating rate on the transducers was in the area of 7 watts/gram(c).

The strain gage beam is selected as backup for the Core/Reflector Radial Displacement-Fwd and Aft measurements. This transducer indicates slightly superior performance compared to the LVDT; however, it is also much larger in size, which limits its use. Modifications would be required to meet the installation requirements for the Core/Reflector Radial-Forward measurements. A new design is under investigation to decrease the volume.

There is no available transducer that meets all of the flight measurement requirements. In addition, all transducer candidates will require development effort to obtain acceptable installation hardware.

11.6 REFERENCES

1. Preliminary Test Report LA-4159-MS - Los Alamos Scientific Laboratory, January 1969.
2. WANL-TME-1863, "NRX-A6 Transducer Evaluation Report."
3. DRM 52023, "Experimental LVDT Test, PEWEE I, EP III."
4. WANL-TME-1453, "WANL Transducer Calibrations for NRX-A6."

TABLE 11-1
DESIGN REQUIREMENTS

<u>Characteristic</u>	<u>Axial</u>	<u>Radial Forward</u>	<u>Radial Aft</u>	<u>Traceability</u>
Range	-.300" to +.150"	-.200" to +.150"	-.400" to +.150"	DRM 51913
Accuracy	±.010"	±.010"	±.010"	6775-65-Table 1
Response Time	TBD	TBD	TBD	6775-65-Table 1
Frequency Response	300 Hz	500 Hz	500 Hz	DRM 51913
Reliability	0.999900	0.999900	0.999900	6775-65-3.1.2.1
Maintainability	N/A	N/A	N/A	6775-65-3.1.2.2
Useful Life				6775-65-3.1.2.3
Operating Lifetime	600 minutes	600 minutes	600 minutes	
Operating Life Cycles	60 max	60 max	60 max	
Space Lifetime	3 yrs	3 yrs	3 yrs	
Ground Storage Time	5 yrs	5 yrs	5 yrs	
Environment				6775-65-3.1.2.4
Natural	INERT - EXCEPT DURING OPERATION			6775-65-3.1.2.4.1
Induced				
Nuclear				DRM 51913
Gamma dose rate	1.08(9) R(c)/hr	1.8(9) R(c)/hr	0.9(9) R(c)/hr	
Fast neutron flux	0.7(14) nv	1.0(14) nv	5.2(13) nv	
Fast neutron fluence	2.4(18) nvt	3.6(18) nvt	1.9(18) nvt	
Loads				6775-65-3.1.2.4.2.2
Shock	N/A	N/A	N/A	
Vibration	3g's 150-450 Hz	6g's 80-160 Hz	6g's 80-160 Hz	DRM 51913
Thermal	270°R-600°R	270°R-600°R	50°R-600°R	
Pressure Range	12.8-740 psi	12.8-740 psi	12.8-740 psi	
Transportability	N/A	N/A	N/A	6775-65-3.1.2.5
Human Performance	OPERATION SIMPLE AS POSSIBLE			6775-65-3.1.2.6
Safety	Normal	Normal	Normal	6775-65-3.1.2.7
Fluid Compatibility	LH ₂ , GH ₂ , GN ₂ , GH _e , Air			6775-65-3.3.1.9
Design-Displacement	(VP), LVD T, S/G			6775-65-3.3.1.17
Electromagnetic Interface	MIL-E-6051	MIL-E-6051	MIL-E-6051	6775-65-3.3.9
Installation	DRM 52031	DRM 52035	DRM 52035	939J723

TABLE 11-2
DESIGN APPROACH CHARACTERISTICS (TRANSDUCERS)

<u>Characteristic</u>	<u>Performance</u>			
	<u>Design A (VP) 300XSCTR (Calculated)</u>	<u>Design B LVDT 300-SK-119</u>	<u>Design C S/G Beam</u>	<u>Design D Load Cell (Calculated)</u>
Range	±.300"	±.300"	±.300"	±.300"
Accuracy	±.012"	±.015"	±.012"	±.012"
Frequency Response	25 Hz	25 Hz	25 Hz	25 Hz
Response Time	≤5 ms	≤5 ms	≤5 ms	≤5 ms
Thermal	140°R to 900°R	140°R to 1000°R	140°R to 660°R	140°R to 1060°R
Pressure	0-1000 psi	TBD	TBD	Unknown
Vibration	TBD	TBD	5g's 25 to 700 Hz	Unknown
Reliability	TBD	TBD	TBD	Unknown
Radiation		Survived with unknown error	Exhibited 2%FS error with	2% FS error with radiation to
Fast Neutron Fluence	3.6(19) nvt	2.16(17) nvt	6.0(17) nvt	6.0(17) nvt
Fast Neutron Flux	1.0(15) nv	Unknown	Unknown	Unknown
Gamma	5.8(9) Rad(c)/hr	2.5(9) Rad(c)/hr	1.9(9) Rad(c)/hr	1.9(9) Rad(c)/hr
Design	1.9x0.68 dia.	2.0"x0.5 dia.	1.5" dia. x4.5"	4.5"x1.0" dia.
Fluid Compatibility	TBD	TBD	TBD	TBD
Operating Lifetime	TBD	TBD	TBD	TBD
Operating Life Cycles	TBD	TBD	TBD	TBD
Space Lifetime	TBD	TBD	TBD	TBD
Ground Storage Time	TBD	TBD	TBD	TBD
Electromagnetic Interface	TBD	TBD	TBD	TBD
Installation				

TABLE 11-3
COMPARISON MATRIX - CORE AXIAL DISPLACEMENT

Characteristic	Requirement	Design A (VP)	Design B (LVDT)	Design C (S/G Beam)	Design D (Load Cell)	Selection
Range	+ .150" - .300"	+ .300"	+ .300"	+ .300"	+ .300"	--
Accuracy	+0.010" -0.010"	+ .012" (calculated)	+ .015"	+ .012"	+ .012" (calculated)	A-C-D
Frequency Response	300 Hz	25 Hz	25 Hz	25 Hz	25 Hz	--
Response Time	TBD	≤ 5 mil. sec. (calculated)	≤ 5 mil. sec. (calculated)	≤ 5 mil. sec. (calculated)	≤ 5 mil. sec. (calculated)	--
Thermal	270 to 600° R	140 to 900° R	140 to 1000° R	140 to 660° R	140 to 1060° R	--
Pressure	12.8-740 psi	0-1000 psi (predicted)	TBD	TBD	Unknown	--
Vibration	3g's 150-450 Hz	3g's 150-450 Hz (predicted)	3g's 150-450 Hz (predicted)	5g's 25-700 Hz	Unknown	--
Reliability	0.999900	TBD	TBD	TBD	Unknown	--
Fast Neutron Flux	0.7(14) nv	1.0(15) nv (predicted)	Unknown	1.75(14) nv	Unknown	A-C
Fast Neutron Fluence	2.4(18) nvt	3.6(19) nvt (predicted)	2.16(17) nvt (survived, error Unknown)	6.0(17) nvt (exhibited ~2% FS error)	6.0(17) nvt (>2% FS error)	A
Gamma	1.08(9) Rad(c)/hr	5.8(9) Rad(c)/hr (predicted)	2.5(9) Rad(c)/hr	1.9(9) Rad(c)/hr	1.9(9) Rad(c)/hr	--
Design	Available space ~1.7"x1.1" dia.	1.9x0.68 dia.	2.0x0.5 dia.	1.5" dia. x4.5"	4.5"x1.0 dia.	A-B
Fluid Compatibility	LH ₂ , GH ₂ , GN ₂ , GH ₂ , Air e	TBD	TBD	TBD	TBD	--
Electromagnetic Interface	MIL-E-6051	TBD	TBD	TBD	TBD	--
Operating Life time	600 minutes	TBD	TBD	TBD	TBD	--
Operating Life Cycles	60 max.	TBD	TBD	TBD	TBD	--
Space Lifetime	3 years	TBD	TBD	TBD	TBD	--
Ground Storage Time	5 years	TBD	TBD	TBD	TBD	--

TABLE 11-4
COMPARISON MATRIX - CORE RADIAL DISPLACEMENT - FORWARD

<u>Characteristic</u>	<u>Requirement</u>	<u>Design A</u> (VP)	<u>Design B</u> (LVDT)	<u>Design C</u> (S/G Beam)	<u>Design D</u> (Load Cell)	<u>Selection</u>
Range	+ .150" - .200"	+ .300"	+ .300"	+ .300"	+ .300"	--
Accuracy	+ .010"	+ .012" (calculated)	+ .015"	+ .012"	+ .012" (calculated)	A-C-D
Frequency Response	500 Hz	25 Hz	25 Hz	25 Hz	25 Hz	--
Response Time	TBD	5 mil. sec. (calculated)	5 mil. sec. (calculated)	5 mil. sec. (calculated)	5 mil. sec. (calculated)	--
Thermal	270 to 600° R	140 to 900° R	140 to 1000° R	140 to 660° R	140 to 1060° R	--
Pressure	12.8-740 psi	0-1000 psi	TBD	TBD	Unknown	--
Vibration	6g's 80-160 Hz	6g's 80-160 Hz (predicted)	6g's 80-160 Hz (predicted)	5g's 25-700 Hz	Unknown	--
Reliability	0.999900	TBD	TBD	TBD	Unknown	--
Fast Neutron Flux	1.0(14) nv	1.0(15) nv (predicted)	Unknown	1.75(14) nv	Unknown	A-C
Fast Neutron Fluence	3.6(18) nvt	3.6(19) nvt (predicted)	2.16(17) nvt (survived, error Unknown)	6.0(17) nvt (exhibited 2% FS error)	6.0(17) nvt (2% FS error)	A-C-D
Gamma	.1.8(9) Rad(c)/hr	5.8(9) Rad(c)/hr (predicted)	2.5(9) Rad(c)/hr	1.9(9) Rad(c)/hr	1.9(9) Rad(c)/hr	A
Design	Available space 4.0"x2.0"x2.5"	1.9x0.68 dia.	2.0x0.5 dia.	1.5" dia. x4.5"	4.5"x1.0 dia.	A-B
Fluid Compatibility	LH ₂ , GH ₂ , GN ₂ , GH _e , Air	TBD	TBD	TBD	TBD	--
Electromagnetic Interface	MIL-E-6051	TBD	TBD	TBD	TBD	--
Operating Lifetime	600 minutes	TBD	TBD	TBD	TBD	--
Operating Life Cycles	60 max.	TBD	TBD	TBD	TBD	--
Space Lifetime	3 years	TBD	TBD	TBD	TBD	--
Ground Storage Time	5 years	TBD	TBD	TBD	TBD	--

TABLE 11-5
COMPARISON MATRIX - CORE RADIAL DISPLACEMENT - AFT

Characteristic	Requirement	Design A (VP)	Design B (LVDT)	Design C (S/G Beam)	Design D (Load Cell)	Selection
Range	+ .150" - .400"	+ .300"	+ .300"	+ .300"	+ .300"	--
Accuracy	+ .010"	+ .012" (calculated)	+ .015"	+ .012"	+ .012" (calculated)	A-C-D
Frequency Response	300 Hz	25 Hz	25 Hz	25 Hz	25 Hz	--
Response Time	TBD	≤ 5 mil. sec. (calculated)	≤ 5 mil. sec. (calculated)	≤ 5 mil. sec. (calculated)	≤ 5 mil. sec. (calculated)	--
Thermal	250 to 600° R	140 to 900° R	140 to 1000° R	140 to 660° R	140 to 1060° R	--
Pressure	12.8-740 psi	0-1000 psi (predicted)	TBD	TBD	Unknown	--
Vibration	6g's 80-260 Hz	6g's 80-260 Hz (predicted)	6g's 80-260 Hz (predicted)	5g's 25-700 Hz	Unknown	--
Reliability	0.999900	TBD	TBD	TBD	Unknown	--
Fast Neutron Flux	5.2(13) nv	1.0(15) nv (predicted)	Unknown	1.75(14) nv	Unknown	A-C
Fast Neutron Fluence	1.9(18) nvt	3.6(19) nvt (predicted)	2.16(17) nvt (survived, error Unknown)	6.0(17) nvt (exhibited ~2% FS error)	6.0(17) nvt (>2% FS error)	A-C
Gamma	0.9(9) Rad(c)/hr	5.8(9) Rad(c)/hr (predicted)	2.5(9) Rad(c)/hr	1.9(9) Rad(c)/hr	1.9(9) Rad(c)/hr	--
Design	Available space ~ 4.0"x2.0"x5.0"	1.9x0.68 dia.	2.0x0.5 dia.	1.5" dia. x4.5"	4.5"x1.0 dia.	A-B-C
Fluid Compatibility	LH ₂ , GH ₂ , GN ₂ , GH ₄ , Air	TBD	TBD	TBD	TBD	--
Electromagnetic Interface	MIL-E-6051	TBD	TBD	TBD	TBD	--
Operating Lifetime	600 minutes	TBD	TBD	TBD	TBD	--
Operating Life Cycles	60 max.	TBD	TBD	TBD	TBD	--
Space Lifetime	3 years	TBD	TBD	TBD	TBD	--
Ground Storage Time	5 years	TBD	TBD	TBD	TBD	--

Figure 11-1. Linear Variable Differential Transformer
Development Model 300 - SK - 119

Figure 11-2. Variable Permeance Displacement Transducer
Development Model 300 X S CTR

Figure 11-3. Strain Gage Beam Displacement Transducer
Development Model 979D713

12.0 DEMODULATORS

12.1 REQUIREMENTS

A means for demodulation and a carrier source must be provided for each VP or LVDT displacement transducer, VP or VR pressure transducer, and VP or VR accelerometer in the engine. Requirements by measurement location and transducer type are listed in Table 12-1. Paragraph 12.1.1 lists the requirements for the demodulators themselves.

12.1.1 Demodulator Requirements

Signals from variable reluctance, variable permeance, or LVDT transducers are modulated signals, formed by imposing a stimulus frequency signal f_s , upon a carrier frequency signal f_c . In general, $f_s \ll f_c$. The functions of the demodulator are to provide the carrier signal excitation to the transducer and to extract the carrier signal from the modulated transducer output, leaving the recovered signal proportional to stimulus.

The requirements for the demodulator are listed in Table 12-2.

12.2 DESIGN APPROACH CHARACTERISTICS

The demodulators considered in this study are required to be compatible with variable reluctance, variable permeance, and LVDT sensors as specified for use on NERVA flight vehicles. Trade-off items include: accuracy, size, cost, complexity, type of output, difficulty of adjustment, insensitivity to temperature change, power supply requirements, and weight.

Since the demodulator is required to operate with a variety of transducers, all of the requirements above are considered static - that is, they are not a function of measurement location.

Priority will be given to circuitry employing on-off (non-active) operational modes, since such circuitry is particularly suited to radiation environments and high reliability design.

12.3 DESIGN APPROACH DESCRIPTION

The following information describes the method of operation of each demodulator considered.

12.3.1 The Analog Demodulator

Figure 12-1 is a block diagram for the analog demodulator considered. The unit is similar in all respects to the units used for NRX-A3, NRX/EST, NRX-A5, NRX-A6, and XE-P. The demodulator serves as a carrier signal source to the transducer, establishes a correct phase relationship between excitation and output, synchronously detects the transducer output, and averages the transducer output.

Refer to Figure 12-1. The carrier frequency generator portion of this diagram represents a major point of effort for this device, because of amplitude criticality.

It may be seen from Figure 12-1 that the demodulator amplifies the transducer output, and corrects its phase to compensate for phase shift in the transducer. The modulated signal will either be in phase or 180 degrees out-of-phase with the carrier at this point. Rectification next occurs on a synchronous basis with the carrier. Finally, filtering extracts the carrier signal from the output and recovers the stimulus signal. The output is an analog signal closely similar to the stimulus; for use by a digital data system it now must undergo analog-to-digital conversion.

Figure 12-2 illustrates what occurs to the signal as the process proceeds to its conclusion. In the case shown, the transducer is being statically stimulated.

12.3.3 The Digital Demodulator

A synchronous sampling process is used in the digital demodulator to accomplish the same function as the analog unit performs. In essence, every cycle of the carrier waveform is sampled at the correct point to produce an output proportional to the stimulus signal.

Figure 12-3 is a photograph of a single channel, prototype digital unit.

Figure 12-4 is an enlargement of a single cycle of some of the waveforms of Figure 12-2. Note that the rectified output signal must pass through its own average value in progressing toward its peak value, V_{pk} . The transducer output is very closely sinusoidal; therefore there is a fixed relationship between the average value and the peak value:

$$V_{avg} = .636 V_{pk}$$

Also, in the case of sinusoidal output the average value is crossed at specific times in the cycle, notably when $\theta = 39.1$ degrees and 140.9 degrees. These facts lead to an important conclusion: If sampling of the transducer output can be performed just as the output passes through the average value it is not necessary to rectify or to filter to obtain a knowledge of that value. Further, if the output and carrier signals are correctly phase-related, the proper times to sample the transducer output (to obtain its average) are when the carrier signal is at $\theta = 39.1$ or 140.9 degrees. This is because the carrier and the output signals both pass through their averages simultaneously.

Digital data systems employ analog-to-digital conversion. If this conversion can be controlled to permit sampling at the aforementioned points, the digital value of the output will be obtained.

To exactly duplicate the function of the analog demodulator, some means of translation of sampling point to output is necessary. A sample-and-hold amplifier can be placed after the demodulator, but before the data system. The demodulator can then be placed after the demodulator, but before the data system. The demodulator can then be utilized with either an analog or a digital data system; elimination of this amplifier restricts use to a digital system, but simplifies hardware.

It is evident from Figure 12-4 that the rate of change of the transducer output signal is high when $\theta = 39.1$ or 140.9 degrees, and a very short aperture time in the analog-to-digital conversion process would be required. However, the relationship between the average value and the peak is precisely known. It is possible to sample at the peak (90 degrees) of the waveform and simply scale down the value obtained, using the ratio:

$$\frac{V_{avg}}{V_{pk}} = .636$$

A much longer aperture time is possible in this case.

Figure 12-5 depicts the circuits used to perform the task described above.

Carrier drive to the transducer is produced as follows: an 80 KHz crystal-controlled multivibrator (2 transistors) is frequency-divided by an ordinary 4-stage

binary counter (scale-of-16) yielding a 5 KHz square wave signal. A filter tuned to 5 KHz makes this signal sinusoidal, and applies it to the amplifier stage, which then drives one or more transducers.

It may be recalled that it is desired that the transducer output signal be sampled at its 90 degree point, with the output scaled down to .636 times its peak value. Further, if the output and input are in phase, sampling may be accomplished when the carrier signal passes the 90 degree point. Two things are necessary:

- 1) a means for detecting the 90 degree (or other known) point.
- 2) a means for correcting phase alignment.

In Figure 12-5 the switching arrangement will permit selection of any one of 16 separate equally spaced points along the carrier waveform. For example, suppose the switches were set such that the AND gate output goes to logic 1 when the counter contains $\overline{2}^3 \cdot \overline{2}^2 \cdot \overline{2}^1 \cdot \overline{2}^0$. This point occurs at precisely 90 degrees on the carrier waveform. The condition $\overline{2}^3 \overline{2}^2 \overline{2}^1 2^0$ occurs at 67.5 degrees on the carrier waveform. Thus the switching arrangement, along with the AND gate, permits selection of any 22.5 degree segment of the carrier waveform. The variable delay multivibrator serves as a fine-tuning device within such a segment; the aperture delay multivibrator simply gives a fixed delay equal to the aperture time required by the digital voltmeter, sample-and-hold amplifier, or the data system. Now, it is obvious by the technique used that the sampling time is infinitely variable throughout the full 360 degrees of the input waveform. Since it is only necessary to sample the transducer output at its peak to compensate the phase shift, both of the requirements described above have been met by a single circuit. (See Figure 12-6, a waveform chart for the digital demodulator technique.)

12.4 COMPARISON MATRIX

Table 12-3 is a compilation of results of analysis of the trade-off items of paragraph 12.2 as a function of demodulator type.

12.4.1 The Analog Demodulator

The present analog demodulator system is a WANL implementation of a unit originally designed by Crescent-East, Inc. The unit itself was designed in 1967. No accuracy tests were performed since 1967, and data prior to that time are sketchy. However, WANL IC-4694 (ISFS-1086), dated July 15, 1967, reports drift and gain stability for four units tested at 0.5%, and overall accuracy at "less than $\pm 1\%$ over a 3 month period." Later tests conducted on similar (but not identical) demodulators show linearity of $\pm 0.5\%$ over the full scale range of the device.

Four channels (two chassis) of these demodulators were installed at the Plum Brook Reactor Facility in August, 1967, and have operated well since.

References (Section 12.7) 1, 2, 3 are data sources for the analog demodulator information. Following are statements concerning significant comparison matrix trade-off items for the analog demodulator.

12.4.1.1 Accuracy

The original specifications for overall accuracy, linearity, and drift of the analog demodulator were exceeded by all units shipped to NRDS for testing. Those in the field are slightly different from the unit now at Plum Brook, primarily in that they are slightly older versions of it. The specifications as listed are proven by long-term calibration reports taken from the NRX-A3 and NRX/EST demodulators prior to and after testing at NRDS. References are listed above.

12.4.1.2 Size

The biggest disadvantages of the analog demodulator are its size, and the fact that this size cannot be greatly reduced. Most of the circuits are analog, and require biasing potentiometers, offsetting networks, and some means of balancing. A program of size reduction would be beneficial, and a reduction is possible to about 6 inches by 5 inches by 5 inches, excluding power supplies. The circuit is not reducible to a single chip, probably requiring about 10 to 20 MSI chips ultimately.

12.4.1.3 Output

An analog output voltage with a peak span of 0-10 volts is available. A variable output is also available, and may be adjusted to any desired full-scale potential from 0 to 10 volts.

12.4.1.4 Difficulty of Adjustment

The initial setup of the calibration signal is arduous, and must be checked several times. However, once the adjustment is correct, it will remain so for long periods of time, even several months.

12.4.2 The Digital Demodulator

Data sources for the information in the following paragraphs are the laboratory testing records taken as described between February and June of 1970. Reductions of these data have been made in DRM 51916.

12.4.2.1 Size

The sampling section of the digital demodulator now occupies 3 microcircuit chips, but could be placed on a single chip if desired. The transducer drive section employs two chips, two transistors, a packaged filter, and a small but powerful operational amplifier. It is possible that the entire demodulator could be placed on a single chip. It should be noted that the drive section can operate with a number of transducers; a sampling section is necessary for each transducer.

12.4.2.2 Cost

The digital demodulator has a present cost of about \$225 per channel, including the sample-and-hold unit. Without this unit the cost is less than \$100 per channel. Both of these figures can be reduced by using medium scale integration techniques.

12.4.2.3 Output

The digital demodulator, when used with a sample-and-hold amplifier, presents an analog output potential, equal in magnitude with the transducer output. When used with a digital data system in which channel sampling can be locked to the sample command, no sample-and-hold amplifier is used. Instead, the transducer output is applied directly to the data system and the demodulator is used to apply a narrow "sample" command at the proper point in time.

12.4.2.4 Difficulty of Adjustment

The digital demodulator needs no calibration unit, since the transducer calibration curve applies to the demodulator as well. The only required adjustment is the setting of the sampling point, which is merely a matter of peaking the signal output reading with any static stimulus except zero.

12.5 SELECTION OF DESIGN

On the basis of the following advantages as seen in Table 12-3, the digital demodulator concept is selected as the prime NERVA candidate:

Accuracy

Size (See Sections 12.4.1.2 and 12.4.2.1)

Cost (See Sections 12.4.2.2)

Ease of adjustment (See Sections 12.4.1.4. and 12.4.2.4)

Power Supply Requirements

Weight

The analog demodulator is recommended only as a potential backup unit, requiring substantial further development.

12.6 REFERENCES

1. WANL IC 4694 (ISFS 1086), "Demodulator Long-Term Drift and Gain Stability Test. "
2. WANL ISFS 2244, "Instruction Manual for the WANL Demodulator System. "
3. WANL IC 5191 (ISFS 1206), "Demodulator Comparison Test for NRX-EST LVDT Data. "
4. WANL SI-AEP-1396, dated November 5, 1970.

TABLE 12-1

FLIGHT CARRIER TRANSDUCER REQUIREMENTS

Type	Measurement Location	No. Channels	Range Prime Candidate Transducer
Vibration	Core Support Plate	9	+15 g's VR Accelerometer
Displacement	Reactor/Pressure Vessel	3	±.060 inch LVDT
Displacement	Core Radial	8	±.49 inch LVDT
Displacement	Core Axial	3	±.050 ±.150 inch LVDT
Diff. Press.	Core Axial	4	30-220 psi VP or VR Pressure
Diff. Press.	Final Seal Chamber	3	0-50 psi VP or VR Pressure
Diff. Press.	Reflector Inlet to Core Exit	4	650-800 psi VP or VR Pressure
Diff. Press.	NSS Inlet From Turbine to Core Inlet	3	0-50 psi VP or VR Pressure
Diff. Press.	Structural Support System	4	0-100 psi VP or VR Pressure
Diff. Press.	Reflector Inlet to Turbine Inlet	3	0-75 psi VP or VR Pressure
			<u>44</u> Channels

Additionally, it is possible that the following channels will use carrier type devices.

Type	Measurement Location	No. Channels	Range Prime Candidate Transducer
Pressure	Structural Support System Plenum	4	60-1200 psi VP or VR Pressure
Pressure	Reflector Inlet Plenum	3	20-1200 psi VP or VR Pressure
Pressure	NSS Outlet to Turbine	3	60-1200 psi VP or VR Pressure
Pressure	NSS Inlet from Turbine	3	60-700 psi VP or VR Pressure
			<u>13</u> Channels

TABLE 12-2
DEMOMULATOR REQUIREMENTS

Signal Input Level (from transducers)

Variable reluctance or variable permeance pressure 300 millivolts peak

Variable reluctance or variable permeance accelerometers 500 millivolts peak

LVDT's 3.5 millivolts per mil displacement
per rms volt carrier excitation
(Thus, for a 100 mil displacement with
a 5 V rms excitation a 1750 millivolt
output can be expected.)

Maximum Tolerable Input 2.00 V (rms)

Minimum Input Level 0.010 V (rms)

Excitation to Transducers (from Demodulator)

Frequency 5,000 $\pm$ 50 Hz

Amplitude 5.0 $\pm$.025 volts

Distortion less than 3%

Power Level (minimum) 1.0 $\pm$.500 watts
Per transducer
attached

Output Signal

Accuracy $\pm$ 0.5% of full scale
stimulus

Type Analog to data system
or Pulse Command

Frequency Response 0 - 1000 Hz

Power Supply Requirements

Input Voltage $\pm$ 15 VDC, $\pm$.1 v

Input Current 1.0 Ampere per
channel maximum

TABLE 12-2 (CONT'D)
DEMODULATOR REQUIREMENTS

General Requirements

Radiation Levels	Same as for I and C Electronics
Reliability	0.99990
Maintainability	Card Replacement Preferred
Operating Lifetime	600 minutes
Space Lifetime	3 years
Ground Storage Time	5 years
Electromagnetic Interference	MIL-E-6051

TABLE 12-3
DEMODULATOR COMPARISON MATRIX

	<u>Analog Demodulator</u>	<u>Digital Demodulator</u>
Sensor Compatibility (both LVDT's and VRT's)	One model, card changeover from LVDT to VRT	Two models, one for LVDT, one for VRT
Accuracy	Overall 1.0% Linearity 0.5% Noise-no measurement Drift 0.5%	Overall .33% Linearity .28% Noise .19% Drift-no measurement
Size	Now 19" x 7" x 20" (2 channels) Size reduction possibilities good	Now 6" x 4" x 4" Size reduction possibilities excellent
Cost	\$750 per channel	\$225 per channel
Complexity	Simple in concept	Very simple in concept
Output	Analog, 0-10V	Analog (voltage the same as input) or pulse-command
Difficulty of Adjustment	Initial adjustment difficult No repeat adjustments	Initial adjustment moderate No repeat adjustments
Insensitivity to Temp. Change	<.5% over operating range	Not measured
Power Supply Requirements	110V a.c. at 1 ampere (per channel)	+15V d.c. at 130 ma -15V d.c. at 30 ma
Weight	Approximately 20 pounds (reduceable to 3 pounds)	Approximately 1 pound

Figure 12-1. Typical Analog Demodulator

Figure 12-2. Analog Demodulator Waveforms (Static Waveforms)

Figure 12-3. The Digital Demodulator

Figure 12-4. Basic Waveforms

Figure 12-5. Block Diagram of Digital Demodulator

Figure 12-6. Digital Demodulator Timing

APPENDIX 12-A

DIGITAL DEMODULATOR TESTING

SUMMARY

Testing of two models of the WANL Digital Demodulator was performed between February 1970 and June 1970. Both an engineering model and a prototype were tested. Results may be summarized as follows:

Overall accuracy (LVDT's)	0.33%	
Overall accuracy (VRT's)	0.22%	(1-sigma values)
Linearity (worst case)	0.28%	
Noise (worst case)	0.19%	

Methods of calculation are summarized later, and aid in determining definition of these quantities.

The figures given refer to the accuracy of the demodulator and the associated sample-and-hold unit. Significant errors in the sample-and-hold amplifier, associated with signal polarity, were found.

Burst diaphragm and modulated frequency checks were made to get a qualitative evaluation of transient response of the demodulator.

DESCRIPTION OF THE TEST SETUP

Figure A-1 illustrates the test setup used in determining accuracy values.

Figure A-2 illustrates the test setup used for burst-diaphragm transient testing.

The transducers employed were:

1. A Crescent East +125 mil Linear Variable Differential Transformer, Model 125-3K-5/58-9. Serial No. 3153-6.
2. Wiancko 0-800 psia, Variable Reluctance Pressure Transducer, Model No. 54726, Serial No. 50001.

a. Test Setup for Testing Demodulator

b. Test Setup for Testing Sample-and-Hold Amplifier

Figure A-1. Test Setups

Figure A-2. Transient Testing Setup

In using the setup of Figure A-1-a in testing the demodulator overall linearity, accuracy and noise, physical stimulus was applied to the transducer, and the modulated AC output measured using a true RMS meter capable of accurate readings at 5 KHz, the carrier frequency. The sampling section of the demodulator was always peaked during setup for maximum output, by alteration of the sampling point, as described in the main text of this report. The digital voltmeter on the output of the sample-and-hold amplifier permitted an accurate comparison of demodulator output versus input. After initial peaking of the waveform at the beginning of the run, no further peaking was permitted.

After data on the testing of the demodulator using variable reluctance devices was complete, accuracy information proved to be better than expected. Later tests were conducted with LVDT's, but the accuracy did not appear as good. Further analysis led to suspicion that the sample-and-hold amplifier, a commercial unit, might be the cause. It was suspected that crossover of this unit from positive to negative output might be erroneous, since this happens with LVDT's but not with reluctance pressure transducers. For this reason, the circuit of Figure A-1-b was used to evaluate the sample-and-hold amplifier. The demodulator merely served to fix the sampling point in this case.

The accuracy testing using variable reluctance and LVDT devices so far described may be thought of as static testing, since the stimulus signal is essentially a direct current signal. Obviously, it is necessary to have a significant frequency response in a pressure device, to insure that transients are adequately measured. To evaluate the ability of the demodulator with transient signals, the setup of Figure A-2 was used. Principally, it consists of a pressure transducer connected to a diaphragm, with a means whereby it can be pressurized. A knife blade ruptures the diaphragm quickly upon command. A strain gage pressure transducer of known capability is connected to the same manifold, and serves as a control transducer for data comparison.

DESCRIPTION OF THE TESTING AND DATA REDUCTION

Engineering Model Testing

In the time period from early February, 1970 to late April, 1970, tests were conducted to determine accuracy of the digital demodulator unit itself, using an engineering model in a breadboard setup.

Figure A-3-a is a block diagram of the digital demodulator. During engineering model tests, the transducer driving amplifier was the McIntosh audio amplifier shown in Figure A-3-b at the right rear. In the center of this picture is the demodulator chassis with the filter and sample-and-hold amplifier mounted toward its rear.

For testing of the variable reluctance pressure transducer in the static mode, pressure was varied from 0 to 800 psia and back to 0 in steps of 100 psi. The test was repeated 8 complete cycles. The output of the transducer in millivolts rms and the output of the demodulator were recorded. Care was taken to insure (at first) that transducer drive was constant. Later, this proved to be an unnecessary precaution, since drive seemed to remain constant as a result of the design.

Figure A-4 is a plot of transducer stimulus versus demodulator output, and of transducer stimulus versus transducer output. It is easily noted good linearity is evident, although a marked shift occurs in transducer output. This is a normal condition; it results from an inability on the part of transducer manufacturers to produce exactly balanced coils. Figure A-5 shows the demodulator output versus input for this case. The demodulator has been off-biased to compensate for the transducer zero offset. If this off-bias condition is subtracted, the graph of Figure A-6 results. This graph gives an idea of the linearity of the demodulating technique, and some concept also of the noise potential.

Actually, it is necessary to reduce the large quantity of data taken to truly see linearity and noise. A plot of average data, such as Figure A-6, tends to mask noise effects by the averaging process. The data reduction process will now be explained.

Refer to Figure A-7. This is a tabular listing of the reduced data. Column A is the stimulus pressure. Column B is the average of 8 readings of the transducer output. Column C is the correction of column B for zero shift. This is accomplished by subtracting the average of the first and last readings of column B from the readings of column B. Thus, column C represents the demodulator stimulus, corrected by zero shift.

$$C_n = \frac{\sum_{\alpha=1}^8 \left[(\text{VRT output}_n) - \frac{\text{VRT output}_{(1)} + \text{VRT output}_{(17)}}{2} \right]_{\alpha}}{8} \quad (1)$$

Column D represents the average of 8 readings of demodulator output at each pressure setting:

a. Schematic Diagram of Digital Demodulator

b. Test Setup of Demodulator Engineering Model

Figure A-3. Demodulator

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[illegible]

$$D_n = \frac{\sum_{a=1}^8 (\text{Demod output}_n)_a}{8} \quad (2)$$

Column E is a scaling of the demodulator output of equation 2.

$$E_n = \frac{.707 \sum_{a=1}^8 (\text{Demod output}_n)_a}{8} \quad (3)$$

Thus, column C represents the stimulus mean $\bar{x}$, and column E represents the response mean $\bar{x}$. The variance can be obtained as follows:

$$s^2 = \frac{\sum_{n=1}^{17} (x_n - \bar{x}_n)^2}{17} \quad (4)$$

Note that the denominator here is 17. This is because the stimulus is precisely known. Had it been less precisely known, it would have been necessary to use $n - 1 = 16$ here. The quantity $(x_n - \bar{x}_n)^2$ is given in Column F, and summarized according to equation 4.

Since all zero shift has been removed from the estimates of equation 4, it is presumed that the resulting estimate is related to only linearity and noise. In effect,

$$s^2 = 8 s_L^2 + s_n^2 \quad \text{where } s_L^2 \text{ is the linearity variance and } s_n^2 \text{ is the noise variance.} \quad (5)$$

The noise variance is calculated as follows. Each reading of the 17 points on 8 runs ($17 \times 8 = 136$ points) was scaled and then has subtracted from it the average of all 8 points at that level. This result is squared, summed, and divided by $a - 1 = 7$. For example, with 800 psia stimulus, the readings from 8 runs were:

<u>Run</u>	<u>Reading</u>	<u>. 707 Reading</u>
1	311 mv	219.877
2	311 mv	219.877
3	311 mv	219.877
4	311 mv	219.877
5	310 mv	219.170
6	310 mv	219.170
7	311 mv	219.877
8	311 mv	219.877

The average of the .707 scaling column is 219.700. This value is then subtracted from each reading and squared.

<u>Run</u>	<u>Reading</u>	<u>. 707 Reading</u>	<u>(. 707 Read - Avg)</u>	<u>(. 707 Reading - Avg)²</u>
1	311	219.877	.177	.0313
2	311	219.877	.177	.0313
3	311	219.877	.177	.0313
4	311	219.877	.177	.0313
5	310	219.170	.530	.2809
6	310	219.170	.530	.2809
7	311	219.877	.177	.0313
8	311	219.877	.177	.0313

These squared deviations are next summed and divided by n - 1:

$$G_n = \frac{\sum_{a=1}^8 (.707 \text{ Reading} - \text{Avg})_a^2}{7} = \frac{.7496}{7} = .1070$$

This figure is then entered in column G of Figure A-7. The average of all entries in this column is the variance due to noise.

$$s_n^2 = \frac{\sum_{n=1}^{17} G_n}{17} \quad (6)$$

Next, using equation 5, the linearity variance is calculated. When s_L^2 and s_n^2 are known, and since it is assumed all errors are from these causes (with the exception of zero shift, which has been corrected) s_t^2 , the total variance, may be calculated.

$$s_t^2 = s_n^2 + s_L^2 \quad (7)$$

The percentage accuracy calculations are easily determined after the variances are known, using equation 8:

$$\% \text{ accuracy} = \frac{100 \sqrt{s_t^2}}{\text{maximum output}} \quad (8)$$

Using equation 8 the percentage linearity, noise and total accuracy were calculated for the variable reluctance case. They are:

Table 1 - Demodulator Accuracies When Used With A VRT

Percentage Linearity	.116%
Percentage Noise	.184%
Percentage Total Accuracy	.217%

For testing with an LVDT in the static mode, the position of the slug of the transducer was varied in 10 mil steps from -100 to 0 to +100 mils (21 steps). Eight complete cycles were taken (168 points). The transducer output (in millivolts rms) and the demodulator output (in millivolts DC) were recorded. Care was taken to maintain transducer drive constant at 5 volts rms.

Figure A-8 graphs transducer output and demodulator output as a function of LVDT position setting. The physical offset of the LVDT is evident in the fact that the right-hand portions of the curves do not superimpose, but have a definite shift. Had the physical null been more closely set, this would not have occurred.

Figure A-9 graphs transducer output, which is demodulator input, versus demodulator output. Note that the linearity seems very good except at the zero crossing point, where the offset effectively changes sign. No attempt was made to correct the offset error in these data; this was because it was evident that careful setup could prevent the offset.

The data reduction of 168 points proceeded with the equations outlined earlier, since similar equations work for the LVDT or the VRT. Refer to Figure A-10, a tabular listing of the data reduction output. Column A is the transducer stimulus. Column B is the average value of 8 runs of the transducer rms output at this point. Since no correction for zero shift was made, column C is omitted, and equation 1 is not applicable in this case. Column D is again the average demodulator output for the given stimulus, as given by equation 2. Column E is the scaling of the demodulator output, and equation 3 accomplishes this. The squared deviations from the mean are in column F. For the variable reluctance case, $\bar{x}$ was taken from column C. However, since no correction for zero shift was made, the value from column B was used for LVDT's. Because of the excessive deviation at zero, probably the result of the sample-and-hold amplifier's inaccuracy there, this point was thrown out, and the remaining 20 were used. Thus, equation 4 is modified to:

$$s^2 = \frac{\sum_{n=1}^{20} (x_n - \bar{x}_n)^2}{20} \quad (9)$$

and the variance is calculated. Again this variance conforms to equation 5 and is the result of linearity and noise variances combined.

The noise variance for LVDT's was calculated as for VRT's, but an interesting sidelight occurred. The noise variance for positive displacements is about ten times that of negative displacements. It was suspected that this was the result of error in the

FIGURE A-8
DIGITAL DEMODULATOR OPERATION WITH AN
LVDT OUTPUT VS. INPUT STIMULUS
(ENGINEERING MODEL)

LVDT DISPLACEMENT FROM NULL POSITION (MILI - INCHES)

[illegible]

sample-and-hold amplifier, and the data bear this out. The cause for this anomaly is still not known. However, because of it, separate values for s_n^2 , s_L^2 , s_t^2 were calculated each side of the zero point in a manner similar to the VRT case. Equation 6 becomes:

$$s_n^2 = \frac{\sum_{n=1}^{10} G_n}{10} \quad (10)$$

Equations 7 and 8 apply as written.

The percentage accuracy figures become:

Table 2 - Demodulator Accuracy When Used With an LVDT
(Engineering Model)

	(-) Displacements	(+) Displacements
Percentage Linearity	.218%	.188%
Percentage Noise	.101%	.326%
Percentage Total Accuracy	.240%	.377%

Prototype Model Testing

A prototype demodulator, with full printed circuit layout, was built and tested. This unit was specifically applicable to LVDT testing, and was thoroughly tested using the same transducer as was used with the engineering model testing program. Figure A-11 is a photograph of the prototype demodulator.

Data were taken in a similar manner, and reduced identically. Figure A-12 is a graph of the transducer output and demodulator output as a function of primary stimulus. It is equivalent to Figure A-8. Notice that the undesirable zero shift caused by a lack of caution during setup has been eliminated in this case. Figure A-13 corresponds for the prototype to Figure A-9. Again, a pronounced zero shift was observed.

Figure A-14 presents the tabular data reduction output for the LVDT test with the prototype unit. The calculated results are:

Figure A-11. The Prototype Demodulator

Figure A-14

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DEMOMULATOR TESTING - LVDTs (PROTOTYPE)

A	B	C	D	E	F	G		
Disp	Avg Excit	Demod	Scaled	Excit Cor	$(X-\bar{X})^2/n$			
		Avg Out	Demod	for Shift				
			Out					
(mils)	(mv rms)	(mv DC)	(mv DC)	(mv rms)				
			.707C	B-25.587	$(B-D)^2$			
-100	777.963	-1093.000	-772.751	752.376	27.165	3.9987		
-90	700.800	-982.975	-694.893	675.211	34.893	4.489		
-80	624.063	-874.250	-618.095	598.476	35.617	3.1060		
-70	546.575	-764.000	-540.148	520.988	41.306	2.1422	$S_n^2 = 1.84909 \approx .1959\%$	
-60	468.475	-653.250	-461.848	442.888	43.917	2.3921	$S_1^2 = 4.707 \approx .2808\%$	
-50	391.887	-544.000	-384.608	366.300	52.984	1.4281	$S_t^2 = 6.586 \approx .3314\%$	
-40	312.175	-430.375	-304.275	286.588	62.410	1.1335		
-30	234.962	-319.875	-226.152	209.375	77.616	1.2050		
-20	157.000	-208.125	-147.144	131.413	97.141	.4909		
-15	118.075	-153.895	-108.790	92.488	86.211	.6337		
-10	80.385	-100.875	-71.319	54.788	82.011	.7765		
-5	45.012	-47.750	-33.759	19.425	126.630	.3927		
0	25.589	-0.250	-0.177	0	645.668			
5	40.737	41.625	29.429	15.150	127.871	3.7042		
10	72.425	92.625	65.486	46.838	48.150	6.7471		
15	109.675	146.625	103.664	84.088	36.132	7.4173		
20	147.587	201.000	142.107	122.000	30.030	16.1377		
30	219.937	303.875	214.840	194.350	25.979	39.3363	$S_n^2 = 17.9696 \approx .5457\%$	
40	293.262	408.125	288.544	267.675	22.260	27.6255	$S_1^2 = 2.7107 \approx .213\%$	
50	369.187	516.125	364.900	343.600	18.378	9.2025	$S_t^2 = 20.4203 \approx .5856\%$	
60	441.625	618.875	437.545	416.038	16.646	25.1977		
70	513.800	721.000	509.747	488.213	16.427	14.2814		
80	585.800	822.625	581.596	560.213	17.674	31.9814		
90	655.012	920.125	650.528	629.425	20.106	21.4846		
100	727.850	1023.250	723.438	702.263	19.466	10.3897		

Table 3 - Demodulator Accuracy When Used With an LVDT
(Prototype Model)

	(-) Displacements	(+) Displacements
Percentage Linearity	.281%	.213%
Percentage Noise	.176%	.546%
Percentage Total Accuracy	.331%	.587%

It may be seen that the accuracy of the prototype unit is not quite as good as the engineering model. The basic difference between these units is the amplifier used to drive the transducer. An improved model of the amplifier used on the prototype is now being assembled.

Since both the models tested exhibited difficulties with LVDT's at the zero crossing point, tests were conducted with the sample-and-hold amplifier. Because it is not actually a portion of the system, it was felt that its accuracy contribution should be determined and considered. Figure A-15 plots the linearity of this device. Figure A-16 is a tabular listing of the sample-and-hold data reduction, organized in a manner similar to that of Figures A-7, A-10, and A-14. It applies to sampling on the positive-going half cycle. Figure A-17 indicates negative half-cycle sampling data.

Table 4 - Sample-And-Hold Amplifier Accuracy

	- Displacement (+ Half Cycle)	+ Displacement (- Half Cycle)
Percentage Linearity	.129%	.578%
Percentage Noise	.070%	.0432%
Percentage Total Accuracy	.1479%	.580%

Both the linearity and total accuracy figures for the - displacement (+ half cycle) indicate that about half of the inaccuracy of the demodulator/sampling unit combination is associated with the sample-and-hold amplifier. The rest is with the demodulator itself. However, on the + displacement, the sample-and-hold inaccuracy masks any demodulator inaccuracy that might occur. It is reasonable, however, to assume that the demodulator is reasonably balanced, and the inaccuracy associated with the negative displacement is representative for the unit. Thus, the reported accuracies of the demodulator/sample-and-hold combination are as shown in Table 5.

[illegible]

[illegible]

Table 5 - Summarized Accuracy For Demodulator

Overall accuracy (LVDT's)	.33%
Overall accuracy (VRT's)	.22%
Linearity (worst case)	.28%
Noise (worst case)	.19%

Transient Testing of the Demodulator

All testing described thus far might be termed static, since a fixed stimulus was utilized everywhere. Some admittedly qualitative tests of demodulator performance with transients have been performed, however.

The test setup of Figure A-2 was used to evaluate demodulator performance in the transient case. As previously described, both a variable reluctance and a strain gage pressure transducer were connected to a common manifold, which was given a pressure transient by bursting its confining diaphragm. The pressure transient is not instantaneous, but is exponential with a time constant of about 50 milliseconds.

Figure A-18-a shows the modulated transducer output on the upper trace, and the demodulator output (from the sample-and-hold amplifier) on the lower trace.

Figure A-18-b is a comparison of the strain gage pressure transducer output (upper trace) and the demodulated variable reluctance pressure transducer output (lower trace). For visual examination, the traces appear to be identical, indicating that, at least as far as this stimulus is concerned, the transducers have equal frequency response capability. It should be pointed out that any response limitation for the VRT case would likely be from the demodulator.

To be certain of the transient response characteristics, a 400 Hz modulation was applied to the 5 KHz carrier frequency, and applied to the demodulator. Figure A-19-a shows the stimulus waveform, while A-19-b shows the response, taken at the output of the sample-and-hold amplifier. The steps associated with each carrier cycle are clearly seen.

On the basis of the transient tests observed, it is reasonable to expect no limitation on frequency until the stimulus frequency exceeds one-tenth the carrier frequency.

Sweep Speed:
50 m sec/cm

- a. Upper Trace - VRT Output, .2 v/cm
Lower Trace - Demodulator Output .2 v/cm

Sweep Speed:
50 m sec/cm

- b. Upper Trace - SG Transducer Output, .05 v/cm
Lower Trace - VRT/Demodulator Output .2 v/cm

Figure A-18. Burst Diaphragm Testing Waveforms

a. Demodulator Input, 5 KHz with 400 Hz Modulation
.5 v/cm 1 m sec/cm

b. Demodulator Output, after carrier removal
.2 v/cm 1 m sec/cm

Figure A-19. Modulated Waveform Testing

CONCLUSIONS

1. The synchronous sampling technique employed in the digital demodulator is workable.
2. With an adequate sample-and-hold amplifier, the inaccuracy can be held to less than $\pm .33\%$.
3. A prototype printed circuit layout exists and has been found to be usable.
4. Two areas bear further investigation:
 - a. A better transducer drive amplifier should be put together.
 - b. An improved sample-and-hold amplifier is needed. Probably, this is available commercially.

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