ETS-1 CONTROL POINT GENERAL INDOCTRINATION COURSE

VOLUME THREE

NTO-T-0025

MASTER

NERVA Test Operations

Nuclear Rocket Development Station
Jackass Flats, Nevada

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ETS-1 CONTROL POINT OPERATOR
GENERAL INDOCTRINATION COURSE

SECTION XVI
NUCLEAR PHYSICS

A. ATOMIC STRUCTURE

In order to understand the nature and characteristic of the NERVA reactors it is desirable to review some of the fundamentals of nuclear physics.

Elements are pure substances that cannot be broken down into simpler substances by simple chemical change or reaction. There are over one hundred identified elements. Some of the better known are carbon, sulfur, oxygen, gold, and copper.

An atom is the smallest particle of an element that can exist by itself and still represent the element. For example, the smallest particle of helium is a helium atom. This is one of the simpler atoms among the elements.

HELIUM
ATOM

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An atom contains a dense central portion called the nucleus, and an outer region wherein very light particles called electrons move in orbits about the nucleus. Almost all of the mass of the atom is contained in the nucleus, yet the nucleus is only 10^{-12} of the total volume of the atom. The volume of the atom is essentially that enclosed by the orbiting electrons. The great mass of the nucleus is the result of the presence and number of nuclear particles called protons and neutrons.

1. Proton. The proton is a positively charged elementary particle with a charge equal in magnitude (but of opposite polarity) to the electron charge e . The mass of the proton is 1.0076 atomic mass units (1 amu is equivalent to 1.660×10^{-24} grams). Every element has a different number of protons in the nucleus and each element is assigned a number which corresponds to the number of protons it contains. This is known as the ATOMIC NUMBER and is designated by the symbol Z .

2. Electron. The electron is an elementary particle with a rest mass, m_e , equal to .00055 amu. When the atom is in an unexcited state, its associated electrons move in orbits about the nucleus, with one electron for each proton in the nucleus.

When an atom is excited (by heat, ultraviolet radiation, etc.) the kinetic energy of the electrons increases. As the electrons orbital position fixes its energy level, an increase in electron energy requires a change in orbital position. It effectively jumps to another shell which permits the higher energy.

3. Neutron. Neutrons are elementary particles that have no charge and may be considered as the combination of a proton (positive charged particle) and an electron (negative charged particle), the electrical sum of which is neutral. The neutron has a mass of 1.0089 amu. The nuclear designation for the neutron is 1_0n .

4. Atoms. For any atom (X) the subscript is the atomic number (Z) and the superscript is the mass number (A), as designated by the relationship A_ZX , sometimes noted as ${}_Z^AX$. The subscript indicates the number of protons in the nucleus, and the superscript indicates the total number of neutrons plus protons in the nucleus. This total is known as the MASS NUMBER. An example

is Helium which has two protons, thus the atomic number is 2. It also has two neutrons, thus the mass number is 4. The designation for Helium is ${}^4_2\text{He}$.

As another example, Hydrogen which has only one nuclear proton can have different numbers of neutrons in the nucleus. However, the chemical properties are found to be the same, even though the physical properties are somewhat different due to the different number of neutrons contained in the nucleus. The designations for the three forms of Hydrogen are:

Hydrogen	(0 Neutron) (1 Proton)	${}^1_1\text{H}$
Deuterium	(1 Neutron) (1 Proton)	${}^2_1\text{H}$
Tritium	(2 Neutrons) (1 Proton)	${}^3_1\text{H}$

Elements having a different mass but the same atomic number are called ISOTOPES. Obviously, if the atomic number (identical to the number of protons in the nucleus) remains constant, the isotopes are identified by the number of neutrons found in the nucleus.

Protons and neutrons are often referred to as nucleons.

In summary, the basic building blocks of matter are the proton and neutron which make up the nucleus of the atom, and the orbital electrons. The following table lists the characteristics of these three particles.

	Symbol	Mass (grams)	Mass (amu)	Charge
PROTON	P or ${}^1_1\text{H}$	1.672×10^{-24}	1.0076	+1
ELECTRON	e or ${}^0_{-1}\text{e}$	9.11×10^{-28}	5.5×10^{-4}	-1
NEUTRON	n or ${}^1_0\text{n}$	1.675×10^{-24}	1.0089	0

5. Ionization. As discussed above, the electrons of an atom can be moved to higher energy states by excitation. They can, with varying difficulty, be excited to the extent that one or more leave the atom completely. The remainder of the atom retains a net positive charge. The departed electron(s) and the remanent atom are charged particles and are called ions. The process is called ionization. Ionization can be caused by such things as high temperatures, electrical discharges, and nuclear radiation. Some ions of interest are:

<u>ION</u>	<u>SYMBOL</u>	<u>DESIGNATION</u>	<u>NUCLEUS</u>
Hydrogen	${}^1_1\text{H}^+$	Proton	1 Proton
Nitrogen	${}^{14}_7\text{N}^+$	Nitrogen Ion	7 Protons 7 Neutrons
Oxygen	${}^{16}_8\text{O}^+$	Oxygen Ion	8 Protons 8 Neutrons

B. NUCLEAR ENERGY

The distinction between chemical energy and nuclear energy should be understood before discussing nuclear energy.

1. Chemical Energy. Atoms of different elements combine to form chemical compounds by sharing orbital electrons. These shared electrons form chemical bonds. Breaking or rearranging chemical bonds can result in the liberation of heat energy. Chemical reactions involve only the orbital electrons.

2. Mass Defect. Laboratory experiments to determine the mass of an atom show that the actual mass is always less than the sum of the masses of the elementary particles that constitute the atom. The difference is called MASS DEFECT. Thus:

$$\begin{array}{r}
 \text{Constituent Nucleon's Mass (amu)} \\
 - \text{Measured Nuclear Mass (amu)} \\
 \hline
 = \text{Mass Defect (amu)}
 \end{array}$$

The equivalence of mass and energy can then be used to show that mass defect has the energy equivalent given by:

$$\begin{aligned} & \text{Mass Defect} \\ & \times 931 \text{ Mev/amu} \\ & = \text{Potential Energy for the Nuclear Reaction} \end{aligned}$$

3. Energy Comparisons. The calculations to determine the energy available from fusion of two Hydrogen atoms and the energy available from fission of one Uranium atom are shown in Figure XVI-2. The calculation for the energy released by the combustion of one molecule of Methane is shown in Figure XVI-3. The results can be summarized as follows:

Methane Combustion	14.4 watt-hour/gram
Fission	2.23×10^7 watt-hour/gram
Fusion	1.87×10^8 watt-hour/gram

4. Fusion. Fusion of heavy hydrogen, ${}^2_1\text{H}$, is the source of much of the energy released in exploding the H-bomb. Self-sustaining fusion reactions are not a reality as yet, although much research is continuing in this area. All present nuclear reactors operate on the nuclear fission principle and further discussion is restricted to fission reactions.

5. Fission. The fission process is the splitting of the nucleus into two fission fragments and accompanied by the release of several neutrons. Since each neutron has the capacity to produce additional fissions, it is the release of these additional neutrons that make a self-sustaining fission reaction possible. Fission reactions can be exponentially divergent as employed in an atomic bomb, or they can be easily manipulated as employed in nuclear reactors.

C. RADIOACTIVITY

Radioactivity is an energy adjustment by an unstable atomic nucleus, resulting in the emission of radiation. These emissions can be particulate or they can be electromagnetic. The most common particulate emissions are alpha particles and beta particles. The electromagnetic emissions are either gamma rays or X-rays. The energies of these nuclear emissions are given up to the material through which they pass. The emissive energy is absorbed by collision with the shielding material. Various materials may be used as shielding against these radiative emissions.

1. Alpha Particle (α). The alpha particle, composed of two protons and two neutrons, is a positively charged particle emitted from a nucleus. It is identical in all measured properties with the nucleus of a helium atom (${}^4_2\text{He}^{++}$). The emission of an alpha particle decreases the atomic number by two units and the mass number by four units.

The alpha particle is easily stopped by a piece of paper.

2. Beta Particle (β). A negatively charged beta particle is essentially an electron emitted at high velocity from the nucleus. Since the nucleus does not contain discrete electrons, the electron must arise from the spontaneous conversion of a neutron into a proton and the energy decrement required to produce the emission.

A positively charged beta particle, called a positron, with the same mass of an electron is emitted by the nucleus as a result of the transformation:

The above two reactions illustrate that the emission of an electron increases the atomic number by one, while the emission of a positron decreases the atomic number by one. The mass number does not change in either case.

The beta particle is stopped by a thin sheet of aluminum.

3. Gamma Ray (γ). The gamma ray is an electromagnetic radiation emitted by a nucleus. In general the gamma ray is much more penetrating than alpha or beta particles. Comparison of the characteristics of the principle nuclear radiations are given in the following table.

RADIATION EMISSIONS

	Symbol	Mass (amu)	Charge	Range		
				Air	Water	Earth
ALPHA	α	4.0	+ 2	Few cm	*	*
BETA	β	5.5×10^{-4}	- 1	Several Feet	*	*
GAMMA	γ	.511 mev	0	1800'	26"	18"
PROTON	P	1.0076	+ 1	Few Inches	*	*
NEUTRON	n	1.0089	0	3000'	6"	15"

* Negligible

D. INTERACTION OF RADIATION WITH MATTER

Charged particles such as alpha and beta particles produce ionization by direct interaction as they pass through matter. During each ionization the particle yields a fraction of its energy. When sufficient energy is lost, the particle reassociates to an appropriate atomic status.

1. Alpha Particle. An alpha particle when sufficiently slowed down attracts two free electrons and become stable helium atoms.

2. Beta Particle. A beta particle reacts in two different manners according to its electrical charge. The β^{-} particle with low energy can be attracted to the outer electron orbit of ions to form stable atoms. The β^{+} particle combines with an electron. When this happens the two particles annihilate each other, releasing two 0.511 mev gamma rays.

3. Gamma Rays. Gamma rays are not charged and do not produce ionization directly, but ionization can be a secondary process. Gamma rays

interact with matter in three different processes: photoelectric effect, Compton effect, and pair production.

a. Photoelectric Effect. In the photoelectric effect, a gamma ray (or photon) interacts with an orbital electron of an atom in such a way that all the energy of the gamma ray is absorbed by the electron, and the electron is ejected from its orbital path. Figure XVI-4 illustrates the photoelectric effect: (1) gamma ray interacts with an orbital electron, (2) orbital electron absorbs entire energy of gamma ray, and (3) orbital electron ejected from the atom.

b. Compton Effect. In the Compton effect, a gamma photon undergoes scattering by interaction with electrons. In each interaction the electron gains energy and recoils, and the photon loses energy. Figure XVI-5 illustrates the Compton effect: (1) the incident gamma ray interacts with an orbital electron, (2) a scattered gamma ray with lower energy is emitted and, the orbital electron recoils and is ejected from the atom.

c. Pair Production. Pair production is the transformation of the energy of a high energy gamma ray into a positron-electron pair. This conversion normally takes place when the photon transverses the strong electromagnetic field surrounding a heavy element nucleus. Figure XVI-6 illustrates the pair production: (1) high energy (> 1.1 mev) photon passes near the nucleus, (2) photon transformed into positron-electron pair, (3) positron and electron are attracted by electrostatic charge, (4) positron and electron annihilate each other, with release of two 0.511 mev gamma rays.

E. RADIOACTIVE DECAY

When a nucleus of an atom spontaneously gives off particles (alpha or beta) it is undergoing the process called RADIOACTIVE DECAY and becomes a new element. This process cannot be altered by physical means, i.e., temperature, pressure or force.

Not all of the atoms of a radioactive element decay at one time. The time for one-half of the atoms present to undergo this process is called the HALF-LIFE. The remaining one-half of the original element will again be reduced to one-half in the same time period. Each radioisotope has its own characteristic half-life. Half-lives may be very short (seconds) or as long as many millions of years.

It should be noted that all elements with an atomic number greater than 83 are radioactive. More than a dozen of the elements with atomic numbers less than 83 also have radioactive isotopes.

F. NEUTRON CHARACTERISTICS

The function of neutrons as building blocks of matter has been discussed. Neutrons are released during fission, and the characteristics of these free neutrons should be understood before discussing reactor theory.

1. Neutron Half-Life. If the free neutron is not absorbed within a short time it decays by beta emission to produce a proton and beta particle.

The half-life of a neutron is estimated to be about 13 minutes.

2. Neutron Energy. Neutrons are classified into three energy groups: FAST, INTERMEDIATE, and THERMAL. A neutron is ejected as a fast neutron during the fission reaction. The fast neutron has an energy between 0.1 mev and 10 mev. The intermediate neutron has energy less than the fast neutron but greater than the thermal neutron. The range generally considered is between 0.5 electron volts and 0.1 mev. The thermal neutrons have slowed down and have lost so much energy that they have the same kinetic energy as the nuclei comprising the surrounding medium.

3. Neutron Interaction with Matter. Neutrons can undergo two main types of reactions with matter. ABSORPTION occurs when a neutron enters the nucleus, a preliminary to a secondary reaction. SCATTERING occurs when the neutron interacts with the nucleus in such a manner that some (or all) of its kinetic energy is transmitted to the nucleus.

There are several kinds of neutron absorption reactions which involve capture of a neutron by a "target" nucleus. These include emission of gamma radiation (n, γ), ejection of an alpha particle (n, α), ejection of a proton (n, p), or fission (n, f).

- c. Proton Ejection (n, p) ${}^{14}_7\text{n} + \text{n} \rightarrow ({}^{15}_7\text{n})^* \rightarrow {}^{14}_6\text{C} + {}^1_1\text{H}$
- d. Fission (n, f) ${}^{235}_{92}\text{U} + \text{n} \rightarrow \text{XY}^* \rightarrow \text{X} + \text{Y} + 2\text{n} + \gamma$
- * Indicates excited states.

4. Nuclear Cross Section. The probability of the interactions between neutrons and atomic nuclei depends on the quantity called NUCLEAR CROSS SECTION. This is the effective area of the nucleus for a particular reaction. The magnitude of the cross section depends on the nucleus involved, the type of reaction, and the energy of the incident neutron. The cross section of a single nucleus is frequently called the MICROSCOPIC CROSS SECTION, and is usually expressed in units of a barn. One barn is equivalent to 10^{-24} cm^2 .

Figure XVI-7 shows the variation of the total cross section (sum of absorption and scattering) with neutron energy for natural uranium and boron.

In the low energy region, the absorption cross section is inversely proportional to the neutron energy. This is called the ($\frac{1}{v}$) region. This is evident in the case of boron. Some elements exhibit a resonance region, where the absorption cross section rises sharply to high values for certain neutron energies. It is to be noted that the cross section for natural uranium has the characteristic resonance region while boron does not. Above the resonance region, the nuclear cross section decreases with increasing neutron energy. At very high neutron energies, the total cross section approaches the geometrical cross sectional area of the nucleus.

5. Reaction Rates. The rate at which a particular nuclear reaction occurs is dependent upon the number of neutrons, their velocity, and the nuclear cross section. The rate of reaction per cubic centimeter of material is equal to the product of the MACROSCOPIC CROSS SECTION and NEUTRON FLUX. The macroscopic cross section is the total effective area of all nuclei per cubic centimeter of material, and the neutron flux is equal to the product of neutron density and neutron velocity. As indicated above, cross sections are a function of the neutron energy. When there exist neutrons having a range of energies or velocities, an integration over the range of energies must be performed to obtain the total reaction rate.

G. FISSION NEUTRONS

The neutrons emitted as a result of the fission process can be divided into two categories: prompt neutrons and delayed neutrons.

1. Prompt Neutrons. An average of about 2.5 neutrons are released for the fission of each U-235 atom. The prompt neutrons, which make up over 99% of the total fission neutrons, are released within about 10^{-14} seconds. Prompt neutrons are released with energies between about 0.1 to 10 mev, and have an average energy of about 2 mev.

2. Delayed Neutrons. The delayed neutrons are released as a result of the decay of beta emitting fission product "daughters." Six delayed neutron groups ranging in half-life from 0.05 to 55.46 seconds have been identified for U-235. Fragments produced during fission which lead to the emission of delayed neutrons are known as delayed-neutron precursors. Bromine-87 is the delayed-neutron precursor of the 55.46 delayed neutron group. It decays by beta emission to produce Krypton-87. The emission of the neutron by ^{87}Kr is prompt so that the observed half-life is that of the preceeding beta emitter, ^{87}Br .

DELAYED NEUTRON GROUP	λ_i (Sec^{-1})	DELAYED NEUTRON FRACTION (Bi)	BIRTH ENERGY (KEV)	HALF-LIFE (SEC)
1	.0125	.000271	250	55.46
2	.0306	.001511	560	22.65
3	.112	.001341	530	6.19
4	.302	.002889	620	2.29
5	1.14	.000910	420	0.608
6	3.02	.000185	430	0.289

$$\sum_{i=1}^{i=6} \text{Bi} = .0071$$

A. ELECTRON SHELLS

B. ELECTRON CONFIGURATION

SHELL	SHELL NUMBER (N)	MAX. ELECTRONS IN SHELL ($2N^2$)	He	Ne	Kr	Rn	Ra
K	1	2	2	2	2	2	2
L	2	8	—	8	8	8	8
M	3	18	—	—	18	18	18
N	4	32 *	—	—	8	32	32
O	5	32 *	—	—	—	18	18
P	6	32 *	—	—	—	8	8
Q	7	32 *	—	—	—	—	2

* EMPIRICAL LIMIT

FUSION	FISSION																				
<p>Hydrogen (1) to Helium (4)</p> $2\left(\frac{1}{1}\text{H}\right) + 2n = 4.0341$ $\text{Helium} = \underline{4.0039}$ $\text{Mass Defect} = 0.0302$ $0.0302 \text{ amu} \times 931 \text{ mev/amu} = 28.2 \text{ mev}$ $(\text{w-hr/mev}) \times \underline{4.44 \times 10^{-17}}$ $(\text{each He atom}) = 125 \times 10^{-17} \text{ w-hr}$ $\text{or } 1.87 \times 10^8 \text{ w-hr/gm}$	<p>Uranium (235) to</p> <table> <tr> <td>(FP)₁</td> <td>138.960</td> </tr> <tr> <td>(FP)₂</td> <td>94.940</td> </tr> <tr> <td>2n</td> <td><u>2.018</u></td> </tr> <tr> <td></td> <td>235.918</td> </tr> <tr> <td>from (U + n)</td> <td><u>236.129</u></td> </tr> <tr> <td>Mass Defect</td> <td>0.211</td> </tr> <tr> <td>0.211 amu x 931 mev/amu</td> <td>= 196 mev</td> </tr> <tr> <td>(w-hr/mev) x <u>4.44 x 10⁻¹⁷</u></td> <td></td> </tr> <tr> <td>(each U atom) =</td> <td>8.71 x 10⁻¹⁵ w-hr</td> </tr> <tr> <td>or</td> <td>2.23 x 10⁷ w-hr/gm</td> </tr> </table>	(FP) ₁	138.960	(FP) ₂	94.940	2n	<u>2.018</u>		235.918	from (U + n)	<u>236.129</u>	Mass Defect	0.211	0.211 amu x 931 mev/amu	= 196 mev	(w-hr/mev) x <u>4.44 x 10⁻¹⁷</u>		(each U atom) =	8.71 x 10 ⁻¹⁵ w-hr	or	2.23 x 10 ⁷ w-hr/gm
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(each U atom) =	8.71 x 10 ⁻¹⁵ w-hr																				
or	2.23 x 10 ⁷ w-hr/gm																				

FIGURE XVI-2

CHEMICAL SYMBOL	CHEMICAL COMPOUND	HEAT OF FORMATION (ΔH_f°)
CH ₄ =	Methane	20.3 kg-cal/gm mol.wt.
CO ₂ =	Carbon dioxide	94.4 kg-cal/gm mol.wt.
H ₂ O =	Water	68.4 kg-cal/gm mol.wt.

$$\text{CH}_4 + 4 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O}$$

$$\text{Heat of Combustion (CH}_4\text{)} = \Delta H_f (\text{CO}_2 + 2 \text{H}_2\text{O} - \text{CH}_4)$$

$$= 94.4 + 2 \times 68.4 - 20.3$$

$$= 210.9 \text{ kg-cal/gm mol.wt.}$$

Converting: 210.9 kg-cal/gm mol.wt. = 14.4 watt-hr/gm

FIGURE XVI-3

(1)

(2)

(3)

PHOTOELECTRIC EFFECT
FOR TRAINING USE ONLY

FIGURE XVI- 4

COMPTON EFFECT
FOR TRAINING USE ONLY

FIGURE XVI-5

(1) GAMMA RAY ENTERS ELECTRICAL FIELD

(2) FORMATION OF POSITRON-ELECTRON PAIR

(3) ELECTROSTATIC ATTRACTION

(4) ANNIHILATION

A. NATURAL URANIUM CROSS SECTION

B. BORON CROSS SECTION

NUCLEAR CROSS SECTION
FOR TRAINING USE ONLY

FIGURE XVI-7

ETS-1 CONTROL POINT OPERATOR
GENERAL INDOCTRINATION COURSE

SECTION XVII
REACTOR PHYSICS

A. FISSION ENERGY RELEASE

The NERVA reactor, as well as nuclear reactors used with electrical power plants, function as heat sources. This heat is generated through the fission process. Each fission produces approximately 200 MEV (million electron volts). The distribution of this fission energy is:

165 MEV	Fission Fragment Kinetic Energy
7 MEV	Instantaneous Gamma Ray Energy
5 MEV	Fission Neutron Kinetic Energy
7 MEV	Fission Product Beta Emission Energy
6 MEV	Fission Product Gamma Ray Energy
<u>10 MEV</u>	Neutronic Energy
200 MEV	Total Energy Per Fission

This can also be expressed in the more familiar terms of kilowatt hours. Thus, the energy released per fission is 200 MEV, or $.3 \times 10^{-11}$ watt-seconds, or approximately 10^{-18} kilowatt hours.

Operation of the reactor at any given power is dependent upon producing the proper quantity of fissions. To decrease the reactor power the number of fissions occurring in a given time interval must be decreased. Reactor physics includes the principles behind the production and control of the nucleus fission reactions.

B. CRITICAL MASS

Although the fission process releases more neutrons than are required to produce a fission reaction, in actual practice some fission neutrons are lost in non-fission processes and therefore are not available to cause additional fission reactions. These losses are due to leakage out of the boundary of the reactor system, and to non-fission absorption in the fuel, core components, and structural materials of the reactor system. A proper balance between the neutrons produced by fission and those lost must be achieved to produce a self-sustaining chain reaction.

If the core of a reactor is insufficient in size, a large number of neutrons will escape from the core and a self-sustaining reaction is impossible. As the core size is increased neutron escape is less likely and the core is more likely to sustain a chain reaction. For a given core geometry and given reactor materials, a minimum core size is required to produce a self-sustaining chain reaction. This is the critical core size. The mass of fissionable material contained in this core is said to be the critical mass for the core only. The effect of core dimension is illustrated in Figure XVII-1.

C. REACTOR CRITICALITY

The conditions for a nuclear chain reaction can be expressed in terms of the MULTIPLICATION FACTOR. The multiplication factor, K , is defined as the ratio of the number of neutrons present in a reactor in any given neutron generation to that in the immediately preceding generation.

For a reactor of infinite size there is no leakage and all neutrons are absorbed or captured within the reactor. A term called infinite multiplication factor, K_{∞} , is used to describe this theoretical condition. The term effective multiplication factor, K_{eff} , takes into consideration the effects of leakage. The K_{eff} applies to the actual reactor configuration.

Six factors are included in determining the K_{eff} . They are: (1) neutrons produced per neutron absorbed, (2) fast fission factor, (3) fast non-leakage probability, (4) resonance escape probability, (5) thermal nonleakage probability, and (6) thermal utilization factor.

1. Neutrons Produced per Neutrons Absorbed (η). This term is the average number of neutrons released per thermal neutron that is absorbed in the fuel.
2. Fast Fission Factor (ϵ). The fast fission factor gives the contribution of fast neutrons in producing uranium fission. The product $\eta\epsilon$ gives the total neutron contribution, while the four remaining factors account for neutron attenuation or loss to the fission process.
3. Fast Nonleakage Probability ($\mathcal{L}_f$). The fast leakage factor is the fraction of fast neutrons that do not escape from the reactor before becoming thermal neutrons.
4. Resonance Escape Probability (P). The resonance escape probability is the fraction of neutrons that are not captured by uranium-238 while the slowing down process is taking place.
5. Thermal Nonleakage Probability ($\mathcal{L}_{th}$). The thermal leakage factor is the fraction of neutrons that do not escape from the reactor before being absorbed.
6. Thermal Utilization Factor (f). The thermal utilization factor is the ratio of thermal neutrons that produce fission of the fuel to the total number of neutrons absorbed in the fuel, reactor components, and support materials.

Effective multiplication factor is the product of the six terms defined above:

$$K_{eff} = \eta \epsilon P f \mathcal{L}_{th} \mathcal{L}_f$$

The reactor is said to be CRITICAL when it is sustaining a chain reaction. Figure XVII-2 illustrates the critical condition. As shown at the top of the figure each fission reaction produces 2.43 neutrons. The contribution of fission produced by fast neutrons increases the effective neutrons per fission to 2.58. The next four factors reduce the number of neutrons available to produce the next generation of fissions. One neutron per fission is available to produce additional fissions. Thus the steady-state of the reactor is maintained.

D. SUPERCRITICAL REACTOR

If K_{eff} is less than one, fewer neutrons are produced in each succeeding generation. This is the condition when a reactor is being shut down and the reactor is said to be subcritical.

If K_{eff} is equal to one, the neutron population is constant from generation to generation and the reactor is said to be just critical.

If K_{eff} is greater than one, the neutron population increases from generation to generation. In this condition the reactor is said to be supercritical.

Figure XVII-3 illustrates the supercritical condition. In this example the fast nonleakage probability, $\mathcal{L}_f$, is increased from 0.800 to 0.801. The value of the other factors of the K_{eff} equation are unchanged from those given in Figure XVII-2. The increased $\mathcal{L}_f$ increases the neutrons available to produce fission reaction during each generation from 1.0 to 1.004. Thus the K_{eff} is 1.004.

The increase in the neutron population is given by:

$$\frac{n}{n_0} = e^{\frac{\lambda(K_{\text{eff}} - 1)t}{\beta - (K_{\text{eff}} - 1)}}$$

where:

- e = base of the natural logarithm = 2.718
- K_{eff} = effective multiplication factor
- λ = delayed neutron time constant = .08 seconds
- t = time in seconds
- β = total fraction of delayed neutrons = .0071
- n = number of neutrons at time t
- n_0 = original number of neutrons at $t = 0$

The multiplication for $K_{\text{eff}} = 1.004$ and $t = 10$ seconds is 2.8. Under these conditions the neutron population would increase 2.8 times in ten seconds. The exponential nature of the neutron multiplication causes a rapid increase with respect to time. For example, after one minute the neutron population has increased 485 times while after two minutes it has increased 237,000 times.

(a) CORE CENTERLINE NEUTRON BIRTH.

(b, c, d) ESCAPE PROBABILITY FOR GEOMETRICALLY DISPLACED NEUTRON BIRTH.

CRITICAL MASS

FIGURE XVII-1

ETS-1 CONTROL POINT OPERATOR
GENERAL INDOCTRINATION COURSE

SECTION XVIII
REACTOR PHYSICS AND CONTROL THEORY

A. REACTOR SYSTEM

Most reactors consist of four components: (1) fuel, (2) moderator, (3) reflector, and (4) structural components.

1. Fuel. The fuel is fissionable material used to produce the nuclear energy. The NERVA reactor uses uranium-235.

2. Moderator. The moderator is a material which slows down fast neutrons and converts them to thermal neutrons and thereby increases the probability of additional fission reactions. The NERVA reactor uses graphite as the moderator. The core of the reactor may consist of fuel only or a combination of both fuel and moderator. In the NERVA reactor both uranium-235 and graphite are in the core.

3. Reflector. The reflector is material surrounding a reactor core which scatters or reflects back into the core neutrons that would otherwise escape. The NERVA reactor uses beryllium as a reflector material.

4. Structural Components. The structural components contain and hold the reactor together. The materials used in the structure must be carefully chosen on the basis of radiation resistance and minimum interaction with the control of the reactor.

B. REACTIVITY

The effective multiplication factor (K_{eff}) determines whether the neutron density will remain constant or change within a reactor. Since the

power level is directly proportional to the neutron density, whenever $K_{\text{eff}} = 1.0000$ the reactor is critical and operates at a constant power level. If $K_{\text{eff}} < 1.0000$ the reactor is subcritical and the power level is decreasing. If $K_{\text{eff}} > 1.0000$ the reactor is supercritical and the power level is rising. Notice that the power level, as well as the neutron density, is constantly changing whenever K_{eff} is not equal to 1.0000. The difference between K_{eff} and 1.0000 is known as the EXCESS MULTIPLICATION FACTOR and is expressed as K_{ex} .

$$K_{\text{ex}} = K_{\text{eff}} - 1.0000$$

K_{ex} may be either positive or negative, depending upon whether K_{eff} is greater or less than 1.0000. A useful quantity known as REACTIVITY is given the symbol ρ and is related to K_{ex} as follows:

$$\rho = \frac{K_{\text{eff}} - 1.0000}{K_{\text{eff}}} = \frac{K_{\text{ex}}}{K_{\text{eff}}}$$

According to the above equation, ρ and K_{ex} are identical whenever a reactor is exactly critical, and they have almost the same value whenever K_{eff} is but slightly larger or smaller than 1.0000.

C. REACTOR PERIOD

1. Prompt Critical. The reactor period is defined as that length of time required to change reactor power, or neutron density, by a factor of e . The term e is the base of the natural logarithm and is equal to 2.718. The period for any reactor operated PROMPT CRITICAL is:

$$T = \frac{\lambda^*}{K_{\text{ex}}}$$

where:

$$\begin{aligned} T &= \text{the reactor period in seconds} \\ \lambda^* &= \text{the average time in seconds elapsing between successive generations of prompt neutrons} \\ K_{\text{ex}} &= K_{\text{eff}} - 1.0000 \end{aligned}$$

A prompt reactor does not depend on delayed neutrons to sustain the chain reaction, since there are a sufficient number of prompt neutrons available to maintain the neutron multiplication. Any reactor for which K_{ex} is

greater than β falls in this category; for example, a reactor fueled with ^{235}U has a $\beta = 0.0075$ and is prompt if the value of K_{ex} is greater than 0.0075 or $K_{\text{eff}} > 1.0075$. Since the value of λ^* for the NERVA reactor is approximately 24×10^{-6} seconds, the period for the reactor operation in the prompt critical condition would be extremely short and the power will rise tenfold in less than a millisecond.

Another unit of reactivity in common use is the DOLLAR. This unit is derived from the prompt critical condition of $\rho = \beta$. Accordingly, the dollar is the reactivity of a reactor which is exactly prompt critical.

$$\text{Dollars} = \frac{\rho}{\beta}$$

2. Delayed Critical. The period for any reactor operated DELAYED CRITICAL is:

$$T = \frac{\lambda^* + (\beta - K_{\text{ex}}) \tau}{K_{\text{ex}}}$$

where:

- T = the reactor period in seconds
- λ^* = the average time elapsing between successive generations of prompt neutrons
- β = the total fraction of delayed neutrons
- $K_{\text{ex}} = K_{\text{eff}} - 1.0000$
- τ = weighted average of the mean lifetimes for the six groups of delayed neutrons

The equation for the period of the delayed critical reactor shows the dependence of the period on the presence of delayed neutrons for any reactor as long as K_{ex} is less than β . The effect of the delayed neutrons is to increase the average time between successive generations by as much as a factor of several hundred. This results in a longer, safe period which permits a controlled power rise. Figure XVIII-1 shows the relationship of reactor period as a function of reactivity. The rapid increase in period as reactivity approaches β is evident.

D. NEUTRON MULTIPLICATION

More than 99 percent of all fission neutrons are born within 10^{-14} seconds after fission. All of these neutrons are considered to be prompt neutrons and appear at the instant of fission.

Consider the kinetic behavior of a prompt critical reactor - a reactor in which enough extra neutrons are produced so that delayed neutrons are not needed to sustain the chain reactor. If the initial neutron density is n_0 , it will be $n_0 K_{eff}$ at the end of one generation. The net increase in the neutron density during a single generation is found by subtracting the initial neutron density from that which exists after one generation:

$$\begin{aligned} & n_0 K_{eff} - n_0 \\ &= n_0 (K_{eff} - 1.0000) \end{aligned}$$

Thus, the change in neutron density per generation is equal to $n_0 K_{ex}$. The average time between successive generations for prompt neutrons was represented by ℓ^* which is sometimes referred to as the mean effective lifetime. Since ℓ^* represents seconds per generations, the reciprocal of ℓ^* is generations per seconds. If $1/\ell^*$ is multiplied by $n_0 K_{ex}$, the change in neutron density per second is obtained:

$$\frac{dn}{dt} = \frac{n_0 K_{ex}}{\ell^*}$$

$$n_t = n_0 e^{\left(\frac{K_{ex}}{\ell^*}\right)t}$$

Integrating gives:

From this equation it should be noted that:

- (a) when K_{ex} is positive (a supercritical reactor), the power of e is positive and the neutron density increases exponentially with time;
- (b) when K_{ex} is zero (a critical reactor), the power of e reduces to zero and the neutron density remains constant with time;
- and (c) when K_{ex} is negative (a subcritical reactor), the power of e is negative and the neutron density decreases exponentially with time.

The neutron density in the core determines the fission rate. Therefore, the power level, P , of a reactor is proportional to the neutron density at that time:

$$P = cn$$

where:

P = power

c = proportionality constant

n = neutron density

If n_o represents the initial neutron density at time $t = 0$ and after time t the neutron density has increased to n_t , the power ratio is given by:

$$\frac{P_t}{P_o} = \frac{n_t}{n_o}$$

where:

P_o = power at time $t = 0$

P_t = power after time t

Note that the power level and the neutron density have increased by the same ratio.

E. REFLECTOR EFFECTS

Surrounding the reactor core with a reflector reduces neutron leakage from the core by reflecting or scattering many of the escaping neutrons back into the active core region. Materials used for reflectors should have a high scattering cross section and very low absorption cross section. Some of the fast neutrons which escape into the reflector region are moderated and scattered back to the core region. Since there is almost no neutron absorbing material in the reflector, moderation will usually be more efficient in the reflector than in the core itself. As a result, a larger fraction of the fast neutrons in the reflector will be thermalized than is possible in the fuel containing region of the moderator.

The use of a reflector improves the neutron economy and power distribution.

1. Neutron Economy. Improvement in the neutron economy reduces the amount of fuel required to achieve criticality. It is possible with proper design to reduce the size of the reactor including the reflector to below the size of a similar bare core reactor with the same fuel concentration.

2. Power Distribution. Improvement in the power utilization is a consequence of the flux flattening that occurs across the reactor core when a reflector is employed. This flattening is shown in Figure XVIII-2. The

average flux throughout the core volume is greater for a reflected reactor with the same maximum neutron flux; and since power output is proportion to the average flux, a reflected reactor can be operated at a higher power output.

Because of the flux flattening effect, the power output will be more uniform throughout the core volume. This is desirable from an operational standpoint. A further improvement in flux flattening may be obtained by non-uniform loading of the fuel elements. By increasing the fuel loading in the outer elements and decreasing the central element loading a relatively flat power distribution may be obtained. The NERVA reactor utilizes a six region core of this type.

F. REACTOR CONTROL

From the previous discussion of neutron multiplication, the neutron ratio can be expressed as:

$$\frac{n_t}{n_o} = e^{\frac{(K_{ex})t}{\lambda^*}}$$

By definition the reactor period, T, is that time required for the neutron density to change by a factor of e. If $T = \frac{\lambda^*}{K_{ex}}$ is substituted in the above equation then:

$$\frac{n_t}{n_o} = e^{\frac{t}{T}}$$

Replacement of the neutron density ratio by the power ratio gives:

$$\frac{P_t}{P_o} = e^{\frac{t}{T}}$$

This equation shows that the change in power as a function of time is dependent upon the reactor period. Thus control of reactor period is an effective means of controlling the reactor power level.

If the K_{ex} is limited to values between 0 and β , the delayed neutrons are essential in maintaining the chain reaction. The overall effect of the delayed neutrons is to increase the complete cycle time for any generation of neutrons.

Operation of reactors at small K_{ex} values permits control of the reactor by the relatively slow process of mechanically positioning control rods or drums.

Figure XVIII-3 shows the variation of the relative neutron level with time upon the introduction of a small step change in K_{ex} . Initially, within a very small time after the original disturbance, the neutron level increase will be determined by the prompt neutron lifetime, λ^* . However, after a short time interval has elapsed, the delayed neutrons will become effective and will cause the rapid flux rise to diminish considerably. The initial portion of the curve is termed the prompt jump portion while the remainder is called the stable period.

For a negative step insertion of reactivity, the neutron level will show an initial decrease. Within the short time interval before the delayed neutron becomes effective, neutron level will be a mirror image of its positive insertion. However, as time progresses, the flux change will flatten out. As the precursors of the short lived delayed neutron group disappear, the flux will eventually decrease exponentially in a manner determined by the longest lived delayed group.

A secondary consideration which effects reactor control is the fact that delayed neutrons are emitted with an energy of about 0.5 Mev as opposed to 2.0 Mev for the prompt neutrons. Because of this lower energy, fewer collisions are necessary for thermalization, the fast leakage is less, and the effect on K_{eff} is greater than for an equal number of prompt neutrons.

Figure XVIII-4 shown the response on neutron multiplication to several values of reactivity insertion.

G. REACTOR OPERATION WITH NEUTRON SOURCE

If a source of neutrons is inserted into a subcritical reactor with a multiplication factor of less than one at the end of a sufficiently long time interval, the number of neutrons present in the reactor will be:

$$\frac{N}{N_0} = \frac{1}{1-K_{eff}}$$

This ratio is known as the subcritical multiplication factor. The result of this equation is shown graphically in Figure XVIII-5 for various values of

K_{eff} . As K_{eff} approaches 1, more and more time is required for the neutron level to stabilize. When $K_{\text{eff}} = 1$, the reactor is critical and the subcritical multiplication factor approaches infinity.

If the reactor is almost critical, it may happen that this subcritical multiplication of the source provides enough neutrons to make the reactor appear critical. This condition is termed SOURCE CRITICAL.

If a reactor is just critical and contains no source, it will maintain the same neutron density over a long period of time. If a source is added, the neutron density will rise at a constant rate. The increase for each second is constant and is equal to that number of neutrons which is contributed by the source in one second. When the source makes a substantial contribution to the total flux, e.g., at very low neutron levels, its presence cannot be disregarded. With the neutron levels commonly encountered in power operation, usually greater than 10^{13} neutrons/cm³, the contribution of the source is insignificant when compared to that of fission and may therefore be disregarded.

In a supercritical reactor, the neutron density increases exponentially. If a source is added to this supercritical reactor, the neutron density still increases exponentially, but at a faster rate. As in the case of the critical reactor, the contribution of the source must be considered when operating at very low neutron levels. At the higher neutron levels where the source furnishes but a minute fraction of the total, it becomes insignificant.

H. FACTORS AFFECTING REACTIVITY

The factors affecting reactivity are divided into two groups: (1) those having an immediate effect on reactivity, and (2) those having an observed effect only after long periods of operation. The first group is of importance to the NERVA engine and includes temperature and pressure coefficients. The second group, important to reactors used to produce electric power, includes fission-product poisoning such as xenon and samarium.

1. Temperature Coefficient of Reactivity. The temperature coefficient of reactivity is defined as the change in reactivity for a one degree change in temperature and is represented by α_T .

In an operating reactor, the temperature changes as the power demand varies. A power-level increase is a direct result of more fissions releasing more heat. As the average temperature of the reactor rises, the coolant and moderator expand and become less dense. Because there are now fewer particles per cm^3 , the moderator is less effective in slowing down neutrons and more leakage is observed. The overall effect is a reduction in K_{eff} or the addition of negative reactivity. Reactivity and temperature change are related thus:

$$\Delta K_T = \alpha_T (T_2 - T_1) = \alpha_T \Delta T$$

where:

ΔK_T = the reactivity change resulting from temperature change

α_T = temperature coefficient

T_2 = final temperature

T_1 = initial temperature

ΔT = temperature change

Notice from this equation that whenever the reactivity and the temperature change move in the same direction, α_T is positive and is known as a POSITIVE TEMPERATURE COEFFICIENT. If the reactivity and the temperature change move in opposite directions, α_T is negative and is, of course, a NEGATIVE TEMPERATURE COEFFICIENT. Any reactor having a positive temperature coefficient is very difficult to control. Therefore, most of the operating reactors use water for a moderator, and take advantage of the relatively large negative temperature coefficients.

The real significance of the negative temperature coefficient is that it tends to oppose any change in the average temperature in the core. If, for example, control rods are withdrawn by error and multiplication is increased, the power level will rise. But just as soon as the temperature in the core increases, negative reactivity appears and reduces multiplication. Therefore, the power is returned to a safe level before it becomes dangerously high.

2. Pressure Coefficient of Reactivity. The pressure coefficient of reactivity is defined as the change in reactivity for a one-pound change in pressure and is represented by α_p . Added pressure makes the coolant

moderator more dense by increasing the number of particles per cm^3 . The moderator is more effective in slowing down neutrons and causes K_{eff} to rise. Reactivity and pressure are related as follows:

$$\Delta K_p = \alpha_p (P_2 - P_1) = \alpha_p \Delta P$$

where:

ΔK_p = reactivity change due to pressure change,

α_p = pressure coefficient,

P_2 = final pressure,

P_1 = initial pressure,

and

ΔP = pressure change.

For pressurized water reactors as well as the NERVA reactor, pressure and reactivity move in the same direction, and the pressure coefficient of reactivity is positive.

3. Xenon Poisoning. Xenon is of special interest because of its great abundance and extremely high thermal neutron cross section of 3.2×10^6 barns. About 0.3 percent of all thermal fissions of ^{235}U yield ^{135}Xe directly as a fission fragment. By far the greater amount comes from the radioactive decay of ^{135}Te which has a fission yield of 5.6 percent. The half-life for ^{135}Te is so short that ^{135}I is considered to be a direct product of fission. The entire decay chain is represented thus:

After a reactor has operated at a constant neutron level for about 40 hours, the xenon reaches an equilibrium value which is dependent on the neutron flux. These poisoning effects are expressed in terms of reactivity change due to poison and are represented by the ratio:

$$\frac{\text{number of thermal neutrons absorbed by poison}}{\text{number of thermal neutrons absorbed by fuel}}$$

The greater the flux, the greater is this ratio. It reaches a maximum of about 0.5 for fluxes in excess of 10^{15} neutrons/ cm^2 /second. Figure XVIII-4A shows the equilibrium values for different flux levels. These equilibrium values indicate that at any particular flux, xenon is undergoing transmutation

at the same rate at which it is being produced. In an operating reactor the transmutation of ^{135}Xe is represented by the equation:

^{136}Xe is stable, has a low thermal absorption cross section, and offers no serious problem. Note that when the reactor is operating, neutrons are plentiful and ^{135}Xe is kept at a fixed level mainly because of the above reaction.

Whenever a reactor is shut down, xenon rapidly builds up, reaching a peak after about 10 to 11 hours. See Figure XVIII-6A. This always occurs because ^{135}Xe is still being produced from the decaying ^{135}I and it is no longer being burned out since there is now a shortage of neutrons. This ^{135}Xe must decay with its normal half-life of 9.2 hours.

The ^{135}Xe build-up after shutdown depends on the operating flux before shutdown; the greater the operating flux, the higher will be the xenon peak. Notice that the xenon peak after shutdown following operation at higher flux is many times greater than the equilibrium value. ^{135}Xe offers no real problems when operating with fluxes of 10^{13} or less, but for higher fluxes the build-up of ^{135}Xe after shutdown may prevent the reactor from being started up again for a considerable length of time.

4. Samarium Poisoning. ^{149}Sm is the second most important fission-product poison because of its high thermal absorption cross section of 66,000 barns. ^{149}Sm stems from ^{149}Pm in a manner analogous to the formation of ^{135}Xe from ^{135}I . The complete decay chain is represented thus:

Since the half-life of ^{149}Nd is insignificant compared to that for ^{149}Pm , ^{149}Pm is considered to be a direct fission product and has a fission yield of 1.4 percent. Because ^{149}Sm is not radioactive, it presents problems somewhat different from those encountered with ^{135}Xe . The equilibrium concentration and the poisoning during reactor operation are independent of the neutron flux and reach a maximum value of 0.012. See Figure XVIII-6B. The stable nuclide ^{149}Sm can disappear in but one way. It absorbs a neutron and changes to ^{150}Sm which is of no importance.

The build-up of ^{149}Sm after shutdown depends on the power level before shutdown. ^{149}Sm does not peak as ^{135}Xe does, but rather increases slowly to a maximum value of 0.042.

I. REACTOR DRUM CONTROL

The control system provides a method of safety starting up the reactor, varying its power level and shutting it down. The control system accomplishes this by changing the neutron density within the core. The NERVA reactor is a reflector controlled reactor in which the position of twelve control drums regulate the reflection of neutrons back into the reactor core.

The control drums are cylinders of beryllium equally spaced in the beryllium reflector. There is a sheet of Boral (aluminum and boron) on one-half of each control drum which acts as a neutron absorber. With the control drums in the zero degree position, the Boral is next to the core and maximum neutron absorption takes place. With the control drums turned to the 180 degree position, the beryllium is next to the core and the Boral is farthest from the core. This provides maximum neutron reflection back into the core. Control of the reactor is attained by rotating the drum so that more or less Boral is presented to the reactor.

J. MEASUREMENTS OF REACTOR PARAMETERS

Various techniques are available for the determination of reactor drum worth, reactivity coefficients and shutdown margin. Basically, all of these methods involve measuring reactivity deviation from a critical condition resulting from the perturbation of the variable to be measured.

The method used to determine individual drum worth at NTO consists of bringing the reactor critical with 11 drums ganged and obtain period measurements by incremental rotation of the remaining drum. This method allows the complete drum span to be measured. Through use of the inhour equation the resultant period measurement may be converted to a corresponding reactivity value.

Individual integral worth is determined by rotating the drum from 0° to 180° with the reactor critical at the ganged position of the remaining 11 drums. Again, the resulting period may be converted to a reactivity worth by means of the inhour equation.

A secondary method of checking the individual integral worth consists of maintaining the reactor critical in power control using 11 drums in the ganged position. As the remaining single drum is stepped outward, a resultant inward gang movement occurs in order to maintain a constant power level. By comparing the change in the ganged position a related integral worth for the single drum may be obtained. Figure XVIII-7 shows the results of a typical drum worth calibration curve.

Temperature coefficient determination for NRX reactors are made by establishing a low reactor power level while in power control, and allowing the core to heat up slowly. As heating takes place, the drums rotate out to maintain a constant power. This drum movement can then be related to reactivity per temperature rise and the temperature coefficient obtained. Because of the widely varying heatup rates of all the reactor components, this method of coefficient determination is subject to some uncertainty.

A characteristic unique to NERVA type reactors is the reactivity addition due to the introduction of hydrogen coolant to the core. This effect which is due to more efficient moderation may be measured by bringing the reactor critical at a low power level with no coolant flow and switching to power control. When the drums have stabilized at the critical position, gaseous ambient hydrogen flow is started through the core which causes the drums to move inward to compensate for the positive reactivity effect. By measuring the new drum position as a function of flow rate, a total worth may be obtained which is primarily due to hydrogen moderation but partially due to the core compaction effect. The reactivity due to core compaction may readily be determined by repeating the gas flow mentioned above using gaseous nitrogen at equivalent hydrogen flow rates. The effect thus measured may then be subtracted from the overall effect to determine the hydrogen contribution.

REACTIVITY AND PERIOD
RELATIONSHIP
FOR TRAINING USE ONLY

FIGURE XVIII - 1

FLUX DISTRIBUTION WITH AND WITHOUT
REFLECTOR
FOR TRAINING USE ONLY

FIGURE XVIII-2

REACTOR TRANSIENT RESPONSE
FOR TRAINING USE ONLY

FIGURE XVIII-3

MULTIPLICATION INCREASE
FOR SEVERAL VALUES OF REACTIVITY
 FOR TRAINING USE ONLY

FIGURE XVIII - 4

**SUBCRITICAL MULTIPLICATION
FOR SEVERAL VALUES OF K_{eff}**
FOR TRAINING USE ONLY

FIGURE XVIII - 5

A. XENON POISONING

B. SAMARIUM POISONING

DRUM WORTH CALIBRATION
FOR TRAINING USE ONLY

FIGURE XVIII -7

ETS-1 CONTROL POINT OPERATOR
GENERAL INDOCTRINATION COURSE

SECTION XIX
REACTOR DESCRIPTION

A. INTRODUCTION

In the nuclear rocket engine, a nuclear reactor is used as the source of energy to produce thrust. This type of energy source has several distinct advantages over the chemical combustion rocket engine. The major advantage is that it allows a high specific impulse to be achieved because, primarily, the propellant is not burned and thus the exhaust gas has a lower molecular weight. Specific impulse is proportional to the square root of temperature and inversely proportional to the square root of the molecular weight. With the NERVA engine a specific impulse of 700 to 800 can be readily attained as contrasted with 200 to 400 for the chemical engines. With a gaseous core reactor a specific impulse of 2000 to 3000 could be achieved because of the higher exhaust gas temperatures that are possible. Another significant advantage of the nuclear energy source over the chemical energy source is that it produces about a million times as many watt-hours of energy for each gram of fuel consumed. The major disadvantages are the radiation produced during operation and the residual radioactivity (fission products) after operation.

The reactor used in XE-1 has been developed from the LASL Kiwi-B4 reactor and is very similar to NRX-A5 which was tested in June 1966. It is a U-235 fueled, graphite and hydrogen moderated, beryllium reflected, and hydrogen cooled reactor. The primary nuclear control elements are twelve drums located in the reflector.

B. FLOW PATH, TEMPERATURES AND PRESSURES

A simplified drawing of the XE engine is shown in Figure XIX-1. The turbopump is enclosed within the upper thrust structure. This pump extracts the liquid hydrogen from the propellant run tank and pumps it into the nozzle tubes for regenerative cooling. Figure XIX-1 shows the relation of the reactor to the engine. The hydrogen flow after passing through the nozzle tubes enters the inlet plenum of the outer reflector. Under operating conditions, the temperature of the hydrogen entering the reactor is 132°R . The reflector consists of 12 beryllium sectors, each containing a control drum. Boral plates in these drums supply the poison for reactor control. The hydrogen cools the various parts of the reflector, and the gas temperature reaches 214°R as it enters the simulated shield. After passing through the simulated shield, the hydrogen enters the core. Here fission energy increases the gas temperature to about 4090°R . After this, the gas exits through the throat of the nozzle. The reactor, which produces 1130 megawatts of power, is a right circular cylinder approximately 3 feet in diameter and 5 feet long. About 77 pounds per second of liquid hydrogen are supplied by the turbine driven pump which obtains its turbine gas from a hot bleed port on the nozzle. The hot gas is mixed with cold hydrogen prior to entering the turbine in order to obtain gas temperatures compatible with the turbine and turbine line materials.

There are numerous coolant channels in the graphite fuel elements. The fuel element cluster is supported by a hydrogen cooled Inconel tie rod which passes through the center of the unfueled element and is attached to the upper support plate. The full power temperatures and pressures at selected points within the reactor are as follows: The core exit pressure is 563 psia, with the gas temperature at 4090°R . Maximum material temperatures within the core exceed 4000°R when calculated on a statistical hot channel factor basis. The pressure drop across the core is 140 psi which results in an inlet pressure of 703 psia. The dome end plenum pressure is 709 psia and the temperature is 214°R . The reflector inlet pressure is 748 psia and the temperature is 132°R . The structural support for the XE reactor differs from that of the Kiwi-B4 since the XE reactor is designed to withstand the environmental loads which can be experienced during boost and flight operations. The reactor is

supported by a titanium support ring which is contained within the flange of the pressure vessel and attaches to the reflector. The top support plate is mounted on a titanium cone which rests against the reflector. The reactor is supported radially by seal rings.

C. REACTOR DESIGN

The NRX reactor is designed to withstand the structural and vibration loads introduced by the booster and flight environment. The core is both axially and laterally mounted to tolerate up to 4g loads in any direction at the low frequency end of the spectrum and up to 5g for frequencies of 2,000 cycles per second. The lateral support is supplied by the seal rings which are activated by springs on a graphite cylinder called the inner reflector.

1. Kiwi-B4-A. The core vibration disclosed by the Kiwi-B4-A test in November 1962 was a major problem requiring solution. This condition was definitely proven to be a fluid dynamic instability. In the Kiwi-B4-A design, the pressure on the outer periphery equalled the core outlet value. Internal pressures in the crevices between the fuel elements were of higher value and produced forces to move the elements radially outward. Counteracting forces were produced by the cluster springs and the pressures behind the fuel elements which resulted in substantial core vibrations and damage.

2. NRX-A. In the NRX-A design, the instability problem was corrected by arranging the core lateral support system so that the pressure on the core circumference is always greater than that which could exist in the internal crevices. The distributed seal system is designed to assure the proper pressure distribution along the periphery. In addition, a core band was added to introduce a rapid reduction in internal pressures at the core inlet. With the assurance that the net pressure-induced forces on the fuel elements must always be radially inward, then no instability can occur.

3. Power Density Considerations. Since variations that would be minor in other power reactors are of major significance in this reactor, the thermal and nuclear design required careful attention. For example, the large temperature rise across the reactor of 4000°R introduces unique problems. A power density variation of only 5% results in a 200°R change in outlet temperature. A change of this magnitude makes a significant difference in the performance of the fuel elements. The development of precise analytical methods

for predicting the power source density throughout the core was required. The highly position-dependent neutron spectra required the use of multi-energy-group diffusion and transport methods. Also, since the reflector is at low temperature when at power, the effect of chemical bonding on nuclear reaction cross sections had to be considered. The analytical techniques were verified by critical testing. The predicted values in this particular experiment agreed, on the average, with the experiment to within ± 4 percent. In isolated edge channels, the experimental power was underestimated by as much as 18 percent.

Jet orifices are used in conjunction with the fuel elements to ensure uniform distribution of the energy across the elements. The temperatures resulting from the power source distribution are calculated using codes that include two-dimensional conduction through the fuel element. Measured values of the pressure drop through particular channels and the element's fuel density are introduced into the analysis. At the present time, the specification of the orificing is performed in an orderly manner. A data system supplies the nuclear and thermal designer with all the needed information which is introduced into a code for specification of the proper orifice. The entire procedure between selection of a fuel element for insertion into the core and the specification of the orifice requires less than one-half of a day.

4. Material Considerations. The many requirements of a satisfactory fuel element eliminate most of the known materials. In addition to being capable of containing the fissionable element, a satisfactory material must possess:

- a. Suitable nuclear and radiation resistance properties;
- b. Mechanical properties at operating temperatures to withstand the temperature gradients and pressure differences imposed by the energy production and fluid flow conditions;
- c. Capability to withstand the rapid changes in temperatures required by the rapid startup requirements of a nuclear rocket engine;
- d. Suitable low-temperature physical properties to withstand the shock and the vibration loads caused by the booster operation;

- e. Sufficient corrosion resistance to hydrogen to maintain its structural integrity and contain the fissionable materials for the required engine operating times.

The temperature requirements eliminate all the elemental materials except graphite, tungsten, rhenium, tantalum, molybdenum, and niobium. The only temperature-compatible compounds are some of the metallic carbides, nitrates, and borides. While needed physical data is lacking on most of these materials, the choices rapidly narrow to a few possible materials.

Graphite was chosen for the NERVA fuel element. It has excellent high-temperature properties, with a sublimation temperature of 6700°R, and relatively high tensile strengths at operating temperature (~2000 psi). While the mechanical design was simplified by the choice of graphite as the fuel element material, the design of the reactor remained a formidable task. The relatively good low-temperature characteristics of graphite with respect to vibrational and shock loadings eased the problem of mounting the core so that it can resist booster induced vibration damage.

Graphite's ability to withstand thermal shock has allowed a design which can be subjected to rapid thermal transients. The high operating temperatures cause a more subtle problem of accommodation for the expansion of the core and the sealing between the cryogenic regions of the reactor and the high operating temperature regions.

D. REACTIVITY CONSIDERATIONS

An important part of designing the reactor is the achievement of the correct reactivity balance. First, within the relatively narrow range (about \$8) of the control drum reactivity span, it is necessary to establish the proper split between the negative reactivity or shutdown margin and the positive or excess reactivity. The former is important from the safety point of view, while the latter is important for control purposes. Furthermore, it is necessary to predict very accurately the control drum positions for criticality. This is because of the sensitivity of core power density to the position of the control drums. As mentioned earlier, the fuel elements are orificed to obtain a uniform temperature distribution across the core. However, this remains valid for only a limited range of control drum positions. Beyond that range, part of the core will run too hot and part too cold. The

predicted cold critical drum position for XE-1 is 88.9° . Thus, the shutdown margin is about $-\$4$ and the excess reactivity is about $+\$4$. The integral control drum bank worth curve is shown in Figure XIX-2.

During the operation of the reactor there are reactivity changes, called reactivity feedback effects, caused by changes in the reactor temperatures and in the amount of hydrogen in the reactor. These changes for XE-1 are expected to be very similar to those for NRX-A5 which are summarized in Table XIX-1. As will be noticed, the total cold to hot swing is $-\$0.67$ which requires an outward motion of the control drums by about 10 degrees.

E. CONTROL DRUM ACTUATOR SYSTEM

The position of each of the control drums is controlled by its individual control drum actuator. The control drum actuator system is made up of two basic parts: the actuator control system and the actuator mechanism. Each of the 12 actuator control systems receives an identical drum position command signal from the engine control system, conditions it, and supplies the required current to a servo-valve torquemotor which controls the actuator mechanism. The actuator consists basically of two opposing pistons connected by a rack which engages a pinion gear on the actuator output shaft. An extension shaft connects the output shaft to the control drums. Lateral motion of the piston, therefore, is translated to rotary motion of the control drum. The actuator mechanism and its control components are shown schematically in Figure XIX-3.

Normally, gaseous hydrogen is used for the working fluid although helium is used when the Engine Test Compartment is not inerted. Coolant to remove the energy deposited by gamma and neutron irradiation is supplied from the pressure vessel dome and exhausted overboard.

In order to insure reliability during operation, the actuator mechanism has been designed to operate at least 150 hours at room temperature conditions followed by a one-hour operation in a combined environment of low temperature (250°R), high radiation, and vibration equivalent to that expected during use. Prototypes of the actuator have been successfully tested. Irradiation testing has been initiated, but full radiation hardening has not been demonstrated. For use during XE testing, an external shield has been installed above the reactor vessel, and the actuators are mounted above this shield.

1. Control Drum Actuator Mechanism. The control drum actuator mechanism is shown schematically in Figure XIX-3 and a cutaway view in Figure XIX-4. The principal parts are the cylinder, the pistons and connecting rack, the pinion gear and output shaft, the position feedback potentiometers, the pneumatic and manual locks, and the electro-pneumatic servo valve consisting of the torquemotor and bleed nozzles.

During power operation the hydrogen pressure is nominally 215 psia and the temperature may range between 100° to 560°R . The hydrogen coolant gas from the reactor dome ranges from 60° to 560°R . The actuators are designed so that the consumption per actuator of 100°R hydrogen does not exceed 0.02 lb/sec of coolant gas at 700 psia, and 0.0072 lb/sec of drive gas at 215 psia. Seals keep the internal actuator leakage to a minimum. Double seals are provided in all locations where hydrogen might leak into the Engine Test Compartment. The external housing, seals, and mounting means are capable of withstanding 1,000 psig (proof pressure).

The normal operating range of the actuator is 15 to 165 degrees for the control drum, although the pistons do not bottom against the piston covers until -7 or +187 degrees is reached. A snubbing system, consisting of a soft stop and rebound springs, limits motion within zero and 180 degrees when moving toward the limits of the operating range at maximum velocity and limits the rebound from overshoot of the operating range. With the 215 psia nominal pneumatic supply pressure, a net torque of 140 inch-pounds can be applied to the drums for outward motion. Although not a part of the actuator, the control drum design includes a scram spring which acts toward zero degrees. It has a preload of 75 inch-pounds, and a spring gradient of 130 inch-pounds/revolution. Internal friction is equivalent to approximately 10 inch-pounds.

The output shaft drives three position potentiometers. The output of decks A and B are auctioneered, the higher providing the feedback signal. Deck C is used for remote position indication but may be used for a feedback signal if both A and B should fail. A higher voltage drop across the double diode at deck C biases the signal out for normal comparison with A and B.

The servo valve consists of the torquemotor and the bleed valves. Rotation of the torquemotor armature controls the flow of gas through the two nozzles, increasing the flow through one while decreasing it through the other.

As indicated in the schematic, the pneumatic drive gas enters the actuator and passes through two orificed channels to the cylinders at the top of the two pistons. As more gas is bled from one of the nozzles, the pressure above that piston drops with respect to the other and piston motion results. The bellows opposite the nozzle are for damping but bellows B is adjusted to provide a higher force than A and biases the torquemotor to the scram position on loss of control current.

The actuator can be locked in the nominal zero degree position ($0-15^{\circ}$) by insertion of a lock pin into a slot in the output shaft. The pin is capable of withstanding twice the maximum output torque of the actuator. The lock pin is spring loaded to the engaged position and pneumatic pressure is required to withdraw the pin. In addition, a manual key lock provides for blocking the pin in this engaged position even if pneumatic pressure is applied. The key can be removed only when the key lock is in the locked position.

2. Control Drum Actuator Controls. Each of the control drum actuators has the associated controls shown in Figure XIX-3. The position demand from the engine control and override system is combined with the measured control drum position and supplied to the error amplifier. The measured drum position is also differentiated in the rate amplifier. The combined output of the error amplifier and the rate amplifier is limited such that control drum speed does not exceed $100^{\circ}/\text{sec}$. Both of these amplifier stages contain a lag network to limit extraneous noise signals from passing through to the torquemotor. Trim pots are provided for adjustment and calibration of the outputs. The summed error and rate signals are then conditioned in the mixer stage amplifier. The driver amplifier supplies the current to the torquemotor coils. The magnitude and direction of this current determine the pneumatic forces acting to control the control drum motion. The torquemotor current passes through two series contacts of the scram relay which opens on scram. Torque for inward motion during scram, is provided by the scram springs on the control drums. Depending on the drive gas used, drum velocities of 500-1000 degrees per second are reached during scram. Power for the solenoid valve which operates the pneumatic lock passes through another set of contacts on the scram relay.

<u>Temperature Effects</u>	\$
Due to core expansion	-1.57
Due to thermal base shift	-0.58
Due to Doppler effect in Uranium	-0.46
in Niobium	-0.29
in Tantalum	-0.15
Due to Beryllium contraction	<u>0.06</u>
Subtotal for Temperature Effects	-2.99
<u>Hydrogen Effects</u>	
Due to core hydrogen	1.68
Due to lateral support	0.30
Due to Beryllium reflector	0.03
Due to change in H ₂ worth with temp.	0.07
Due to release of absorbed H ₂	0.00
Due to diffused H ₂	<u>0.24</u>
Subtotal of Hydrogen Effects	2.32
<u>Total of Cold to Hot Swing</u>	<u>\$-0.67</u>

TABLE XIX-1

REACTIVITY FEEDBACK EFFECT IN NRX-A5 AT 1120 MW (THERMAL) AND
71.3 POUNDS PER SECOND FLOW (COLD TO HOT REACTIVITY CHANGES)

**TYPICAL NUCLEAR ROCKET ENGINE
SCHEMATIC DIAGRAM**
FOR TRAINING USE ONLY

FIGURE XIX-1

**XE-1 INTEGRAL CONTROL DRUM
BANK WORTH**
FOR TRAINING USE ONLY

FIGURE XIX-2

FIGURE XIX-3

ETS-1 CONTROL POINT OPERATOR
GENERAL INDOCTRINATION COURSE

SECTION XX
ENGINE SYSTEM COMPONENTS

A. INTRODUCTION

The XE-1 engine system is a close-coupled nuclear rocket engine which uses liquid hydrogen for a propellant and is designed for NERVA ground test development. The engine will be tested in ETS-1 which provides for downward firing with altitude simulation. The engine produces a nominal 57,000 pounds of thrust with the reactor operating at a power level of approximately 1128 MW, a chamber temperature of 4090°R, a chamber pressure of 562 psia, a nozzle flow rate of 70 lbs per second, and a total flow rate of 77 lbs per second. The engine has an overall engine specific impulse of 738 seconds. It is 272 inches long, 102 inches in diameter, and weighs 40,000 pounds.

The engine is designed in two separate modules. The lower module contains the reactor and pressure vessel assembly, nozzle, lower thrust structure, external shield, and houses the control drum actuators and lower module instrumentation. The upper module is made up of the Upper Thrust Structure (UTS) which houses the TPA, lines, valves, and the upper module instrumentation.

The upper module can be remotely replaced on the lower module should a major upper module component fail. All fluid lines and electrical wires which pass from the upper module to the lower module go through remote connectors.

A Test Stand Adapter (TSA) provides the necessary transition from the engine to the test stand. This unit houses the remote connectors which are

used to attach the engine to the test stand adapter, the remote line disconnects, and all line and instrumentation cables leading from the facility to the engine. The propellant shutoff valve and supporting instrumentation are also housed in the test stand adapter.

The engine system consisted of the following major subsystems: (1) a propellant feed system including a turbopump assembly, lines and pneumatically actuated valves, (2) a reactor assembly controlled by pneumatically operated control drum actuators, (3) a regeneratively cooled U-tube nozzle, (4) a pressure vessel assembly, (5) an external shield, (6) an upper and lower thrust structure, (7) a pneumatic actuation system, (8) a controls system, and (9) a diagnostic instrumentation system.

The turbopump assembly delivers liquid hydrogen propellant through the pump discharge line to the nozzle manifold inlet. The hydrogen cools the nozzle as it passes through the nozzle tubes and into the reactor. The hydrogen passes through the outer reflector, simulated shield, flow screens, core support plate, core and passes out the nozzle.

A portion of the hot hydrogen from the nozzle passes through the hot bleed port where it is mixed with cooler hydrogen from the pressure vessel dome through the diluent line. The mixed gas then flows through the turbine inlet line to the turbine and on out through the turbine exhaust lines and nozzles.

B. PROPELLANT FEED SYSTEM

The propellant feed system supplies high pressure liquid hydrogen to the nozzle manifold. This system includes the turbopump assembly, pump inlet, pump discharge, turbine inlet and diluent line assemblies, and the associated pneumatically actuated valves. The following is a brief description of the main components of the propellant feed system.

1. Turbopump Assembly (TPA). The TPA includes a single-stage centrifugal pump, a power transmission section which couples the pump and turbine assemblies and is cooled and lubricated by hydrogen, and a two-stage turbine.

Under rated design conditions the pump delivers 77 lbs/sec of liquid hydrogen at approximately 50°R and 932 psi to the nozzle through the pump discharge line. The design flow rate of the turbine at 21,600 rpm is 7.0 lbs/sec of hydrogen at 1140°R and 520 psia.

Although the engine control system provides for overspeed protection of the TPA, a blast shield which surrounds the turbine rotor has been included in the engine system design. The primary purpose of this shield is to protect the emergency cooldown piping system should the TPA inadvertently overspeed and the rotor fails structurally. It is estimated that the TPA will retain its structural integrity up to 30,000 rpm at rated temperature.

2. Pump Inlet Line Assembly. The pump inlet line assembly is made from an 8-inch stainless steel pipe and runs from the facility run tank to the pump inlet. The line increases in diameter in the section that contains the propellant shutoff valve (PSV). This section of line contains the Tank Safety Valve (TSV), the propellant shutoff valve, a flow meter, filter screen, and expansion bellows.

The Tank Safety Valve RSV-132 is located in the propellant supply line just below the run tank. It is a backup for the propellant shutoff valve and provides for shutoff of the propellant supply during inerting, purge and chilldown of the engine system. This is a pneumatically operated butterfly-type valve. In the event of an electrical failure or loss of pneumatic pressure, the valve closes. Should failure occur during engine operation, an automatic shutdown will be initiated due to either turbine overspeed or a rapid change of pressure (dp/dt).

An 8-inch turbine type flow meter and a screen type filter are located in the main propellant feed line downstream of the TSV. The meter is designed for propellant flow rates from 8 to 81 lbs/sec. The filter is made from 0.1-inch stainless steel screen and protects the PSV and TPA from foreign particles in the line.

The PSV is used to initiate and stop the flow of hydrogen to the TPA during engine operation. It is a poppet-type valve equipped with steel springs to provide the closing force and a pneumatic actuator for opening. Should the electrical or pneumatic supplies to this valve fail, an automatic

shutdown would be initiated by either a turbine overspeed or a rapid change of pressure (dp/dt). The pneumatic requirements for the valve are 500 psig helium.

3. Pump Discharge Line Assembly (PDL). The PDL assembly provides a flow path for the hydrogen propellant from the pump discharge port to the nozzle torus. The PDL is made from 5-inch diameter stainless steel tube and contains expansion joints to provide flexibility. The line contains the pump discharge shutoff valve and the pump discharge check valve. The pump discharge shutoff valve is attached to the line segments by bolted flanges and the pump discharge check valve is attached with Marman type joints.

The line and components have the following ratings at 1200 psig and ambient temperatures.

	<u>TPA Outlet to Check Valve</u>	<u>Check Valve to Nozzle Inlet</u>
Proof Pressure, psig	1260	1500
Design Yield Pressure, psig	1500	1800
Design Ultimate Pressure, psig	1800	2100

The line section below the check valve is designed with higher ratings than the section above the valve since this section is part of the emergency cooldown system.

The PDSV is a butterfly-type valve actuated to the closed position with 500 psig helium and opened by spring force. The valve is used to isolate the pump inlet line and TPA from the rest of the engine during pump chilldown. The PDSV is a fail-open valve and remains open during the engine operation, so no corrective action is required as a result of electrical or pneumatic failure to this valve.

The PDKV is a swing-type valve and is located in the pump discharge line upstream of the cooldown supply junction. It is used to prevent back-flow of propellant or cooldown fluid in the pump discharge line.

Provisions are supplied for venting the pump discharge line during TPA chilldown. This vent line is located upstream of the pump discharge valve and contains the pump discharge vent valve.

The PDVV is identical to the PDSV, but fails in the closed position. The valve is used to control flow from the pump discharge line to the facility vent system during chilldown of the TPA. During engine operation the valve is closed, so requires no corrective action as a result of electrical or pneumatic failure.

4. Turbine Inlet and Diluent Line Assemblies. The hot hydrogen to drive the TPA is provided through the diluent and turbine inlet line assemblies.

The diluent line is a 3-inch diameter nickel alloy pipe which carries gaseous hydrogen from the pressure vessel closure to the hot bleed port. The diluent flow is controlled by an orifice and measured by a venturi. Expansion bellows are included in the line to provide flexibility.

The assembly contains a counterflow jacketed elbow section where hydrogen from the diluent line is mixed with hydrogen from the nozzle. This section is cooled by the diluent flow.

The turbine inlet line (TIL) provides a path for the mixed hydrogen gas from the jacketed elbow to the turbine inlet. The TIL is 3.5-inch diameter made of nickel alloy and includes a gimbal bellows to provide flexibility. The Turbine Power Control Valve (TPCV) and the Turbine Block Valve (TBV) are mounted in the turbine inlet line assembly.

The pressure factors applicable to these line assemblies are:

$$\frac{\text{Design Limit Pressure}}{\text{Limit Pressure}} = 1.5$$

$$\frac{\text{Ultimate Pressure}}{\text{Limit Pressure}} = 2$$

$$\frac{\text{Proof Pressure}}{\text{Limit Pressure}} = 1.05 \times \frac{\text{yield stress at test temp}}{\text{yield stress at design temp}}$$

The flow of hot gas to the TPA assembly is controlled by the TPCV. The TPCV is a butterfly-type valve operated by an electro-pneumatic actuator

which provides continuous control from the closed to the open position.

The TPCV actuator consists of an electrically controlled servo amplifier and a pneumatically operated actuator. Should the TPCV fail, the test would be terminated and flow to the TPA would be terminated by closing the TBV. Should a power or pneumatic failure occur, the TPCV will remain in the position at which it is when the failure occurred. Pneumatic requirements are 215 psig of GH_2 . Helium may be used to functionally check out the valve.

The TBV is in series with the TPCV and is used to safely shutdown the engine in the event of a failure of the TPCV. The pneumatic and electrical supplies for the TPCV and TBV are independent. The TBV is identical to the TPCV, except it is driven by a pneumatic actuator. Should the electrical supply to this valve fail, the TBV will close, initiating a system shutdown. Should the pneumatic supply fail, the valve will assume the minimum torque position. Pneumatic requirements are 500 psig of helium. The actuator is positioned either open or closed by three-way solenoid valves.

5. Emergency Cooldown Line Assembly. The emergency cooldown line extends from the test stand adapter to the pump discharge line below the pump discharge check valve. This line provides the flow path for cooldown fluids from the facility to the engine.

The line contains the cooldown shutoff valve (CSV), cooldown check valve (CKV), and expansion joints to provide for flexibility. The interface connections of this line are of the Marman type. The line is made from 5-inch diameter tubing and is designed for service at 1200 psig at an ambient temperature at 540°R . The design safety factors applied to this line are:

Proof Pressure, psig	1500
Design Yield Pressure, psig	1800
Design Ultimate Pressure, psig	2100

The CSV is identical to the PDSV and is used to prevent flow into the engine during chilldown of the cooldown line, and early in the power program. During engine operation, this valve is opened early in the power program and remains open until power is reduced to a low level. The valve fails open,

so requires no corrective action upon failure of the electrical or pneumatic supplies.

The CKV is identical to the PDKV and is located downstream of the CSV to prevent flow of propellant into the cooldown supply line during engine operation.

The line assembly is provided with a vent system which flows into the main facility vent system. The flow of fluids through the vent is controlled by the Cooldown Vent Valve (CVV). The CVV is identical to the PDSV, except that it fails in the closed position. This valve is used during chilldown of the cooldown line. The valve will remain in the closed position during engine operation, except opened as required to maintain a hard chill on the cooldown line. Because the valve is closed during operation, no corrective action is required should a failure occur in the electrical or pneumatic supply.

C. REACTOR

To be supplied by WANL.

D. NOZZLE ASSEMBLY

The nozzle is a convergent-divergent design with a 10:1 expansion ratio. The hydrogen propellant from the pump discharge line enters the nozzle assembly through a torus inlet manifold at the exit end of the nozzle, flows through the tubes to provide regenerative cooling of the nozzle wall, and emerges radially from the forward ends of the tubes into the reflector inlet plenum. The nozzle tubes are formed by brazing stainless steel U-section channels to the stainless steel jacket. A portion of the hydrogen from the inlet manifold is diverted through three exterior tubes to cool the pressure vessel flange and bolts used to fasten the nozzle. A hot-bleed port is located in the convergent section of the nozzle to bleed off gases for the turbine drive.

E. PRESSURE VESSEL ASSEMBLY

The pressure vessel assembly consists of two major components, a cylinder and a closure. These components enclose and support the reactor assembly and form a pressure shell for the hydrogen propellant. In addition,

the pressure vessel assembly transmits thrust and differential pressure loads to the lower thrust structure. The pressure vessel is rated at 890 psig at LH_2 temperature, and 740 psig at ambient temperature.

F. UPPER THRUST STRUCTURE

The upper thrust structure is semi-monocoque, aluminum, cylindrically-shaped structure which attaches to the upper end of the external shield and to the test stand adapter. The structure transmits the thrust and inertia loads as well as moments from the shield to the test stand adapter. The structure also houses and supports the TPA and connecting lines, valves, instrumentation, and electrical harness. The upper thrust structure, the TPA, associated lines, valve, and instrumentation form a remotely replaceable module, which can be removed from the engine system and replaced by a like module in the event of a malfunction of a component within the module. The upper thrust structure is purged with GN_2 during engine operation to prevent an accumulation of GH_2 should a leak develop. It is expected that the temperature within the upper thrust structure will approach liquid nitrogen temperature during certain phases of engine operation. All components located within the upper thrust structure envelope are either designed to operate at liquid nitrogen temperatures, or are being protected so that they will not exceed their design temperatures.

G. EXTERNAL SHIELD ASSEMBLY

This shield provides sufficient attenuation of radiation from the reactor to enable non-radiation hardened components to be mounted within the UTS without jeopardy to engine system testing.

The shield is 102 inches in diameter and 17.5 inches thick. It is made of aluminum and contains $\frac{1}{2}$ inch diameter stainless steel balls and borated water. The total weight is approximately 20,000 lbs, 14,500 lbs of which are balls and water. There are three horizontal sections of which the one nearest the reactor contains only borated water and the other two contain steel balls and borated water. The balls and water can be removed to simplify handling problems and to reduce residual radiation levels after a test. The shield contains longitudinal penetrations for propellant lines, control drum actuator shafts, and tubes and electrical wiring.

The water in the shield is protected from freezing by a layer of insulation located on the upper side. The pressure transducers mounted on the upper side of the shield are heat sunk to the shield and covered with insulation to prevent damaging the transducers should the temperature in the upper thrust structure reach liquid nitrogen temperatures.

H. LOWER THRUST STRUCTURE

The lower thrust structure is a conically shaped, semi-monocoque titanium structure which attaches to the upper end of the pressure vessel and to the external shield. The structure transmits the thrust, inertia loads, and moments from the pressure vessel to the external shield. The structure also provides accessibility to the engine components and instrumentation located within its envelope.

I. PNEUMATIC SYSTEM

This system provides the pneumatic actuation gases to operate the control drum actuators, engine valve actuators and the remote assembly drive motors.

This system consists of four subsystems:

1. A 500 psi He system which operates the CSV (cooldown shutoff valve), PDSV (pump discharge shutoff valve), PSV (propellant shutoff valve), CVV (cooldown vent valve), PDVV (pump discharge vent valve), and TBV (turbine block valve).
2. A GH_2 system at 225 psia which operates the control drum actuators.
3. A 225 psia GH_2 system which operates the TPCV (turbine power control valve).
4. A GN_2 system which provides the drive gases for the remote assembly actuators of the TSA (test stand adapter).

The TPCV and control drum actuator supplies are tied into a 225 psia He supply. This He system will be used during checkouts and low power physics experiments when the engine test compartment is not sealed.

The pneumatic system contains bellows to provide the necessary flexibility of On-Mark connectors at the engine interface, and 10 filters to prevent foreign particles from entering the individual actuators.

For corrective action required in the event any of the pneumatic supplies fails, refer to the individual components operated by the various supplies.

J. TEST STAND ADAPTER

The Test Stand Adapter (TSA) provides the necessary transition from the engine to the test stand. All lines and electrical connections between the engine and facility pass through this structure.

The TSA is a truncated cone 42.89 inches long. It is 105 inches in diameter at the interface with the UTS, and 165 inches in diameter at the interface with the test stand. The interface with the UTS is provided with remotely actuated structural connections, (1) remotely actuated Marman couplings on the propellant feed line, the cooldown supply line, and the TPA discharge and cooldown vent line, (2) On-Mark quick disconnects in the engine and TPA purge line, the shield water fill and vent lines, the helium pneumatic supply and vent lines, and the helium pneumatic supply, and (3) Amphenol plugs to make and break connections for the instrumentation and control wiring.

Twelve 5/8-inch diameter structural bolts equally spaced on the periphery of the TSA mate with captive nuts on the UTS. Pneumatic torque motors drive the bolts to assemble and disassemble the UTS from the TSA structure. A secondary method of disassembly is provided, if necessary, by releasing the captive nuts with the Engine Installation Vehicle (EIV) remote manipulator.

Three Marman couplings, each actuated by two pneumatically driven jack screws, provide for joining of the 8-inch diameter propellant feed line and the 5-inch diameter cooldown supply line, and the 5-inch diameter TPA discharge and cooldown vent line. Secondary disassembly of these joints is provided by the fact that one jack screw will disengage the couplings, and the jack screws may be turned using the EIV remote manipulator.

Six On-Mark quick disconnect couplings are used to make and break the remainder of the fluid lines in the system.

Amphenol electrical connectors are used to complete the electrical connections for control and instrumentation through the TSA/UTS remote interface.

K. INSTRUMENTATION AND ELECTRICAL WIRING

The engine system has provisions for mounting transducers for measuring temperatures, pressure, vibrations, and flow. The outputs from these transducers are used for both control and diagnostic purposes.

The electrical wires which transmit instrumentation and control signals to and from the transducers and actuators are contained in a harness in the UTS and TSA. All critical signals leading to or from the engine are redundant. The redundancy is provided by either redundant wires or redundant components. All engine RSV's have a 2-conductor shielded cable through the engine for each solenoid operated pilot valve carrying the control signals.

The control drum actuators and TPCV actuator have two torque motors located on the actuators and can operate on only one of these torque motors. In these cases, each individual component has separate wires running from the component to the facility.

L. ACTUATION GAS SYSTEM

The actuation gas system to be used at ETS-1 during the XE test series consists of four separate supplies to operate the engine valves and control drum actuators and for operating the remote Marman and structural connectors as shown in Figure XXI-12. The TPCV is operated from a 225 psig GH_2 supply, the control drum actuators are operated from a separate 225 psig GH_2 supply, and the six on-off engine valves are operated from a 500 psig helium supply. The structural connectors and the remote Marman clamp actuators located in the TSA are operated from a 90 psig GN_2 supply. Each of these supplies originates at the facility gas storage tanks, is filtered, and reduced in pressure prior to entering the engine.

1. Control Drum Actuator Pneumatic Supply. The control drum actuators can be operated from either a 225 psig He or GH_2 pneumatic supply. The He supply will be used during system checkouts and low power physics tests. The GH_2 supply will be used during the power tests.

Both of these supplies enter the engine through a common line which contains a double block and bleed system to prevent inadvertent pressurization of this system during non-operating period. All three valves in the

block and bleed system are equipped with key locks to prevent inadvertent pressurization of this system during non-operation periods.

The main control valves in the system which are used during power operation, 5ORSV 868, 880, 877, fail in the open position so that pneumatic pressure to control drums can be maintained in the event of loss of electrical power or actuator power during a test. Valve 50 RSV 868 fails closed to prevent He from entering the system should electrical power or actuator pressure be lost during a test.

Each of the systems pressure is reduced from the 2500 psig facility supply pressure to operating pressure by pressure regulating valves. The lines and systems downstream of the pressure regulator valves are protected from over-pressurization by a relief system.

The gas entering the control drum actuators passes through a cryogenic trap where it is filtered through a 20 μ filter. It is then further filtered through 10 μ filters prior to entering the actuator.

In the event of a failure of the pneumatic supply system, an emergency shutdown will be initiated. The control drums will roll in and shut down the reactor. For a description of the sequence of events during a scram shutdown, refer to the section on engine controls.

The opening and closing times of all of these valves are unimportant to engine operation in as much as they are opened prior to startup, and remain in that position during the entire run.

2. TPCV Pneumatic Supply. The pneumatic supply system for the TPCV is identical to the control drum actuator supply up to the point where the line branches. From this point to the engine, the line contains one hand operated valve 50 GLV 2337 which will be locked opened during operation, and two filters, 5 μ and 10 μ .

3. Engine Valve Pneumatic Supply. The six on-off valves in the primary engine piping system are operated from a 500 psig helium supply. These valves are the PSV (propellant shutoff valve), PDSV (pump discharge shutoff valve), CSV (cooldown shutoff valve), PDVV (pump discharge vent valve), CVV (cooldown vent valve), and TBV (turbine block valve). This supply originates from the high pressure facility storage tanks. The pressure to the

valves is reduced to 500 psia by 50 PRV 485. A relief valve 50 RV 2211 is in the system downstream of 50 PRV 485 to protect this portion of the system from over-pressurization in the event of a failure of the pressure regulator.

Valve 50 RSV 702, the primary control valve to initiate flow, fails in the open position to prevent the loss of helium flow, in the event the valve or power supply fails during the test period.

Although precautions have been taken to prevent a loss of actuation pressure during a test run, the following would occur should the system fail:

a. PSV. Failure of the pneumatic supply would cause a loss-of-flow shutdown. For sequence of events during shutdown period, refer to the controls section.

b. PDSV and CSV. Both of these valves fail in the open position, which is the normal operating position. They are not used during the run, so no immediate corrective action is required.

c. TBV. This valve fails in the closed position and will initiate a scram shutdown should an electrical failure occur.

d. PDVV and CVV. Both of these valves fail in the closed position, the normal operating position, and no immediate action is required should the electrical or pneumatic supplies fail.

4. Remote Marman and Structural Connector Pneumatic Supply. As with the other pneumatic supplies, the GN_2 supply for the remote Marman and structural connector actuators originates at the high pressure facility gas storage tanks. The supply is reduced from 2500 psig to 500 psig through pressure reducing valve 50 PRV 416. The supply then divides. One branch supplies the pilots to solenoid valves 801 thru 815. The pressure in this branch is controlled to 85 psi by 50 PRV XXX. The other branch flows through solenoid valves 801 thru 815 and to the actuator. The pressure in this branch is controlled from 85 to 10 psi by 50 PRV 405 so that a variable torque may be applied to the actuators.

LIST OF FIGURES

<u>FIGURE</u>	<u>TITLE</u>
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XX-8	Turbopump Assembly (TPA)
XX-9	Pump Discharge Shutoff Valve (PDSV)
XX-10	Pump Discharge Check Valve (PDKV)
XX-11	Turbine Power Control Valve (TPCV)
XX-12	XE Pneumatic Control System Flow Diagram

XX-17

FIGURE XX-3

NERVA
TRAINING

LOWER THRUST STRUCTURE
FOR TRAINING USE ONLY

FIGURE XX-3

XX-19

FIGURE XX-5

PRESSURE VESSEL CLOSURE
FOR TRAINING USE ONLY

FIGURE XX-5

TURBINE POWER
CONTROL VALVE (TPCV)
FOR TRAINING USE ONLY
XX-25

FIGURE XX-11

ETS-1 CONTROL POINT OPERATOR
GENERAL INDOCTRINATION COURSE

SECTION XXI
ENGINE OPERATING CONDITIONS

A. INTRODUCTION AND SUMMARY

The ultimate objective of the NERVA program is a flight vehicle powered by a nuclear rocket engine; consequently the relationships between the performance characteristics of that flight vehicle and the nuclear rocket engine that we are learning how to build is a matter of interest and importance. Understanding of the performance of the nuclear rocket engine begins with the overall system of which the engine is a part. As such, this discussion is intended first to identify specifically the important vehicle performance parameters, then to identify the specific engine performance parameters in such a way that the two sets of parameters may be meaningfully related. A more detailed examination of the engine performance parameters and the relationships among them also is of interest. Finally, the basic philosophy with which these performance characteristics are evaluated and the means by which the associated evaluations are used to permit improved understanding of the engine performance is mentioned as a conclusion.

B. ENGINE PERFORMANCE CHARACTERISTICS

1. Vehicle Performance

Although the performance of the engine system is of primary importance in connection with ground testing operations and is the

primary subject treated in this discussion, it is of interest to consider briefly the relationship between the engine performance and the flight vehicle performance of which the nuclear engine system is to be a part.

From a general point of view there are two primary vehicle performance parameters. These two parameters are thrust and specific impulse and they are quite independent. Although these two parameters are of vital interest in connection with vehicle performance, consequently, are of great significance in connection with mission analyses; the two parameters are not specifically meaningful in connection with the ground testing of the engine system itself. It is important, however, to be able to relate the performance characteristics of the engine to those of the vehicle; consequently, it is important to examine the engine performance characteristics that are directly and indirectly related to these vehicle performance parameters, thrust and specific impulse.

By way of definition, thrust is simply the force acting upon the vehicle by virtue of the flow of propellant through the peculiarly shaped device called the nozzle. Specific impulse is the ratio of that thrust to the mass flow rate of propellant expanding through that nozzle. In simplest terms - neglecting back pressure and employing several simplifying assumptions - thrust can be accounted for by summing a momentum term and a pressure-area term and these terms may be related to the engine parameters with the equation:

$$F = \dot{m}v_e + p_e A_e$$

where F = thrust

$\dot{m}$ = mass flow rate

v_e = gas velocity at the nozzle exit plane

p_e = static pressure at the nozzle exit plane

A_e = flow area at the nozzle exit plane

Note that the dimensions of each term are force so a consistent set of units is implied.

As mentioned specific impulse is the ratio of thrust to the mass flow rate of propellant expanding through the nozzle.

$$I_{sp} = \frac{F}{\dot{m}} = v_e + \frac{p_e A_e}{\dot{m}}$$

Specific impulse may be regarded as a kind of efficiency term or a measure of the propulsion effectiveness of the propellant flow. Note that to a first approximation, by neglecting the pressure-area term which is normally small compared to the momentum term, I_{sp} is proportional to the exit gas velocity.

More interesting relationships between thrust and specific impulse and the engine performance parameters will be discussed in more detail below.

2. Engine Performance

a. Definition of Engine System

A schematic diagram of the familiar hot bleed cycle nuclear rocket engine is shown in Figure XXI-1. Note that the engine system includes a run tank, propellant pump and drive turbine (combined on a single rotating shaft and called the turbopump assembly) reactor

heat source, and the thrust producing nozzle. Schematically the flight configuration engine is identical with the ground test version. Some differences between these two systems do exist and it is important to keep these differences in mind.

The system as shown appears to be self-contained. In reality it isn't quite, because some means must be incorporated for control. Control can be effected in many ways but current plans involve two primary control functions, and a third which has some important operative implications but which has relatively minor influences on engine performance near the design point.

The control of the heat generation rate of the reactor is effected by the angular position of the reactivity controlling drums. Secondly, propellant flow rate is independently controlled by the position of the turbine power control valve which governs the flow of hot gas to the turbine. The third performance detail which is susceptible to outside influence is basically the pressure in the run tank.

Some complications must be introduced at this point because tank pressure alone is not sufficient to specify completely the inlet propellant conditions. Unless the propellant (liquid hydrogen is the only propellant under consideration in this discussion) is in a saturated condition, its temperature also is susceptible to external influence. It may be of interest that present requirements do not specify saturated liquid hydrogen as the propellant feed for nuclear rocket mission applications; consequently, two run tank parameters are necessary to specify the inlet propellant conditions. Except for startup the range of influence on the overall system performance that is possible through

adjustments of run tank conditions generally is very small indeed compared to the other two control functions.

b. Vehicle and Engine Performance Relationships

As indicated above, the performance of the engine system is governed primarily by two parameters. It is presumed that the run tank temperature and pressure are fixed. The inclusion of sensing devices and control units permits the turbine power control valve position and control drum position to be set in a manner specified by the controllers. As a result, the independent variables that actually govern the engine performance can be selected at will and the performance can be controlled by programming two independent performance parameters. The selection of which two is virtually arbitrary, but it should be emphasized that the performance of the entire system is fixed or controlled when any two variables are specified because the TPCV and the control drum positions represent two degrees of freedom. In addition, and as indicated above, a third condition, for example, propellant inlet enthalpy as a function of run tank temperature and pressure also is required. As pointed out above, the influence on overall engine performance by changes in run tank temperature or pressures over practical ranges is slight. The influence is not so slight when the run tank conditions exceed the "practical" ranges however; one may recall the Phoebus IA performance as a case in point.

The number of significant variables that govern engine performance is seen to be two. It will be recalled that vehicle performance also is governed by two significant parameters and it would be useful indeed if the engine performance parameters can be related to the vehicle

performance parameters. The interesting phenomenon of choked flow through the nozzle throat is a basis for a very convenient relationship between these two sets of parameters.

It will now be shown that thrust can be related to the single engine performance parameter, chamber pressure, and the system geometry and specific impulse can be related to the single engine performance parameter, chamber temperature. The latter statement is made with some slight reservation which is developed in detail below.

Mass Flow Rate

First consider the total mass flow rate through the nozzle throat, remembering that the Mach number at the throat is unity. One dimensional, isentropic flow of an ideal gas is presumed for all the following derivations, but the difference between the real system and the ideal one which lends itself to a simple analysis will be shown to be quite small.

The continuity relationship at any cross section of the flow area gives:

$$m = \rho v A$$

$$\text{where } \rho = \text{density}$$

$$v = \text{velocity}$$

$$A = \text{cross sectional flow area}$$

At the throat, the velocity is sonic which, for a perfect gas, may be expressed:

$$v_* = a = \sqrt{\frac{kRT_*}{m}}$$

The so called Mach relationships permit conversion of this flow rate equation to an expression involving the chamber conditions as follows:

$$\frac{T_o}{T} = 1 + \frac{k-1}{2} M^2$$

$$\text{and } \frac{p_o}{p} = \left(1 + \frac{k-1}{2} M^2\right)^{\frac{k}{k-1}}$$

where M = Mach number

and the subscript $_o$ implies total or stagnation conditions.

At the nozzle throat

$$M = 1.0$$

$$T = T_*$$

$$p = p_*$$

and since the chamber conditions are the total and stagnation conditions

$$T_o = T_c$$

$$\text{and } p_o = p_c$$

where the subscript $_c$ refers to chamber

Substitution gives

$$\frac{T_c}{T_*} = 1 + \frac{k-1}{2}$$

$$\text{and } \frac{p_c}{p_*} = \left(1 + \frac{k-1}{2}\right)^{\frac{k}{k-1}}$$

where:

a = velocity of sound

k = ratio of specific heats

R = universal gas constant

T = static temperature

m = molecular weight of the flowing gas

The subscript $*$ implies the nozzle throat or any station at which the flow is choked.

The density of the flowing gas at the throat is readily obtained from the ideal gas law.

$$p \nu = RT$$

where p = static pressure

ν = specific volume

thus

$$\rho = \frac{m}{\nu} = \frac{pm}{RT}$$

Substituting

$$m = A_* \sqrt{\frac{k m}{R}} \cdot \sqrt{\frac{p_*}{T_*}}$$

This equation has the familiar form of the choked flow equation except that the pressure and temperature are the static conditions of the flowing gas at the throat. It is usually more convenient to relate mass flow rate to the total temperature and stagnation pressure which are precisely the chamber conditions.

and substituting these relationships in the flow rate equations gives

$$m = A_* \sqrt{\frac{k \mathcal{M}}{R}} \frac{p_c}{\left(1 + \frac{k-1}{2}\right)^{\frac{k}{k-1}}} \cdot \sqrt{\frac{1 + \frac{k-1}{2}}{T_c}}$$

or after algebraic simplification

$$m = A_* \sqrt{\frac{k \mathcal{M}}{R} \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \cdot \sqrt{\frac{p_c}{T_c}}$$

which is the familiar form of the choked flow equation. Note that the first term on the right is the throat area, consequently it depends only on the nozzle geometry, the second term is a function only of the physical and thermal properties of the flowing gas, and the third term is a function only of the chamber conditions (temperature and pressure). Mass flow rate then is in no way dependent on downstream conditions - a very important and useful fact.

Thrust

Now with a convenient expression for mass flow rate in terms of the chamber conditions, it is a simple exercise to relate thrust to the chamber condition, but several interesting details become apparent. As above

$$F = m v_e + (p_e - p_a) A_e$$

The exit velocity, v_e , is easily related to the exit Mach number

$$v_e = M_e a_e$$

but

$$a_e = \sqrt{\frac{kRT_e}{m}}$$

where

a_e = velocity of sound at the nozzle exit plane.

Substituting in the thrust equation

$$F = A_* \sqrt{\frac{k m}{R} \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \cdot \frac{p_c}{\sqrt{T_c}} \cdot M_e \sqrt{\frac{k R T_e}{m}} + (p_e - p_a) A_e$$

Rearranging and introducing factors equivalent to unity wherever convenient

$$F = A_* \sqrt{k^2 \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \cdot M_e p_c \sqrt{\frac{T_e}{T_c}} + \left(\frac{p_e}{p_c} p_c - p_a\right) A_e$$

Substituting the Mach relationships

$$F = A_* \sqrt{k^2 \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \frac{M_e p_c}{\sqrt{1 + \frac{k-1}{2} M_e^2}} + \left[\left(1 + \frac{k-1}{2} M_e^2\right)^{-\frac{k}{k-1}} p_c - p_a \right] A_e$$

Although a transcendental relationship is implied note that the exit Mach number, M_e , is expressible as a function of the gas properties and the nozzle geometry, A_e and A_* ; consequently, thrust is seen to be a function of nozzle geometry, gas properties, chamber pressure and back pressure, although the latter is generally not a large term and in space its

magnitude is zero. Of primary significance is the fact that thrust is quite independent of chamber temperature.

Specific Impulse

As above specific impulse is given by

$$I_{sp} = \frac{F}{\dot{m}}$$

Dividing the thrust equation by the expression for mass flow rate gives

$$I_{sp} = \frac{A_* \left[\frac{k^2 \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}}{1 + \frac{k-1}{2} M_e^2} \cdot M_e p_c + \left[p_c \left(1 + \frac{k-1}{2} M_e^2 \right)^{-\frac{k}{k-1}} - p_a \right] A_e \right]}{A_* \sqrt{\frac{k \dot{m}}{R} \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}} \cdot \sqrt{\frac{p_c}{T_c}}}$$

and upon simplification

$$I_{sp} = \left\{ M_e \left[\frac{kR}{\dot{m} \left(1 + \frac{k-1}{2} M_e^2 \right)} + \left[\left(1 + \frac{k-1}{2} M_e^2 \right)^{-\frac{k}{k-1}} - \frac{p_a}{p_c} \right] \frac{\frac{A_e}{A_*}}{\sqrt{\frac{k \dot{m}}{R} \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}}} \right] \right\} \sqrt{T_c}$$

It is seen that except for the ratio term $\frac{p_a}{p_c}$ which vanishes as the back pressure goes to zero, specific impulse is a function only of chamber temperature. Chamber pressure, for most practical purposes, has been eliminated.

For a given system then, these two equations show the significant relationships that:

- (1) Thrust and Chamber Pressure are uniquely related and for a given back pressure:
- (2) Specific Impulse and Chamber Temperature are uniquely related.

c. Engine Operating Map

1. Nozzle Performance

The recognition that two, and only two, engine performance parameters are needed to specify the performance characteristics of the entire engine and the convenient relationships between chamber pressure and thrust, and chamber temperature and specific impulse, imply that a plot of one of these variables against the other will permit graphical representation of the steady state operation of the entire engine system. Such plots have been made and used extensively on this and other rocket programs. We call them engine operating maps.

Figure XXI-2 is an example of the engine operating map for the XE-1 engine. Note that the map shows chamber temperature in degrees Rankine plotted against chamber pressure in pounds per square inch absolute. Flow rate through the nozzle throat is a unique function of chamber temperature and chamber pressure. The relationship implied by the map develops from the interesting characteristic of choked flow and is associated with the fact that the velocity of gas in the plane of the nozzle throat is at its local sonic velocity which is a function of the local static temperature. Flow rate is given by the following equation which was seen to be related to the chamber temperature, chamber pressure, the flow area and the properties of the flowing gases as derived above.

$$m = C_n A_* \sqrt{\frac{k}{R} \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}} \cdot \frac{p_c}{T_c}}$$

C_n , the nozzle coefficient, has been introduced to account empirically for the difference between the real gas flow and the isentropic,

one dimensional flow of an ideal gas used in the derivation above. The value for C_n as determined from Sacramento Test Area experiments and confirmed by data from some of the NRX-A3 tests is .983 using a throat area equal to the area of the inscribed circle tangent to the coolant tube crowns.

This equation implies that unique lines of constant flow rate can be plotted on the engine operating map. Figure XXI-2 shows a family of such lines.

The propellant fluid flows into the system at some very low enthalpy condition. Thermal energy is added by the reactor and the propellant gas is discharged by the system at a very high enthalpy. The difference between these two unit enthalpys multiplied by the mass flow rate of gas is a measure of the power required by the system and supplied by the reactor. But chamber temperature and chamber pressure imply the unit enthalpy; inlet enthalpy is implied by the temperature and pressure conditions in the run tank as mentioned above. The difference, multiplied by the flow rate which as seen above is a function only of chamber temperature and chamber pressure gives power.

$$Q = (h_{out} - h_{in}) m$$

where:

Q = thermal power

h_{out} = unit enthalpy of exit gas

h_{in} = unit enthalpy of inlet fluid

Lines of constant power also can be plotted on the engine operating map as shown in Figure XXI-2. Note that these lines of constant power imply a particular inlet enthalpy; consequently the lines are subject to some adjustment if run tank conditions are varied. That adjustment is very small when the values of chamber temperature and chamber pressure are near the normal operating point but the adjustments become significant in the range of the map near the origin.

In summary, then the relationship among these four variables chamber temperature, chamber pressure, power, and flow rate is specified by the nozzle configuration alone and is independent of the performance of the remainder of the engine system as such. When the assumption that the chamber is truly a plenum is made, that is that there are no temperature or pressure gradients within the nozzle thrust chamber, the operating map depicts the operating characteristics of the nozzle at all times. Thus, a point on the operating map represents the chamber temperature, chamber pressure, power and flow rate at any instant in time. It is not restricted to steady state conditions.

2. Engine Performance

It was pointed out above that the entire engine operation was constrained by two parameters. Therefore any point on the operating map implies steady state values of all temperatures, pressures and flow rates everywhere in the engine system, control drum positions, valve positions, turbopump shaft speeds, etc. Elaborate computer programs are available to calculate values of these parameters for all arbitrary combinations of chamber temperature and chamber pressure. Figure XXI-3 shows some of these additional engine performance parameters and the meaning or implication of some of them are herein presented.

By way of introduction, the analysis procedures which permit calculation of these performance parameters are very complicated and the use of high speed computing techniques is essential. The computer requires as input a detailed description of the system geometry, for example, flow channel diameters and lengths, solid material dimensions, etc., material thermal properties, turbopump and valve characteristics, heat transfer and fluid pressure drop relationships, heat generation rate distributions, etc. With such input information and, for example, the chamber temperature and chamber pressure profiles, all system characteristics are calculated.

Figure XXI-3 shows the limits of many of these operating characteristics which are expressed as operating constraints. Note that steady state is implied for all of them except chamber temperature, chamber pressure, power and flow rate. The map shows a characteristic figure bounded by various operating conditions that represent various limits. The figure implies that operation within the bounds established will permit satisfactory, stable operation at steady state. It does not imply that transient operation beyond these limits is unacceptable.

The curved lines to the left imply the limit imposed by the highest allowable temperature of a structure within the reactor. The dashed line implies a maximum structure temperature that is satisfactory under all conditions and the solid line a short distance to the left implies a higher structure temperature that is limiting. An operating point to the left of the solid structural limit line would imply steady state operation with the internal structure overheated. It must be emphasized that a

transient spike crossing the line and returning to the safe operating range is not necessarily detrimental.

In the same vicinity as the structural limit line is a region called the pump stall region. An operating point in that vicinity implies temperature, pressure and flow rate conditions in which the pump will be stalled. Note that the pump mechanics will not permit a single line to represent the boundary between a stalled and an unstalled condition.

The upper horizontal line is an arbitrary chamber temperature limit. In reality, nozzle coolant tube wall temperature is a truly limiting parameter. A slightly curved line representing that limiting wall temperature value is shown above the straight horizontal line. The straight line is, of course, a test limit determined from the wall temperature limit at the maximum allowable chamber pressure but no structural damage is implied by operation above the line provided the wall temperature limit is not exceeded.

The nearly vertical lines on the right represent several performance limitations. The line on the left represents the most severe limitation to engine operation as seen for this particular system. That limit is the core pressure drop. On previous tests the limiting condition has been pressure vessel internal pressure and for those systems the vertical pressure vessel limiting pressure line would have been found to the left of the core pressure differential line. Other characteristics are noted out since they are outside the closed operating figure they simply imply that other parameters produce more restrictive operating conditions. The nearly straight diagonal line at the lower right represents operating

conditions for the turbine power control valve in the fully open condition or more precisely 80° open. Steady state operation appreciably to the right of that line is, of course, impossible without hardware modifications to the system.

The feedback reactivity lines imply a hydrogen density distribution within the core such that a fixed and noted reactivity must be controlled by the control drums. The reactivity associated with this hydrogen is commonly called the feedback reactivity. It does not imply that the reactor is prompt critical when the system operating point is below and to the right of the one dollar feedback reactivity line. It only implies that this reactivity is inserted by a high flow rate of hydrogen through the core and the equivalent reactivity must be removed by some other means, for example rotating the control drums inward, to compensate.

The remaining two straight lines represent controller limitations for the XE system.

Finally, an additional line called the operating line is seen to extend from a point near the origin to the small triangle which represents the normal, full power design, operating condition. The line represents the basis for the controller designs that permit automatic start up from the ambient conditions, zero power point in the lower left region to the full power operating point at the upper right. Operation along other lines within the closed figure is quite permissible; indeed much deliberate operation off the so called "operating line" was conducted during the NRX/EST test series and similar operation is anticipated during the XE series.

3. Comparison of Flight and Ground Test Configurations

To complete this discussion of engine operating conditions it will be of interest to examine and compare the differences and similarities between the performance of an engine test vehicle on the ground and the performance of an engine in space. There are three significant differences in the environments to which the engine test and the flight engine are exposed. Probably the most important of the three is back pressure. By back pressure is meant the ambient pressure into which the flowing propellant gas is ejected. In space, of course, this back pressure is zero and at Jackass Flats the back pressure would be approximately $12\frac{1}{2}$ lbs per square inch absolute were it not for the combined performance of the engine test compartment and the duct which produces a partial simulation of a more realistic back pressure.

It has been shown that the flow characteristics upstream of the nozzle throat are independent of downstream conditions; consequently they are independent of the back pressure. Conditions can be quite different in the divergent section of the nozzle for varying back pressures and an examination of some of these differences will be useful.

As the propellant gas flows from the nozzle throat, ideally it expands supersonically thus increasing in velocity and thereby maximizing the momentum change which produces thrust. The static pressure of the gas diminishes as the velocity increases and indeed can diminish below the ambient back pressure at the exit plane. Under certain circumstances when this exit static pressure is less than the back pressure the expanding gas will be found to break away from one portion of the exit cone and ambient gas will flow subsonically into the void. This asymmetrical flow condition exists for these XE and NRX type nozzles until the chamber pressure is

approximately 370 psia. Above that chamber pressure the flow is sufficient to eject the flow symmetrically and the nozzle is said to "flow full". It will be seen that the assumption of one dimensional flow is grossly unrealistic when the nozzle is not flowing full; consequently the thrust and specific impulse equations derived previously are not valid. It must be emphasized however, that the conditions upstream of the throat are unaffected by these downstream conditions. It will also be observed that as back pressure is diminished the chamber pressure at which the nozzle flows full is reduced until at zero back pressure flow separation is impossible and the nozzle will always flow full.

The associated flow asymmetrically is not geometrically stable. The separated region normally travels around the nozzle at a low velocity with the result that at low chamber pressure the plume often appears to whip back and forth. The resulting asymmetric loads create some problems in the design of these nozzles but to date the designs have been adequate to accommodate the associated asymmetrical loadings and vibrations and no performance problems have been encountered. Again it is emphasized that the conditions upstream of the throat are quite the same whether or not the nozzle flows full; consequently, for ground testing of the engine system, except for the nozzle itself, the importance of back pressure is not great.

From another point of view however, back pressure is of great importance. The turbine drive gas must discharge into the same ambient condition as the nozzle. The turbine performance is very sensitive to the pressure ratio between the first turbine inlet stage and the turbine outlet until the turbine flow chokes. The inlet pressure can be grossly

approximated by chamber pressure and the outlet pressure by the back pressure, therefore choking of the turbine will occur when the chamber pressure is roughly twice the back pressure. The bootstrap startup characteristic of the engine system is very sensitive to turbine performance and since the initial portion of the bootstrap occurs at low chamber pressure, the start up performance of the engine system is extremely sensitive to back pressure. As a result, considerable effort is devoted to altitude simulation which is another way of saying realistic back pressure simulation.

Gravity

The effect of gravity on the engine system performance is another difference which occurs when the engine system is tested on the ground and when it is used for space flight. Gravity will have an influence on engine performance only when a free surface exists. Except for short duration situations generally but not always of minor importance during start up, the propellant free surface exists only in the run tank. When run tank NPSP is low, however, the possibility for the formation of cavitation within the pump impeller exists with related influence on pump performance. Much study of these related influences has occurred recently in connection with the so called zero NPSP pump but a review of these considerations is quite beyond the scope of this discussion. Under normal circumstances the effects of gravity are eliminated from the consideration of the performance of the engine system by preventing the existence of a free surface in the propellant.

Ambient Conditions

The third significant difference between the ground test vehicle and the flight model is associated with the environmental conditions to

which the system is exposed. Aside from the heat transfer which is considerably different when the pressure vessel and nozzle, pump and lines are exposed to air or nitrogen at ambient temperature or to the vacuum of space, the primary performance differences in the two cases stems from the condensation of that air or nitrogen and the associated liquid air or liquid nitrogen rain which can influence instrumentation performance significantly.

In addition the influence of the hard vacuum of a space environment results in many subtle and some not so subtle effects on material performance that are frequently outside or beyond our experience in ground testing.

Although these differences do exist, the similarities between the performances of an engine system on the ground and in space are overwhelming. The interior heat generation rates, fluid and material, temperatures, fluid pressure and flow rates are not significantly influenced. Since these are the major performance characteristics which are of consequence, ground testing permits confirmation of most of the information required for the design and fabrication of the flight vehicle.

C. TEST DIAGNOSTICS

In conclusion, it might be of interest to note that evaluation of engine system performance is anticipated during the series of ground test in a location called the Test Diagnostic Center. The important engine variables are displayed on a console in the Test Diagnostic Center and they are examined by senior, and thoroughly experienced, source engineering personnel during the course of the engine testing. Of particular use in this connection is an X-Y plotter, one axis of which is driven by a chamber

temperature signal and the other axis of which is driven by a chamber pressure signal. The result is an actual operating line drawn on the most up-to-date engine operating map available. Since lines of constant flow rate and lines of constant power are pre-computed and traced on the engine operating map the location of the pen at any instant provides a calculated value of nozzle flow rate and thermal power. All four of these parameters are independently measured or computed from measurement signals and since any two are redundant the use of this plotting technique permits great confidence in the power calibration of the system when the measured and the plotted values agree. This information is available to the Test Director and the operating crew during the runs if they wish and it is of particular interest to the source engineering groups which provide the staff for the Test Diagnostic Team.

FIGURE XXI-2

ETS-1 CONTROL POINT OPERATOR
GENERAL INDOCTRINATION COURSE

SECTION XXII
ETS-1 RE-ENTRY PROCEDURES

A. PURPOSE

No job is so important that action cannot be taken to perform it safely. Re-entries must be conducted with care, taking into consideration the potential hazards of cryogenic fluids, high pressure systems, and nuclear radiation exposure. Specific and detailed standard operating procedures are to be adhered to in order to insure the safety of a re-entry team.

B. SUPPLEMENTARY MATERIAL

Two NTO documents are included as supplementary material to Section XXII of the ETS-1 Control Point Operator General Indoctrination Course.

1. NTO Standard Operating Procedure for ETS-1 Test Re-entries, NTO-SOP-0094.
2. Radiation Exposure Standards, NTO-A-0022, section VII-3-1.

ETS-1 CONTROL POINT OPERATOR
GENERAL INDOCTRINATION COURSE

SECTION XXIII
ETS-1 SAFETY SYSTEM

A. INTRODUCTION

The purpose of the ETS-1 safety system is to preserve the health and safety of NERVA Test Operations personnel working at the facility. An adequate safety program begins with proper design and construction of the facility. To implement the safety program specialized warning devices and safety equipment are provided. In addition, safety procedures are established for both the normal environment and for unusual and hazardous conditions. But the success of the safety program depends upon each individual being well informed and taking the appropriate action in the case of an emergency.

B. SUPPLEMENTARY MATERIAL

The basic areas of the ETS-1 safety system are described and discussed in Section XI of the ETS-1 Instrumentation and Controls Introductory Course. This section follows as supplementary training material to the ETS-1 Control Point General Indoctrination Course.

ETS-1 INSTRUMENTATION AND CONTROLS
INTRODUCTORY COURSE

SECTION XI
SAFETY SYSTEMS

A. INTRODUCTION

The Safety Systems provide for the protection of personnel and facilities during facility activation, test operations, and shutdown periods. These systems have been integrated into a single control unit located in the control room, the Lead Safety Engineer console, Figures XI-1, -2, -3.

B. GENERAL DESCRIPTION

An outline of the salient features of each of the Safety Systems follows:

1. Area Surveillance and Warning System. The system consists of strategically located klaxons, sirens, area beacons, tunnel door lights, door closure lights, site traffic lights, and emergency switches. The system is designed to help monitor and guide the movement of personnel throughout the ETS-1 complex.

Safety system detectors, analyzers, pressure indicator switches, door microswitches, and emergency switches actuate components of the ASWS according to the Alarm Logic Chart, Table XI-1. Where the ASWS receives several alarm conditions simultaneously, the more conservative logic will be presented.

The capability to manually operate all warning lights in either the green, amber, or red mode is being installed.

2. Radiation Monitoring System. The Radiation Monitoring System consists of 15 gamma detectors, 2 neutron detectors, and 3 airborne particulate/gas detectors located in appropriate areas at ETS-1. This system serves to define the radiation environment at ETS-1 for personnel safety purposes. Portable detectors are also available. Detector meters and calibration capabilities exist on the LSE console.

The gamma detectors are ionization chamber types with built-in strontium-90 check sources. The gamma detectors have the following ranges: indoor 0.1 to 100 mR/hr; outdoor 1.0 to 1,000 mR/hr; and extreme (near reactor on Test Stand) 1 to 10^6 r/hr.

The neutron detectors are boron-lined proportional counters located near each end of the hot face of the shadow wall. Their detection range is about 10^3 to 10^7 n/cm²/sec.

3. Fire Protection System. This system provides capability for water deluge of 27 zones at ETS-1. Only 12 of these are presently in use for protecting the Test Stand, LH₂ Dewar, High Pressure Gas Area, Propane Tank, and Truck Unloading Area. The other zones presently serve as spares.

The water source for this system is the 2.5 million gallon Process Water Tank and the 150,000 gallon Utility Water Tank. From here the system water is routed through 3 valve pits.

The FPS has master controls on the LSE console, Figure XI-3. There are also three local control panels located in the forward areas. The FPS is integrated with the ASWS as shown in the logic chart. An area layout of the Fire Protection System is shown in Figure XI-5.

4. Oxygen Detection System. This subsystem basically consists of oxygen detectors at locations where oxygen concentrations above or below certain levels could cause dangerous conditions. At ETS-1 the two classes of unsafe conditions these detectors would indicate are:

- a. A liquid oxygen leak and hence a high oxygen alarm.
- b. An oxygen deficiency (O₂ displaced by N₂ or He) indicated by a low oxygen alarm. The meters indicate concentration at the LSE console.

The high and low level O_2 detector alarm points are normally set at 24% and 16%. It is felt that 24% is sufficiently higher than the normal indication (21%) to show an alarm and 16% is the level below which immediate biological effects have been observed.

Additional oxygen detectors are scheduled for placement in the High Pressure Gas Bottle Building where a nitrogen or helium leak could occur. The detectors are normally set at zero in a GN_2 atmosphere. A portable oxygen detector is also available for use at ETS-1.

5. Combustible Gas Detectors. Two general types of combustible gas detectors are in use at ETS-1, one for hydrogen (H_2), the other for propane (C_3H_8). Both are used to detect these combustible gases in the LEL (lower explosive limit) range. The LEL for propane in air is 2% (by volume), while for hydrogen the LEL in air is 4%.

The combustible gas analyzers are frequently calibrated against a known concentration of the gas which they are designed to measure. The alarm points on these are normally set at 50% of the LEL to provide a margin of safety. Portable combustible gas analyzers are also available for use at ETS-1.

6. Meteorological Station. ETS-1 has a meteorological station to monitor local weather conditions. Parameters measured and recorded are wind speed, wind direction, ambient air temperature, and barometric pressure.

7. Criticality Monitoring System. A neutron monitoring system will be used at ETS-1 to detect accidental criticalities. The system consists of 3 channels of extremely sensitive BF_3 thermal neutron detectors, where 2 of 3 detector alarm logic will be used.

The detectors are located near the engine test compartment side shields on the hot face of the shadow wall.

8. Emergency Switches. Six emergency switches are located throughout the ETS-1 above-ground areas. These manually-operated switches should be used to indicate one of several unsafe conditions; (a) a hazardous condition undetected by any safety system sensor, or (b) personnel caught above ground during a test countdown. In either case, whenever an emergency switch is manually actuated it would transmit a signal to the LSE console and sound all above-ground sirens.

9. Safety System Recorders. The Safety System has recording capabilities which include 2 eight-point continuous recorders and 2 sixteen-point periodic recorders.

C. SAFETY SYSTEM COMPONENT LOCATIONS

Figures XI-4, -5, -6 show the locations of the various system components.

Area Beacons

Atop control point building

Atop fill station

Atop NE end of shadow wall at test stand

Tunnel Door Lights

- 1, 2 Main tunnel entrance/exit at control point
- 3, 4 Side tunnel entrance/exit at control point
- 5, 6 Tunnel entrance/exit at utility equipment building
- 7, 8 Tunnel entrance/exit at fill station
- 9, 10 Tunnel entrance/exit at high pressure gas storage area
- 11, 12 Tunnel entrance/exit at LH₂ dewar area
- 13, 14 Tunnel entrance/exit at test cell building
- 15, 16 Tunnel entrance/exit at test stand

Sirens/Klaxons

Control point area

Fill station area

Test cell area

Above ground areas

Remote Area Gamma Monitors

- A-1 Outside main tunnel entrance
- A-2U In tunnel at control point building
- A-3 In utility equipment building
- A-4U In tunnel near bend at knock-out plug
- A-5 Inside mechanical equipment room at fill station building
- A-6U In tunnel outside forward control room
- A-7 On test stand at level of top of shadow shield (Future)

- A-8U In mechanical and electrical equipment room of test cell building
- A-9U In test cell building
- A-10U In test stand building
- A-11 At northeast end of the shadow shield
- A-12 At southwest end of the shadow shield
- A-13 At test stand at head of stairs to exhaust duct
- A-14 At test stand above duct vault door
- A-15 At bottom of stairs outside of exhaust duct vault

Neutron Monitors

- N-1 Near northeast end of front of shadow wall
- N-2 Near southwest end of front of shadow wall

Particulate and Gas Monitors (Future)

- P-1) At air intake filters for tunnel and control point building
- G-1) - ventilation systems in utility equipment building
- P-2) At air intake filters for forward control room and test
- G-2) - stand building in the utility equipment building
- P-3U)
- G-3U) - Inside test stand building

Combustible Gas Detectors

- CG-1 Inside steam generator enclosure (C_3H_8)
- CG-1a Inside steam generator enclosure (C_3H_8)
- CG-5 In valve house in HP gas storage area (H_2)
- CG-6 In hydrogen revetment area (H_2)
- CG-7 On top of test stand inside base of flare stack
(AFER Console) (H_2)
- CG-8 In line between check valve and LH_2 storage flare stack
(AFER Console) (H_2)
- CG-10U Inside test stand building (One each H_2 and C_3H_8)
- CG-2, 3, Inside engine test compartment (H_2) (Future)
4, 9
- CG-13 At air intake filters in utility equipment building (C_3H_8)

Oxygen Detectors

- O₂-1 At top of test stand in base of flare stack
- O₂-2 In steam generator enclosure (LSE Console)
- O₂-8 In line between check valve and LH₂ storage flare stack
- O₂-11 In high pressure gas storage building (LSE Console)
- O₂-12U Inside the test stand building
- O₂-4, 5, Inside engine test compartment (Future)
6, 10

Emergency Switches

- SW-1 At top of the test stand near elevator
- SW-2 At intermediate level on test stand near stairs
- SW-3 Between elevator and shadow shield at ground level
- SW-4 At tunnel entrance in LH₂ dewar area
- SW-5 At tunnel entrance in valve house, HP gas storage area
- SW-6 On outside north wall of compressor room, fill station
 building

Safety System Recorders (At LSE Console)

- Two 8-channel continuous recorders
- Two 16-channel periodic recorders

FIGURE XI-1

LSE CONSOLE - LEFT
FOR TRAINING USE ONLY

FIGURE XI-1

LSE CONSOLE - CENTER
FOR TRAINING USE ONLY

FIGURE XI-2

FIGURE XI-2

FIGURE XI-3

3810' TO 3848'		3848' TO 3866'		3866' TO 3886'		3886' TO 3901'		3901' TO 3916'		ABOVE 3916'	
DELUGE	DELUGE	DELUGE	DELUGE	DELUGE	DELUGE	DELUGE	DELUGE	DELUGE			
Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8				

RS Z1 CLOSE	RS Z2 CLOSE	RSV Z3 CLOSE	RSV Z4 CLOSE	RSV Z5 CLOSE	RSV Z6 CLOSE	RSV Z7 CLOSE	RSV Z8 CLOSE
OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN

RESET	RESET	RESET	RESET	RESET	RESET	RESET	RESET
Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8

LPZ1 ALARM	LPZ2 ALARM	LPZ3 ALARM	LPZ4 ALARM	LPZ5 ALARM	LPZ6 ALARM	LPZ7 ALARM	LPZ8 ALARM
NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL

LPZ9 ALARM	LPZ10 ALARM	LPZ11 ALARM	LPZ12 ALARM	LPZ13 ALARM	LPZ14 ALARM
NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL

LH DEWAR AREA		H P GAS STORAGE		UNLOAD STATION		PROPANE TANK	
DELUGE	DELUGE	DELUGE	DELUGE	DELUGE	DELUGE	DELUGE	DELUGE
Z15	Z16	Z17	Z18	Z19	Z20	Z21	Z22

RSVZ15 CLOSE	RSVZ16 CLOSE	RSVZ17 CLOSE	RSVZ18 CLOSE	RSVZ19 CLOSE	RSVZ20 CLOSE
OPEN	OPEN	OPEN	OPEN	OPEN	OPEN

RESET	RESET	RESET	RESET	RESET	RESET
Z15	Z16	Z17	Z18	Z19	Z20

LPZ15 ALARM	LPZ16 ALARM	LPZ17 ALARM	LPZ18 ALARM	LPZ19 ALARM	LPZ20 ALARM
NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL

RSVZ21 CLOSE	RSVZ22 CLOSE	RSVZ23 ALARM	RSVZ24 ALARM	RSVZ25 ALARM	RSVZ26 ALARM	RSVZ27 ALARM
OPEN	OPEN	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL

RESET	RESET	RESET	RESET	RESET	RESET	RESET
Z21	Z22	Z23	Z24	Z25	Z26	Z27

LPZ21 ALARM	LPZ22 ALARM	LPZ23 ALARM	LPZ24 ALARM	LPZ25 ALARM	LPZ26 ALARM	LPZ27 ALARM
NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL

GV-1 NORMAL	GV-2 NORMAL	GV-3 NORMAL
ALARM	ALARM	ALARM

LWP1 NORMAL	LWP2 NORMAL	LWP3 NORMAL
ABNORMAL	ABNORMAL	ABNORMAL

28VDC SPARE	M2 28VDC M1	8-L 28VDC 5-L
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SIREN SILENCE	LOCAL ALARM SILENCE	SUPERVISE	DELUGE
ON OFF	ON OFF	ACKNOWLEDGE	ACKNOWLEDGE

LSE CONSOLE – RIGHT
FOR TRAINING USE ONLY

FIGURE XI-3

FIGURE XI-4
SHEET 1 OF 3

LSE SAFETY GRAPHIC DISPLAY
FOR TRAINING USE ONLY

FIGURE XI-4
SHEET 2 OF 3

LSE SAFETY GRAPHIC DISPLAY
FOR TRAINING USE ONLY

FIGURE XI-4
SHEET 3 OF 3

LSE SAFETY GRAPHIC DISPLAY
FOR TRAINING USE ONLY

FIRE PROTECTION SYSTEM
FOR TRAINING USE ONLY

FIGURE XI-5

- NOTES: (1) A blank in Table indicates detector cannot affect condition or status of warning device.
 (2) Lights at locations 1 and 2 turn green. Outside lights at locations 3 thru 9 turn green.
Inside lights at locations 3 thru 9 turn red. (See Section XI-C for door light locations.)
 (3) Same as for Note (2) except that door light at location 8 turns red.

ACTION → STATION	SIREN	KLAXON	BEACONS			SAFETY GRAPHIC	LSE CONSOLE		LOCAL SIGNAL		DOOR LIGHTS	NRDS FIRE STATION
			TEST STAND	FILL STA.	CONT. POINT		AUD.	VIS.	AUD.	VIS.		
A - 2U, 4U, 6U, 7, 8U, 9U, 10U, 13, 14, 15						Red	Yes	Yes	Yes	Yes		
A - 1, 3			Yel.	Yel.	Red	Red	Yes	Yes	Yes	Yes		
A - 5			Yel.	Red	Yel.	Red	Yes	Yes	Yes	Yes		
A - 7, 11, 12			Red	Yel.	Yel.	Red	Yes	Yes	Yes	Yes		
G - 1, 2, 3U P - 1, 2, 3U						Red	Yes	Yes	Yes	Yes		
CG - 1, 1A	Yes		Red	Yel.	Yel.	Red	Yes	Yes			Note (2)	
CG - 5, 6	Yes		Yel.	Red	Yel.	Red	Yes	Yes			Note (2)	Yes
CG - 7, 8						Red	Yes	Yes		A FER		
CG - 10U	Yes		Red	Yel.	Yel.	Red	Yes	Yes			Note (3)	
CG - 2, 3, 4, 9						Red						
O ₂ - 1, 8						Red	Yes	Yes		A FER		
O ₂ - 2, 12U						Red	Yes	Yes	Yes			
O ₂ - (Gas Storage)						Red	Yes	Yes	Yes	Yes		
O ₂ - 4, 5, 6, 10						Red						
SW - 1, 2, 3	Yes		Red	Yel.	Yel.	Red	Yes	Yes			Note (2)	
SW - 4, 5, 6	Yes		Yel.	Red	Yel.	Red	Yes	Yes			Note (2)	
Criticality Alarm System		Yes	Red	Red	Red	Red	Yes	Yes			Note (2)	Yes
FPS Deluge Zones - 1, 2, 3, 6, 7, 8, 9, 10	Yes		Red	Yel.	Yel.		Yes	Yes			Note (2)	Yes
FPS Deluge Zones - 15, 17, 21, 22	Yes		Yel.	Red	Yel.		Yes	Yes			Note (2)	Yes
CO ₂ - Compressor Room	Yes		Yel.	Red	Yel.		Yes	Yes			Note (2)	
CO ₂ - Fill Station Reels							Yes	Yes				

TABLE XI-1 RECOMMENDED ALARM LOGIC

ETS-1 CONTROL POINT OPERATOR
GENERAL INDOCTRINATION COURSE

SECTION XXIV
TEST OPERATIONS

A. RUN WEEK ACTIVITIES

1. Procedural Controls. The complexities of the XE-1 test program (a sophisticated facility, split organizational responsibilities, short work-around times etc.) requires that all test operations including pre-test setups and post-test clean-up, be accomplished in accordance with detailed procedures appropriate to the task. Moreover, these procedures must be available sufficiently in advance of need to permit the necessary reviews both at NRDS and off-site where source engineering review is required.

A seven-day lead time for facility setup procedures was established during the recently completed FEP series. This period of time was found to be sufficient to accommodate all necessary reviews and any consequent changes. This same requirement will, therefore, be retained for the XE test programs and will be expanded to include the post-test facility secure procedure. Similarly, Program Directive 1054, issued by NRO, requires that test operating procedures be provided to off-site participants no less than 26 days prior to run day so that all technical and safety reviews may be accomplished.

a. Pre-test Procedures. The pre-test procedures cover both facility setup and console status checklists. The facility setup procedures detail all activities required to prepare a particular system for the intended operation such as instrumentation setups and valve setups. The procedures are prepared by the responsible systems engineer and reviewed and approved by the cognizant ETS-1 Department Manager. The setup procedures are also

reviewed by the Manager, Engine Test Operations, to ensure that the facility status will be compatible with the objectives of the particular test to be conducted. All system setup is accomplished by the cognizant system engineer in strict accordance with these procedures beginning on R-2 day. All setup procedures will be completed by 1200 hours on R-1 day.

b. Console Status Checklists. The console status checklists are prepared by the console operators and are reviewed and approved by the Deputy Test Director. These procedures are used primarily to ensure that the systems controlled by a given console will remain in a safe condition when the console is energized. The console procedures can also serve as a verification of facility pressure or valve setups in those cases where system pressures are displayed. The consoles status checklists are completed by the console operators on R-day and are reviewed and approved by the Test Director and Deputy Test Director immediately before the initiation of control room operations.

c. Test Operating Procedures. The Test Operating Procedures define in step-by-step detail all actions necessary to accomplish the objectives of a given XE Experimental Plan. All control room activities beginning with the completion of the area security sweep to the conclusion of post-test cooling will be conducted in strict accordance with the Test Operating Procedures. The Test Operating Procedures will be prepared by the Test Planning section of ETS-1 Test Operations and will be reviewed by all ETS-1 Departments, NTO Health and Safety, Engine Test Operations, NRO/Sacramento, WANL/Large, and SNPO-C. The final copy will be approved by the Manager, Engine Test Operations; the Manager, NTO; and the XE Test Review Board.

The Test Operating Procedure will be developed in three stages as follows:

(1) Preliminary Draft. The first rough draft, and all subsequent issues, will be prepared by ETS-1 Test Planning under the direction of Engine Test Operations (ETO) and will be provided to the ETS-1 Departments and to NTO Health and Safety for comment. Upon the resolution of these comments by ETO, a preliminary draft will be distributed, no later than R-26 days, to the Test Review Board (TRB) members of the respective off-site organizations for source engineering review. External review comments will be provided to ETO, by the TRB, no later than R-19 days.

(2) Simulator Draft. Upon resolution of external comments by the TRB and ETO, a simulator draft will be prepared. The simulator draft will be used for all TSS operator training activities and for the dry run. The Simulator Draft will also serve as the basis for the request, by NRO Safety Division, for SNPO permission to conduct the test. The Simulator Draft will be issued by ETO no later than R-7 day.

(3) Final Draft. The final draft of the Test Operating Procedure will incorporate all modifications resulting from dry runs, test stand simulator work, and any safety requirements placed upon the test. Upon approval by the required agencies, the final draft will become the final Test Operating Procedure by which the Experimental Plan will be accomplished. The final Test Operating Procedure will be issued by ETO no later than R-3 days.

d. Facility Secure Phase. The facility secure phase will be initiated immediately upon completion of the post-test cooldown operations. However, because of the nature and duration of the cooldown activities, some clean-up activities such as GH_2 system clean-up, LH_2 system warmup and inerting, will have begun and will be in various stages of completion. The purpose of the facility secure phase will be to complete these activities, and to conduct all other activities necessary to place the facility fluid systems in a condition which will permit the safe entry of personnel to all areas of the facility consistent with existing radiation hazards. The secure procedures will be prepared, reviewed, approved and conducted by the personnel and in the manner previously described for Facility Setup Procedure.

2. Status Board. The preparation of the Facility for the conduct of a particular EP will be conducted under the control of the XE Status Board. The Status Board will act as an arm of Engine Test Operations and will be chaired by a member of the Test Planning Section of ETS-1 Test Operations. The Board will be attached to the Facility Operations Shift Supervisor (FOSS), and will function as the controlling authority for all facility preparation activities being conducted at ETS-1, beginning on R-3 day. The Board will be relieved of its duties upon the initiation of control room operations, at which time facility control will pass to the XE Test Director. All work at ETS-1, whether associated with facility setup or not, will be scheduled

through the Status Board and conducted in accordance with the schedules and/or priorities established by the Board. All decisions by the Board are subject to review by the Manager, Engine Test Operations, and in those cases where Board decisions can compromise XE Test Objectives or test schedules, the Manager, Engine Test Operations, shall review and approve the specific Board decision.

3. Test Stand Simulator and Facility Dry Runs. Operator training for a specific Experimental Plan will be accomplished by a simulation of the intended Test Operating Procedure, using the Test Simulation System (TSS), and by the conduct of facility dry runs. The present TSS will permit the simulation of all operations controlled by the Test Stand Control System. This simulator capability is being augmented by a Nuclear Exhaust System Simulator including steam generator operational simulation. This combined capability should permit the simulation of essentially the entire run phase of an Experimental Plan.

Although extensive general Simulator training will be obtained by all operating personnel during the Specific Knowledge course of the XE Operator Training Program, training for the conduct of a specific Experimental Plan will be obtained by the accomplishment of a minimum of 4 simulator runs of that Experimental Plan prior to its conduct. Simulator runs will begin no later than R-7 day and will continue through R-1 day. All console operators assigned to participate in the conduct of the Experimental Plan will be required to attend all simulator runs. The simulator runs will include both normal and abnormal or malfunction events.

In addition to simulator training, the operating team will conduct a facility dry run on R-1 day. The purpose of the dry run will be twofold; (1) operator training, and (2) the final assessment of stand operational readiness. R-1 day has been selected since by this time all facility pre-run preparations including facility setup procedures will have been completed.

The dry run will be conducted in accordance with the final Test Operating Procedure and will consist of an operational check of all valves to be used in the forthcoming Experimental Plan and which can be exercised without releasing high pressure gases. Neutronics system checks, consistent with the

existing radiation levels, will also be conducted. The operation of control systems, will be demonstrated insofar as applicable safety restrictions will permit. Those aspects of the Test Operating Procedure which cannot be actually demonstrated will be simulated using the ETS-1 simulator capability. In short, the dry run is intended to be as complete a dress rehearsal for the Experimental Plan as can be obtained.

B. OPERATIONAL RESPONSIBILITIES OF OPERATING TEAM

1. Test Director. The Test Director will discharge the following major operational responsibilities during the course of preparing for and accomplishing the Experimental Plan.

a. Assure that the facility preparation and the test planning effort is consistent with the requirements of the objectives to be achieved by the Experimental Plan.

b. Select the operating team and conduct the pre-Experimental Plan operational training.

c. Understand all Operating Limits or other restrictions applicable to the Experimental Plan.

d. Determine the remedial actions to be taken in the event Operating Limits are exceeded, or other malfunctions occur.

e. Direct the Operating Team in the conduct of orderly and efficient Control Room Operations.

f. Secure the facility in a safe manner and provide for the orderly return of the facility to FOSS cognizance following completion of post-test cooldown.

The first three preceeding items obviously begin some time before R-day. The Test Director, assisted by the Deputy Test Director and the Assistant Test Director, will work directly with ETS-1 Test Planning in the preparation of the Test Operating Procedures to ensure that the objectives of the particular Experimental Plan are met. The Test Director will also be responsible for ensuring that facility preparations will support the planned test program. In this regard, he shall review all facility setup and secure checklists, review all propellant forecasts, and conduct all coordination meetings and all Test Review Board meetings.

Although XE Operator Training begins with the general indoctrination course, an operating team will be selected and trained specifically for the conduct of each Experimental Plan. This training will consist mainly of Test Operating Procedure reviews and simulator training. Included will be discussions of applicable limits and safety restrictions and appropriate remedial actions. The operating team will practice these and other malfunction responses extensively during the simulator activities.

All control room operations will be directed by the XE Test Director. He will be assisted in this responsibility by the Deputy Test Director and Assistant Test Director, who will assume the Test Director and Deputy Test Director roles, respectively, in the event that the Test Director is incapacitated during the course of the run. The Test Director will ensure that all applicable limits are observed and the adherence to the approved Test Operating Procedure. He shall also be responsible for selecting alternate courses of action in the event that deviations to the Test Operating Procedure are required because of unanticipated difficulties with either the facility or test assembly. The following are some representative responses to emergency conditions of differing severity.

- a. Attempt an immediate remedy if Operating Limits are exceeded.
- b. Call for a programmed shutdown if Operating Limits cannot be observed or if test objectives will be seriously compromised by continuing.
- c. Call for a scram if there is a serious reactor or engine control problem.
- d. Call for a flow shutdown and the initiation of appropriate emergency cooling if there is a serious propellant flow problem.

The Test Director is also responsible for the securing and transfer of an operationally safe facility to the cognizance of the FOSS upon completion of post-test cooldown operation. This shall be accomplished by ensuring that the Facility Shutdown phase of the Test Operating Procedures produces a minimal hazard because of the presence of explosive fluids, and that the post-test secure procedures place the facility in an Unrestricted Access condition consistent with existing radiation hazards.

temperatures within the engine, monitoring the actuation gas system, withdrawing individual drums during scram checks, assisting the CTE during critical physics experiments, and selecting the proper temperature feedback signal for the engine controller. The ATE assists the CTE in monitoring the primary engine performance parameters.

(4) Test Stand Engineer. The TSE controls the supply of all facility contained cooldown fluids excepting the LH_2 supplied from dewar V-5001. He is responsible for ensuring that the cooldown limits are not exceeded following LH_2 pulse cooldown or, in the event of an unscheduled flow shutdown, during and immediately following activation of one of the emergency cooling systems. This is achieved by the five independently controlled fluid supply systems; high pressure LH_2 , GH_2 , GN_2 , He, and low pressure LN_2 , which are operated from this console.

(5) Assistant Stand Engineer. The ASE is the fifth member of the TSCS Operating Team and works in close association with the TSE in setting up the cooldown system. The ASE is responsible for the Run Tank and the High Pressure Run Tank. Purge valves for various engine subsystems are also controlled from this console. The ASE also works closely with several of the other facility operators in setting up the gas and cryogenic systems.

(6) Control Systems Engineer. The CSE is responsible for the operation of the automatic programmers and for the monitoring of all of the analog control systems at the ETS-1 complex. This monitoring function includes the recording of control system data, such as frequency response and particular component performance. He reports observed anomalies to the appropriate Control Room Operator(s) and assists in their interpretation. Operation of the programmers includes control of the override settings on the control drums, temperature controller, Log Power controller and the delta P across the engine. The CSE also operates bypass switches to remove various signals from the shutdown chain. The CSE is intimately associated with the control systems and is normally responsible for all phases of installation, checkout, and maintenance of the control system. This responsibility includes the pre-operational setup of the Test Stand Simulation System. During simulator practice sessions, he introduces malfunctions to aid the operators in malfunction detection training.

b. Facility Consoles. The major facility consoles of concern are the Lead Facility Engineer, the Facility Engineer Left, the Facility Engineer Right, the Lead Instrumentation Engineer, and the Lead Safety Engineer. The responsibilities of these console operators are discussed in the following paragraphs.

(1) Lead Facility Engineer. The LFE duties consist of supervising the startup and shutdown of the NES, which includes setting up of the Tank Farm and sealing the Engine Test Compartment (ETC). The LFE is also responsible for the operation of the process water system, ETC purging, fire protection zones 11 and 12, and monitoring shield temperatures. The LFE advises the Test Director of any abnormal behavior, assists in their interpretation and recommends any corrective action that may be required. The Facility Engineer Left (FEL) and the Assistant Facility Engineer Left (AFEL) are responsible to the Lead Facility Engineer during test periods. The LFE will be qualified for all of the operating positions under his jurisdiction.

(2) Facility Engineer Left. The FEL is the operator of the Steam Generator System and as such is responsible for the startup operation and securing of the system. The FEL has controls for bleeding in the flow systems and the instrumentation used in monitoring the steam generator operation.

(3) Facility Engineer Right. The FER is responsible for igniting the flares and monitoring the oxygen and combustible gas concentrations in the flare systems. He has the control valves and instrumentation for transferring LH_2 between the storage vessel and the run tanks. In addition to the above systems, the FER has numerous remote shutoff valves used for control of the high pressure gas systems. He has control over the main header valves on the three gas systems and the purge valves for V-3801.

(4) Lead Instrumentation Engineer. The LIE is responsible for the operation of both the display and recording data system. The LIE controls the selection and calibration of the instrumentation on all of the various operator consoles. Since one of the prime reasons for testing is to gather diagnostic information, the LIE is required to have a very

broad knowledge of the facility and engine components and the data objectives of the test programs. Moreover, because of the breadth of information available to him, the LIE acts as a prime advisor to the Test Director and must, therefore, be able to recognize abnormal and/or potentially hazardous operations.

The LIE is also responsible for the selection and specific training of the Remote Recorder Operator (RRO) and the Digital Data Operator (DDO). During a test period he monitors the operation of the various recording systems and directs the DDO and RRO.

(5) Lead Safety Engineer. The LSE shall be responsible for monitoring hazardous conditions throughout the ETS-1 complex and for the control of the various fire protection systems. He shall advise the Test Director of all known or suspected hazards, suggests remedial actions and shall take corrective action as directed. The LSE also controls access to the general ETS-1 area and test stand proper at all times when access controls are in force.

C. CONTROL OF FACILITY OPERATIONS

During non-test periods (defined as any time other than R-2, R-1 and R-Day), facility activities are conducted under the cognizance of the Facility Operations Shift Supervisor acting for the Manager, ETS-1, and the Facility Operations Manager. The FOSS is the knowledgeable individual who acts as the single focal point for coordination of all day-to-day activities within the facility. During Status Board Control periods, the Board is attached to the FOSS to ensure continuity of facility activities. On Run-Day, the FOSS becomes the Facility Activation Controller (FAC) and directs the Facility Activation Control Team operations under the control of the XE Test Director upon the initiation of control room operations.

The Facility Activation Control Team under the direction of the Facility Activation Controller conducts the final Run-Day setup operations, and upon command from the Control Room, switches control of the required systems and valves, including the control drum system, to the Control Room. These commands are steps in the Control Room Operating Procedure and are accomplished by the FAC team in accordance with approved procedures and checklists. The

members of the FAC team are facility operations personnel thoroughly familiar with the systems and their operation. Whenever the FAC team is in the controlled area outside the Control Point Building, hydrogen headers are depressurized, block and vent conditions established, and the key which permits drum rotation from the control point is in the possession of the Test Director. Entry of the FAC team into the controlled area outside the Control Point Building is under the control of the Test Director. The final action by the team prior to leaving the area is to unlock the mechanical locks on the block and vent valves in the pneumatic line to the control drum actuators.

The FAC team will also be responsible for restoring the systems to their pre-test status upon completion of control room activities. Prior to the team's entry into the controlled area, outside the Control Point Building, the engine is secured, the control drums are locked and the key which permits control drum movement is removed from the ATE Console, the gas headers are purged and depressurized, and remote block and vent conditions re-established. The block and vent condition in the pneumatic line to the control drum is re-established and the valves locked. The team then completes any required venting and purging operations and restores the manual block and vents and any other venting necessary to restore the systems to safe shutdown condition.

ETS-1 CONTROL POINT OPERATOR
GENERAL INDOCTRINATION COURSE

SECTION XXV
ENGINE DOCUMENTATION

A. INTRODUCTION

Considerable documentation is generated prior to, during, and after an engine test series. This documentation is generated by both NTO and off-site engineering groups. Although each and every operator does not need to be completely familiar with all documentation, a general knowledge of the scope and contents of all the documents is desirable. The various documentation pertinent to ETS-1 is discussed with regard to the general scope and content.

B. OFF-SITE DOCUMENTATION

1. Test Plans. The Test Plans document prepared by AGC defines to all participants the scope of a particular engine test series. The document also gives authorization to NTO to initiate long term planning associated with the test series.

2. Test Specification. The Test Specification document prepared by AGC contains the engineering specification, requirements, and related information necessary for conducting a particular test series at NRDS. The Test Specification expands on the Test Plans in that specific engineering requirements for the testing program are given. The normal major documents in the sequence progresses from the Test Plan to the Test Specification and then to the Control Room Operating Procedures.

3. Operational Support Plan. The Operational Support Plan, prepared by the off-site ground support equipment groups, establishes the

sequence of operations to the level necessary to identify items of equipment required to support the operations of a particular test series at NRDS. This document is associated mostly with the Pre-Test and Post-Test Operations.

4. Safety Analysis Report. The Safety Analysis Report, prepared by the off-site safety groups, analyzes in the broad sense the overall safety of assembly, testing, and disassembly operations at NRDS for a block of engines. Items analyzed from a safety standpoint are: management controls, facilities, operations, test hardware, test radiation environment, and accidents and failures.

5. Safety Evaluation Report, Phase I. The purpose of Phase I of the Safety Evaluation Report is to summarize the safeguards required to prevent accidental criticality during operations with the engine assembly at NRDS prior to initial criticality.

6. Safety Evaluation Report, Phase II. Phase II of the Safety Evaluation Report, prepared by off-site safety groups, analyses the operations as planned for one particular engine test series. The Safety Evaluation Report is a comprehensive study of the safety implications of the actual tests to be performed on a given engine in the program.

7. Operating Limits Document, Phase I. Phase I of the Operating Limits Document, prepared by off-site safety groups, defines the constraints within which given engine operations prior to central poison wire removal are to be accomplished at NRDS. The constraints given in this document fall within the safety analysis as presented in Phase I of the Safety Evaluation Report and in the Safety Analysis Report.

8. Operating Limits Document, Phase II. Phase II of the Operating Limits Document, prepared by off-site safety groups, defines the constraints within which given engine operations after central poison wire removal are to be accomplished. This document is either published as an extension of Phase I of the Operating Limits Document to cover all subsequent operations, or the designation of Phase I and II is not used and a revision to Phase I is published to cover all operations.

9. Measurements Requirements List. The Measurement Requirement List is computer listing, prepared by the off-site engineering groups, giving the instrumentation requirements for a particular test assembly. This document gives such information as channel number, range, location, recording requirements, etc.

10. Test Parameter Limits Justification. The Test Parameter Limits Justification document, prepared by AGC, gives the justification for selection of a given set of parameters to be used to judge the abnormal performance of the Test Assembly. The document also gives the justification for selecting the values at which the particular parameter will signal an abnormal condition.

11. Test Prediction Report. The Test Prediction Report, prepared by the off-site analysis personnel, contains the test prediction data for the planned tests. These data can be used to compare the test data on a quick look basis so that it is possible to judge during or after the test that the engine has operated in a nominal manner. In addition to the prediction for nominal operation, predictions are given for emergency shutdowns.

12. Failure Mode Analysis Reports. The Failure Mode Analysis Reports, prepared by various functional groups at either NTO or off-site, provide for a systematic review of the Test Assembly and facility configurations pertinent to performing a successful test program. Each system, subsystem, and/or component is reviewed for all modes of operations and failures and an analysis of the resulting actions made.

C. ON-SITE DOCUMENTATION

1. Program Requirements Document. The Program Requirements Document, prepared as a joint effort of AGC Sacramento and NTO, specifically defines the funds supplied directly to NRDS in support of the NERVA Project. The document covers two major areas: (1) the base support requirements and funding, and (2) the technical operations requirement and funding.

2. Operations Requirements. The Operations Requirements document, prepared by NTO, describes and sets forth the Site Support Contractor services which are required by NTO to execute a given test series. Items covered by this document are those things required in addition to the normal support provided by the Site Support Contractor.

3. Engineering Documents. In order to formalize to some extent the engineering effort with regard to facility modifications and/or additions, a progression of documents are generated. The first document is the Functional Requirements which states the requirements for a modification or addition. The next document in the sequence is the Design Criteria which specifies the design parameters to be used in the design of the modifications. The Design Package is the next document in the sequence. The Design Package gives the actual design of the modification along with the necessary drawings and bill of materials. The last document in the sequence is the Work Permit or Work Authorization which initiates the actual hardware work on the modification.

4. Receiving, Inspection and Assembly Procedure. Formal procedures are prepared by NTO to meet the engineering requirement in the Test Specification for the receiving, inspection, and assembly operations conducted at the MAD Building on a given Test Assembly. These procedures detail the operations to be performed and the methods to be used. These procedures cover such items as: Pressure Vessel and Reactor Assembly (PVARA) receiving, non-nuclear hardware receiving, mechanical assembly and electrical assembly of the Test Assembly.

5. Transfer, Mate-Up and Checkout Procedures. Formal procedures are prepared to carry out the transfer, mate-up to Test Stand and checkout operations on the Test Assembly prior to the power testing. These procedures detail the operations and the methods to be used. Such operations as central poison wire removal, end-to-end instrumentation checks, and control drum system checks are included in this group of procedures. These procedures satisfy the engineering specifications as given in the Test Specification.

6. Subsystem Checkout Procedures. The Subsystem Checkout Procedures are a set of semi-formal procedures prepared and carried out to functionally and operationally check out each subsystem at the Test Stand and Control Point. These procedures are usually carried out after the subsystems have been modified or prepared for the test series. The purpose of the checkouts is to insure that the subsystems are ready for the test series. In many cases, the subsystem checkouts are used to verify that a test specification requirement can be or is being satisfied.

7. Subsystem Checkout Report. The Subsystem Checkout Report prepared by NTO summarizes the results and data obtained during the Subsystem Checkout Program. This report may include the results of the facility checkout runs.

8. Material Disposition Reports. The Material Disposition Reports are prepared and issued by NTO Product Assurance. These reports consist of a collection of completed Quality Reliability Disposition Reports, QRDR's, which denote the disposition of discrepant materials or operation identified during the assembly and pre-test checkout operations.

9. TRB Charter. This document delineates the responsibilities, authority and mode of operation of the Test Specification and Procedure Review Board and the Test Review Board. The TS&PRB and TRB are made up of three members, one each from WANL, AGC, and SNPO-C. NTO normally proves a Recorder to the Boards. NTO is responsible for bringing all action items before the Boards.

10. TS&PRB (Phase I & II) Meeting Minutes. Actions of the Test Specification and Procedure Review Board, TS&PRB, are documented via meeting minutes prepared by the Recorder and approved by the Board members. Minutes are prepared of each meeting where the Board takes action on a particular item that is presented. The Phase I TS&PRB is convened for the Pre-test phase of the operation. The Phase I Board is subsequently replaced approximately two weeks prior to the first test by the Test Review Board, TRB. The Phase II TS&PRB convenes at the time of disconnect of the Test Assembly from the Test Stand and covers the Post-test Operations. Daily status reports are presented to the TS&PRB for information purposes. If no action is taken by the Board, no formal documentation is prepared.

11. Test Review Board Meeting Minutes (TRB). The actions of the TRB are documented via meeting minutes prepared by the Recorder and approved by the Board members. Minutes are prepared for each meeting where the Board takes action on a particular problem. The TRB convenes two weeks prior to the first test and its functions include: approval of Control Room Operating Procedure, approval of changes to procedures, approval of test assembly changes, etc. Status reports are presented to the Board daily, but no minutes are prepared and issued unless the Board takes action on a problem.

12. Safety Review Committee Meeting Minutes (SRC). Prior to each test series a Safety Review Committee is formed to evaluate various safety problems associated with the test facilities and the test operations. The minutes of each of these meetings and the resulting recommendations of the Committee are formally documented and distributed.

13. Support Operational Requirements Document (SORD). The Support Operational Requirements Document is prepared by NTO for each Experimental Plan. The document describes in detail the planned test, specific operational requirements, and test limits. The document also provides the Control Room Procedure and Checklist required to perform the test.

14. Operating Limits Letters. For each Experimental Plan a letter stating the operating constraints within which the particular test is to be performed, is issued to the Test Director by the Manager, NTO. The letter re-emphasizes the operating limits and imposes additional operating constraints that may be necessary because of weather or test assembly conditions.

15. Pre-Test Operation Report. The Pre-test Operation Report prepared by NTO summarizes the Pre-test Operations from start of test assembly build-up to the first Experimental Plan. Major difficulties are noted and the resolutions to problems encountered are given. Data and results of the assembly operations and checkout of the test assembly are also presented.

16. Control Room Operating Procedure. For each experimental plan for an engine test series, a control room operating procedure is prepared by NTO. The control room operating procedure consists of a test description, identification of test and support requirements, identification of test limits, and the run day control room checklist. The control room operating procedure is the last in the sequence of documents which are written to define and then accomplish the actual power tests. The sequence goes from Test Plan, to Test Specification, to Control Room Operating Procedure.

17. DRAGON Memos. For each significant Experimental Plan in a test series, a group of operational and analysis personnel form a Data Review and Analysis Group on NERVA (DRAGON Team). This team functions to evaluate the test results, to evaluate the degree to which test objectives were satisfied, and to determine if the test objectives for subsequent tests are still valid. The results of the evaluation by the DRAGON Team are documented via memoranda. Each topic on which an evaluation is made is the subject of a memo.

18. Eight-Hour Report. The Eight-Hour Report is a TWX report to the government and off-site engineering management from the Engine Test Operations Manager giving a very brief run-down of the test. This report is issued the same day as the run. The report includes such information as major objectives performed, run time, major abnormalities, and success or failure of test.

19. Three-Day Report. The Three-Day Report, prepared by NTO, is written for each Experimental Plan and is an operational report of the test distributed on the fourth working day after the test. The report includes such information about the test as is available three days after the test. Included are such items as test objectives, test description (as run), test results, anomalies, and test chronology.

20. Instrumentation Status Report. The Instrumentation Status Report, issued by the I&C Group, is a summary of the status of the instrumentation and data processing for each Experimental Plan. Instrumentation failures and data processing problems are enumerated.

21. Site Test Report. The Site Test Report document is prepared by NTO and is a report that summarizes an entire test series. This report is more of a data report than the Three-Day Report. The entire test series is summarized by topic instead of by Experimental Plan, EP. The publication date on this report is five weeks after the last EP of the test series.

22. Dosimetry Report. The Dosimetry Report is prepared by the NTO Engineering Group. The report presents all the reduced data obtained from the dosimetry program for a particular test series.

23. Radiochemistry Report. The Radiochemistry Report presents the results of measurements taken during the chemical and radiochemical program on the fuel region components. Such items as weight loss, total fissions, flux distribution, fission product migration, and cladding condition are given in this report.

24. Post-Test Procedures. Formal procedures are prepared by NTO to meet the engineering requirements in the Test Specification for the post-test operations. These operations include the disconnect from the Test Stand and

transfer to the MAD Building, the disassembly, and the post-operative examination procedures. These procedures detail the operations to be performed and the methods to be used.

25. Post-Test Operation Report. The Post-Test Operation Report presents the results and observations made during the post-test operations. A chronology of the disassembly operations is given along with results of visual observations of the test assembly. During the post-operative examination program each component in the test assembly is subjected to a visual examination and in some cases subjected to both non-destructive testing and destructive testing. Results of these observations and testing are reported for each component.

ETS-1 INSTRUMENTATION AND CONTROLS
INTRODUCTORY COURSE

SECTION IV
INSTRUMENTATION FUNDAMENTALS

A. PRINCIPLES OF MEASUREMENT

1. General. During a development program, as well as during acceptance testing of rocket engines, it is of utmost importance to know what measurements are required and the quality of measurements needed and obtained. During development testing design changes are frequently made on the basis of performance parameters. The engineer, and quite often the customer, naturally want to know how reliable, accurate, and precise the data are from which design decisions are being executed in order to validate the performance demonstration. Thus, the instrumentation system has a vast influence upon the testing program.

Ordinarily the following questions must be asked:

- a. What measurements are to be taken?
- b. What methods of measurement are to be used?
- c. What equipment is necessary?
- d. What is the best estimate of instrumentation error?
- e. How reliable are the measurements?
- f. How should the data be analyzed and presented to the design engineers and/or the customer?

The answers to these questions have a direct influence upon the number of tests that need to be conducted to assure the customer that contract requirements are being met. The answers to these questions are equally important to the contractor since excessive testing is costly.

2. Rocket Performance Parameters and Relations. The processes inside a rocket system furnish the relations with which to compute performance and determine design parameters. They are useful as a means for evaluating and comparing the performance of different units, and the establishment of several necessary test conditions for any given performance requirement. The ETS-1 Facility is designed to provide instrumentation for measuring the magnitude of the rocket parameters. The most important rocket engine parameters are given by:

F	=	Thrust
P_c	=	Chamber Pressure
C_F	=	Thrust Coefficient
I_{sp}	=	Specific Impulse
A_t	=	Area of Nozzle Throat
$\dot{w}$	=	Weight Flow Rate

All of these parameters are faithfully monitored or derived from test data in order to show that model specifications are achieved.

a. Thrust (F). Thrust is a measure of rocket engine performance, specifically the amount of reaction force developed by ejection of the propellant--in case of the NERVA engine, hydrogen. Thrust is expressed in pounds and is arrived at by multiplying the speed of exhaust matter by its mass flow rate.

b. Chamber Pressure (P_c). Thrust indicates the pressure of propellant gases on the forward walls of the chamber as well as the exhaust pressure exerted on the nozzle walls.

c. Thrust Coefficient (C_F). Thrust coefficient determines the amplification of the thrust due to the jet expansion in the rocket nozzle as compared to the thrust that would be expected if the chamber pressure acted over the throat area alone.

$$\text{practically } F = C_F P_c A_t \quad (1)$$

$$\text{or from test data; } C_F = \frac{F}{P_c A_t} \quad (2)$$

d. Specific Impulse (I_{sp}). Specific Impulse indicates the amount of thrust which can be derived from each pound of propellant in one

second of operation. It is a measure of the propellant characteristics plus engine efficiency. I_{sp} is expressed in seconds and has essentially the same meaning to the rocket engineer as miles per gallon does to the motorist.

Improved I_{sp} means that more push is being derived from each pound of propellant. Greater I_{sp} can cut the number of stages in a multi-stage rocket, can permit increases in payload or cargo, or can increase velocity and range.

The maximum specific impulse obtainable with chemical rockets is approximately 425. The nuclear rocket is capable of achieving a specific impulse of approximately 2500.

e. Weight Flow Rate ($\dot{w}$). Weight flow rate is an important parameter in itself and influences specific impulse. Weight flow rate is the number of pounds of propellant that are ejected from the rocket engine in one second. The calculation of I_{sp} is performed using:

$$I_{sp} = \frac{F}{\dot{w}} \quad (3)$$

Specific impulse is probably the one parameter that receives most attention. Rocket engine systems are rated as to the I_{sp} output and most space missions are directly dependent on the achievement of thrust per weight flow rate or I_{sp} .

The NERVA program is concerned with all of these parameters. There is a constant search for better ways to measure them as well as requirements for more precise instruments as they become available. Sometimes large amounts of funds are dependent upon the achievement of the performance goals, especially in renegotiations of contracts or in the awarding of new contracts. Obviously the measurements of the pertinent parameters need be accurate in order to demonstrate confidently that a certain achievement has been accomplished.

B. STRAIN MEASUREMENT

1. General. Strain is deformation of a material body under the action of applied forces. All matter is subjected to strain as a result of external forces or as a result of its own weight. Strain is a fundamental engineering measurement.

Strain is expressed in two forms: (1) total strain is defined as total change of the linear dimension of the body, and (2) unit strain is defined as the change of the linear dimension for a unit length and is expressed in terms of length per unit length. For normal strain gage applications the change in linear dimension of a unit length is small compared to the unit length, and the strain is expressed in units of micro-inches/inch.

2. Resistance Type Strain Gage. The proper application of resistance wire strain gages requires some knowledge of the way in which these gages measure strain.

Strain in engineering usage is defined as:

$$\frac{\text{Change in Length}}{\text{Length}} \quad \text{or} \quad \frac{\Delta L}{L} \quad \text{with applied load}$$

Strain gages indicate strain indirectly, taking advantage of the phenomenon that a strained wire exhibits a proportionate change in electrical resistance with applied stress.

$$\Delta R/R = G \Delta L/L \quad (4)$$

where

ΔR = Change in Resistance

R = Resistance

G = Gage Factor

ΔL = Change in Length

L = Length

This method is precise and accuracies to 0.1% of full scale, or better, can be achieved.

Equation (4) can be rearranged to solve for gage factor.

$$G = (\Delta R/R) / (\Delta L/L) \quad (5)$$

Gage factor is the measure of resistance change for a given length change of the gage and is an indication of the gage sensitivity per unit loading. The gage factor value is determined in the laboratory by the strain gage manufacturer. Several commonly used strain gage materials are Constantan, a copper-nickel alloy with a gage factor of approximately 2.0, and Iso-Elastic which is a complex alloy with a gage factor of approximately 3.5.

All strain gage wire is specially selected and drawn to maintain uniform diameter, ductility, temperature coefficient, and resistance. Static measurement of strain requires a special wire with an extremely low temperature coefficient such as Constantan which has a temperature coefficient of 1.0×10^{-5} ohms/ohm/ $^{\circ}$ C. Strain measurements deal also with high frequencies, often at low amplitudes. This type of measurement requires wire with a high fatigue resistance and high gage output voltage, even at the sacrifice of long term stability. Iso-Elastic wire meets the requirements for this type of application. The temperature coefficient of Iso-Elastic wire is 47×10^{-5} ohms/ohm/ $^{\circ}$ C. It can be seen that, with the increase in gage factor between Constantan and Iso-Elastic elements, the increase in resistance per degree temperature change is approximately 3600%. It is therefore important to select the proper gage for the application to which it will be subjected. Several other typical gage factors and temperature coefficients are listed:

<u>MATERIAL</u>	<u>GAGE FACTOR</u>	<u>TEMPERATURE COEFFICIENT</u> <u>ohms/ohm/$^{\circ}$C</u>
Advance	2.1	.0001
Manganin	.47	.00001
Monel	1.9	.002
Nichrome	2.5	.0004
Nickel	-12.1	.006
Platinum	6	.003
Iso-Elastic	3.5	.00047
Constantan	2.0	.00001

The basic strain gage mechanical configuration falls into three categories:

a. Unbonded. The unbonded gage consists of one mill wire supported by insulating rods or standoff mounting supports which are attached to the area under strain.

b. Bonded. The bonded gage consists of one mill wire cemented to carrier sheets in the form of flat or helical grids, which are then bonded to the area under strain. Sectional views of wire and foil strain gages with vertical dimensions exaggerated are shown on the following page.

c. Semiconductor. This type of gage does not fall under the category of wire type gages, but is now used extensively in applications where a strain gage with a high output voltage is required. Semiconductor strain gages have gage factors as high as 175, compared with 2 to 3.5 for resistance strain gages. Semiconductor gages are prepared from silicon crystals and are available in either bonded or unbonded strain gage configurations.

3. Strain Gage Construction. More than a hundred different types of strain gages are available, almost all of which were developed to meet specific conditions. There are four basic variables which enter into the construction of these gages:

a. Filament Material. Filament material is the major variable since the variable actually measured is the resistance change. It is obviously desirable that the ratio of resistance change to strain change be as high as possible. The ratio, or gage factor varies widely depending upon the materials; some materials in fact exhibit a decrease in resistance with stress resulting in negative gage factor. It also has been found that any strain gage will respond to thermal as well as applied, load stresses. This requires special consideration of the temperature effects when selecting filament materials.

b. Grid Construction. Grid construction is determined by several factors. It is necessary that the resistance of the gage be held at some convenient figure. Resistance values of 60, 120, and 350 ohms are

common for wire or foil strain gages. Gage lengths vary from approximately 0.125 to 1.0 inches in the bonded type gages. Gages also are available for measuring strains in different directions. The three and four-arm rosette gages are the most widely used.

c. Lead Wire. Still another variable in the construction of gages is the type of connection between lead wire and the filament of the gage. When gages are used for large strain, hysteresis and premature failure occur. This has been effectively overcome by use of dual lead wire and foil type gages.

d. Bases. A number of bases, or carrier materials, for the filament wires are used. The basic carrier has been either rag bond paper, or special thin paper developed for ease of application and fast drying time. The requirements for a high temperature gage have been met by the use of phenolic impregnated paper, or bakelite carrier bases. These bases are satisfactory to temperatures from 300°F to 500°F. For higher temperatures the metal weld-on type gage may be used to approximately 1500°F. Figure IV-1 includes photographs of typical strain gage types. The application of all gages is a critical point in the use of strain gages for measurement purposes. Special application instructions must be adhered to, with special emphasis on water proofing and leakage resistance.

4. Strain Gage System. The basic strain gage system consists of the strain gage, bridge circuit, interconnecting cable, balance network, power supply, and end-recording instrument.

The most common bridge circuit is the Wheatstone bridge (see Figure IV-2A). A thorough analysis of the Wheatstone bridge circuit is warranted since the bridge circuit is used with strain gages, resistance temperature

transducers, potentiometer transducers, and strain gage type pressure and accelerometer transducers.

a. **Balanced Bridge.** When the bridge is balanced, there is no output voltage developed across the bridge, that is $E_o = 0$ volts. To satisfy this condition the voltage (E) across leg R_1 must be equal to the voltage across leg R_4 .

$$\begin{aligned} \text{or} \quad E_{R_1} &= E_{R_4} \\ I_1 R_1 &= I_2 R_4 \end{aligned} \quad (6)$$

$$\begin{aligned} \text{and} \quad E_{R_2} &= E_{R_3} \\ I_1 R_2 &= I_2 R_3 \end{aligned} \quad (7)$$

Dividing equation (6) by (7) gives the relationship for the balanced bridge:

$$\frac{R_1}{R_2} = \frac{R_4}{R_3} \quad (8)$$

b. **Unbalanced Bridge.** As a strain gage is subjected to increased strain, the resistance of the gage increases and causes the bridge to become unbalanced. The equation for the unbalanced bridge is derived by determining the difference in potential between the two bridge output leads.

Let the resistance of R_1 leg be:

$$R_1 = R + \Delta R$$

Assume the other three legs are equal to R :

$$R_2 = R_3 = R_4 = R$$

$$\text{then:} \quad I_2 = \frac{E}{2R}$$

$$\text{and:} \quad I_1 = \frac{E}{2R + \Delta R}$$

$$\text{so:} \quad E_{R_4} = \frac{E}{2R} (R) = \frac{E}{2}$$

$$\text{and: } E_{R_1} = \frac{E}{2R + \Delta R} (R + \Delta R)$$

$$\text{Therefore: } E_o = E_{R_1} - E_{R_4} = \frac{E(R + \Delta R)}{2R + \Delta R} - \frac{E}{2}$$

$$\text{Rearranging: } E_o = \frac{2E(R + \Delta R)}{2(2R + \Delta R)} - \frac{E(2R + \Delta R)}{2(2R + \Delta R)}$$

$$E_o = \frac{E \Delta R}{2(2R + \Delta R)} \quad (9)$$

ΔR is small compared to $2R$ and may be neglected.

$$E_o = \frac{E}{4} \frac{\Delta R}{R} \quad (10)$$

Equation (10) can be expanded to include the case where all four legs of the bridge are made variable. This configuration is the "Full Bridge" circuit and is illustrated in Figure IV-2B. The basic equation for the bridge circuit becomes:

$$E_o = \frac{E a}{(1 + a)^2} \left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4} \right) \quad (11)$$

Where E_o = bridge output voltage
 E = bridge excitation voltage
 a = ratio R_1 to R_2
 ΔR = change in resistance per leg
 R = leg resistance

c. Bridge Calibration. From equation (11) it is seen that decreasing the resistance of R_2 has the same effect on the bridge output as increasing the resistance of R_1 . Decreasing the resistance of R_3 has the same effect as decreasing the resistance of R_1 . Considering the circuit in Figure IV-2C in which R_1 is a strain gage, bridge output simulating increases or decreases in the resistance of the strain gage can be achieved by decreasing the resistance of R_2 or R_3 respectively.

Shunt calibration for any given value of strain is accomplished by placing a calibration resistor (R_c) across R_3 or R_2 bridge legs. The

value of the calibration resistor is calculated by equating the shunted leg resistance with the strain gage resistance produced by a given strain.

The change in resistance of a strain gage is:

$$R = G \epsilon R_g \quad (12)$$

Where G = gage factor
 ϵ = strain in microinches/inch
 R_g = unstrained strain gage resistance in ohms

The change in resistance of the shunted bridge arm is:

$$\Delta R = R_g - \frac{R_g R_C}{R_g + R_C} \quad (13)$$

provided: $R_g = R_3$

$$G \epsilon R_g = R_g - \frac{R_g R_C}{R_g + R_C}$$

rearranging: $G \epsilon R_g (R_g + R_C) = R_g (R_g + R_C) - R_g R_C$

dividing by R_g : $G \epsilon R_g + G \epsilon R_C = R_g$

rearranging: $R_C = \frac{R_g (1 - G \epsilon)}{G \epsilon}$

$$R_C = \frac{R_g}{G \epsilon} - R_g \quad (14)$$

Equation (14) is basic for the calculation of the calibration resistor; but effects due to long leads between the strain gage or bridge circuit and the calibration resistors are not taken into consideration.

The automatic calibration of any bridge type transducer may be accomplished by shunting the bridge in sequence with four different standard resistors. When shunted by these resistors, the electrical output of the bridge is the same as the electrical output of the bridge corresponding with specific strains. For example the calibration resistors may produce outputs 0%, 25%, 50%, 75%, and 100% of full scale strain.

d. Temperature Compensated Bridge. The strain gage resistance

is affected by changes in temperature of the gage. This change in resistance will appear as an apparent strain on the end-recording instrument. One method of temperature compensation is achieved by using a dummy gage (see Figure IV-2D). The dummy gage is a strain gage element mounted in the same vicinity as the active gage but not subjected to strain. The dummy gage may be mounted on a separate unstrained structure member or if the dummy gage is positioned perpendicular to the strain axis it may be on the same structure member as the active gage. When the dummy gage is subjected to a strain perpendicular to its major axis the transverse strain sensitivity must be considered. Transverse Strain Sensitivity is defined as a ratio of unit resistance change of a gage to the unit unidirectional strain acting perpendicular to its principal axis. Transverse strain sensitivity varies with grid length and type of construction and depends largely on the percentage of the total active strain sensitive element subjected to transverse strain. This is sometimes referred to as Auxiliary Gage Factor and is normally less than 2% of total gage output.

Self-Temperature-Compensated gages are available for use with specific materials. The self-temperature-compensated gages have a very small temperature sensitivity when mounted on the particular material for which it was designed. Apparent strains as small as 0.1 microinch-per-inch per degree F are obtainable. Two methods are commonly used to make self-temperature-compensation gages. The first method utilizes a single-element grid of a special alloy. Gages of this type are called "selected melt." A second method utilizes a grid consisting of two different materials connected in series.

5. Strain Gage Applications. The strain gage is the most flexible transducer yet developed. The basic strain gage elements are used in transducers to measure stress, torque, vibration, pressure, force and acceleration. The only difference is in the application of the strain elements and the methods of indicating and recording the outputs. The development of the transducers now in use by the aerospace industry are the results of a number of years of research and testing of commercially-available units. The original units were of the single active element type without compensation for temperature. These units were replaced with the present four active element balanced bridge with temperature compensation and shunt calibration capabilities.

The final design criteria for the strain gage systems used in the Instrumentation and Control System establish that the electrical output of any gage due to shunt calibration will be standardized and be directly proportional to the output due to physical stimulus. Under this concept, any one of hundreds of transducers can be utilized with any one of the hundreds of channels interchangeably without necessitating an end-to-end physical calibration.

C. PRESSURE AND FORCE MEASUREMENT

1. General. Measurements of pressure and force are among the most important and significant of the many measurements made during a static test firing of a rocket engine. The terms "pressure" and "force" are somewhat synonymous; however, in the field of rocket testing, the terms are individually qualified because of the concern with specific kinds of forces. For instance, "pressure" may be thrust-chamber pressure, hydraulic pressure, or atmospheric pressure; "force" in the aerospace industry usually pertains to rocket-engine thrust or side-forces, perpendicular to the thrust axis, generated by thrust-vector control.

A force is that which tends to change a body's state with respect to rest or motion. Force is expressed in units of pounds. A force acts along a straight line called its "line of action." The line of action of the primary force of a rocket engine is along the thrust axis and is caused by pressures within the thrust chamber.

Pressure is a force exerted against, and distributed over a given surface area. Pressure is expressed in units of force-per-unit-area, such as pounds-per-square-inch (psi). Atmospheric pressure is the force exerted on a unit area of the earth's surface by the weight of the atmosphere. If the measured pressure is greater than the atmospheric pressure, the difference is known as "gage" pressure. Pressures below atmospheric (negative pressures) are expressed in terms of either vacuum or absolute pressure. The sum of the gage pressure and the atmospheric pressure values equals absolute pressure. The absolute pressure is zero in a (near) perfect vacuum.

2. Pressure Measurement. An electric pressure transducer is a primary measuring device that converts an input pressure to an electrical signal of specific amplitude, frequency, or pulse duration proportional to the input pressure, by changing some electrical property (resistance,

reluctance, etc.) of the transducer when energized (excited) by a suitable power supply. The primary means of pressure measurement in testing of rocket engines is by use of electrical pressure transducers, because the electrical output signal from these devices can be transmitted over a long distance to a variety of readout devices. The majority of electrical pressure transducers are of the strain gage, potentiometric or LVDT (linear variable differential transformer) classes.

a. Strain Gage Type Pressure Transducers. Two types of strain gages, bonded and unbonded, are currently being used in strain-gage type pressure transducers, and the transducers are classified accordingly. Basically, the bonded strain gage pressure transducer consists of a flat grid or helix of strain-sensitive wire cemented to a carrier sheet, which may be paper, paper impregnated with plastic, or a similar material. Four gages, usually, are then bonded directly to a force-summing member in the transducer. In the unbonded-type gages, the four strain-sensitive wires are wound on insulators mounted on a force-summing member, or stretched between a fixed point and a movable point, on insulators, in such a manner that the applied force causes elongation or shortening of the wires.

b. Proving-Ring Sensor. The most common form of bonded strain gage sensing elements is the proving-ring type which is used in most Taber Instrument Corporation pressure transducers. The sensor is a compressible toroid on which four strain gages are cemented to the cylindrical surfaces, two on the inner surface and two on the outer surface. Each gage forms one arm of a Wheatstone bridge.

Figure IV-3 shows the exaggerated action of a proving-ring sensor. In IV-3A the gages are shown as 1, 2, 3, and 4. If a force F_y is applied to the ring, it will be distorted (Figure IV-3B) and gages 1 and 4 will lengthen, causing their resistance to increase. At the same time, gages 2 and 3 will shorten and their resistance will decrease. The gages are connected into the circuit in such a manner that their individual resistance changes are additive in the ultimate bridge output, i.e., like changes are in diagonally-opposite arms of the bridge.

In practical applications, the basic pressure transducer consists of a diaphragm, an articulating plunger (or piston), and the sensing ring.

Figure IV-4 shows a typical pressure transducer using this principle. With pressure applied to cavity (c), diaphragm (d) distends toward plunger (b), causing the plunger to compress the sensing ring (a), unbalancing the bridge and producing an output voltage proportional to the pressure in the cavity.

c. Cantilever or Bending Beam Sensing Element. A cantilever or bending beam type system actuated by a pressure sensitive element is often used for measurements in the lower pressure ranges. In one type designed for measuring pressures above atmosphere, a single bellows is used; for differential pressure, an additional bellows is inserted as shown in Figure IV-5. When measuring absolute pressure, the additional bellows is evacuated.

In addition to the bellow-actuated cantilever beam, there are also other variations. A diaphragm, piston, or other pressure sensing element can be used to move the beam. One variation of this type sensor is used by Data Sensors in their pressure transducers. In these, pressure applied to the diaphragm is transmitted directly to the bending beam, producing a proportional change in electrical resistance of the strain elements. Strain gages are bonded on both sides of the beam in such a manner as to provide mechanical and electrical symmetry.

d. Potentiometer Sensing Elements. In potentiometer pressure transducers, the strain gage and cantilever assembly is replaced by a resistance element. A sliding element is connected to the end of the bellows. (See Figure IV-6). An excitation of several volts is connected across the resistance element, and the output is taken from the sliding element and one end of the potentiometer. The potentiometer pressure transducer can also be used in a bridge circuit with the potentiometer serving as two arms of the bridge.

e. Linear Variable Differential Transformer. The linear variable differential transformer (LVDT) is primarily a device to detect displacement or movement. It is used as a pressure sensing element by detecting movement of a bellows or diaphragm. The construction of a pressure transducer that uses a LVDT is similar to the pressure transducer using a potentiometer except that the differential transformer replaces the potentiometer. The movable core of the LVDT is connected to the bellows. Movement

of the core produces a proportional change in the output voltage.

The operation of the LVDT is discussed further under mechanical displacement transducers. However, it should be noted that the LVDT requires an a-c excitation voltage.

3. Force Measurement. Force measuring devices utilize the same principles as strain-gage pressure transducers. Only the construction is different. Force transducers are usually called "load cells" and may vary from 50 to 2,000,000-lb capacity.

For the measurement of force or weight, the force-summing element is often a steel column or flexure with strain gages bonded on the sides. The line-of-action is along the longitudinal axis of the column.

The gages are oriented in such a manner that those in diagonally-opposite arms of the bridge are on the same axis and are stressed at the same rate. Two gages are bonded to the column on the longitudinal axis and the other two are laid tangential to the circumference, or perpendicular to the longitudinal axis (see Figure IV-7). Under compressive load, the dimensions of the column change slightly, stretching the wire of the circumferential grids and shortening the wire of the longitudinal gages. Under tension, the opposite occurs.

Many modern load cells use a proving ring or a bending beam as the sensing element. All of the load cells discussed use strain gage elements connected in a Wheatstone bridge configuration. Temperature compensation provides an operating range over the temperature extremes of $+30^{\circ}\text{F}$ to $+130^{\circ}\text{F}$. Metallic bonded strain gages give a standard 2 or 3 millivolt/volt full-scale output.

Electrical calibration of the load cells is made by using shunt calibration resistors across one leg of the Wheatstone bridge. Mechanical in-place calibration is accomplished by subjecting the load cell to a static force and comparing the output with that of a secondary standard load cell system. The maximum error of the secondary standard load cell is $\pm 0.15\%$. In-place calibrations are conducted under static conditions with the engine suspended from the test stand.

D. TEMPERATURE MEASUREMENTS

1. General. Among the parameters that must be monitored during engine tests are measurements of the temperatures in (1) cryogenic fluids, (2) the reactor, (3) the NERVA engine, (4) the facility system. Both thermocouples and resistance temperature transmitters are used to measure the temperature parameters.

2. Thermocouples. The thermocouple action is due to the Seebeck effect, which states that if two dissimilar metals A and B are connected as shown below and one of the junctions is heated relative to the other, an EMF (electromotive force) is induced in the circuit.

The EMF that will be induced as long as the two junctions are at different temperatures, will vary as some function of the temperature difference, and will reduce to zero when T_1 equals T_2 . Conductor A is positive with respect to B if the current flows from A to B at the cooler of the two junctions.

The output of the thermocouple circuit is a measure of the difference in temperature between the two junctions. To measure temperature at one junction accurately the temperature at the second junction must be kept at a constant known temperature. This second junction is called the reference junction.

The second and third thermoelectric laws are of particular importance in thermocouple applications. The second thermoelectric law states that a third metal C may be introduced in a circuit consisting of two homogeneous metals A and B with their junction at temperatures T_1 and T_2 without affecting the electromotive force (EMF) provided T_3 equals T_4 .

Application of this law allows the connection of copper lead wires between the thermocouple circuit and the recorder.

The third thermoelectric law states that if a pair of metals produce an EMF E_1 when its junctions are T_1 and T_2 , and an EMF E_2 when its junctions are T_2 and T_3 , then the EMF is $E_1 + E_2$ when the junctions are T_1 and T_3 . The third law permits the use of a junction other than 32°F with a simple bias correction. Commercial 150°F thermocouple reference junctions are provided in the ETS-1 test cell building.

The basic thermocouple circuit (see Figure IV-8) includes the thermocouple, 150°F reference junction and copper lead wires. Signal conditioning equipment includes voltage substitution for calibration and zero offset for bias correction.

A standard thermocouple installation for measuring cryogenic fluid temperature is depicted in Figure IV-9.

The usable temperature range of the three types of thermocouples used at ETS-1 are listed on the following page. The corresponding millivolt signals listed are based on an ice bath reference junction.

Copper/Constantan	-425° F to +750° F	-6.202 to +20.81 mv.
Chromel/Alumel	-425° F to +2500° F	-6.436 to +54.92 mv.
Tungsten/Tungsten-Rhenium	+32° F to +4200° F	0 to +39.08 mv.

The thermocouple channel output at any particular temperature is dependent upon the reference junction temperature and the zero offset bias voltage.

3. Resistance Temperature Transmitter (RTT's). The RTT's used at ETS-1 are made of platinum wire which has a high positive temperature coefficient of resistance. The sensor element may be made into a sensor similar in appearance to a wire strain gage or it may be installed in a temperature probe, as shown in Figure IV-10. The RTT is electrically connected as one arm of the Wheatstone bridge, or it is connected across a constant current power supply. In either case, the change in output voltage is a measure of the change in resistance which is proportional to the change in temperature of the sensing element.

The platinum wire provides a sensing element with a higher sensitivity than thermocouples. A pure platinum element with an ice-point resistance of 200 ohms has an average slope of 0.435 ohms/°F in the temperature range of 0 to 500°F. Simulating the bridge output using shunt calibration requires a small calibration resistor. The small calibration resistor causes an excessive current to flow through half of the bridge circuit. To prevent this excessive current, series calibration or voltage-substitution calibration methods are used.

Resistance thermometers are available in three basic temperature measuring systems: (1) the bridge-in-head RTT system, (2) the bridge completion system, (3) constant current system.

a. Bridge-In-Head RTT's. One method of eliminating lead resistance effects in a Wheatstone bridge circuit is to design the bridge so that no switches, relay contacts or long lines are contained within the bridge circuit. This method led to the development of the bridge-in-head RTT. This system measures temperature with an RTT that contains all resistors used to complete the Wheatstone bridge circuit in the probe assembly. Temperature measurements in the 0°F to 500°F region are within the design specifications of these probes. Bridge-in-head RTT's are not used with the ETS-1 complex but are included here for completeness of coverage.

b. Bridge Completion RTT's. Three bridge configurations are used with the bridge completion RTT's. They are: (1) Wheatstone bridge, (2) Double bridge, and (3) Triple bridge. In all three circuits only the resistance-sensing element and connecting lead wires are located in the probe assembly. The bridge completion RTT's are designed to cover the range from -435°F to $+500^{\circ}\text{F}$.

The RTT connected to the Wheatstone bridge through three leads is shown in Figure IV-11A. This places the lead resistance in both R_{10} and RTT legs of the bridge. Provided the lead resistances R_{1A} and R_{1C} are equal the lead resistance is effectively suppressed.

The double and triple bridge circuits use four leads to connect the sensing element to the bridge (see Figures IV-11B and C).

In the double bridge, lead resistances R_{1A} and R_{1B} are connected as two arms of a bridge circuit. Effective suppression of the lead resistance at one end of the sensing element is accomplished, but lead resistance R_{1C} is not suppressed. The double bridge then serves to provide partial suppression of the lead wires.

In the triple bridge lead resistances R_{1A} and R_{1B} are connected as two arms of a bridge circuit, leads R_{1C} and R_{1D} are connected as two arms of a second bridge circuit. Suppression of lead wires at both ends of the sensing element is accomplished by the triple bridge configuration. Errors caused by differences in lead resistance are reduced by a factor greater than 100, as compared with the Wheatstone bridge using three wires.

c. Constant Current System. The constant current system provides another means of suppressing the effects of lead resistance. The circuit is included as Section D of Figure IV-11. The voltage drop across the RTT is constant regardless of the variations in lead resistance between the temperature sensor and the constant current power supply. Variations in output lead resistances will have negligible effect when the circuit is used with a high impedance amplifier. The constant current circuit has the disadvantage that without the offset circuit the output voltage is always greater than zero. The offset circuit provides a bucking voltage which enables the selection of zero output voltage for any desired temperature.

E. FLOW AND SPEED MEASUREMENTS

1. Flow Meters. Fluid meters are devices used to measure fluid flow quantity or fluid flow rate. Fluid meters consist of two distinct functional parts. The primary element is that part which is in contact with the fluid and is acted on directly by some property of the fluid. The secondary element is that part which translates the action of the fluid on the primary element into volumes, weights, or rates of flow for indicating and recording the results.

Fluid meters are divided into two functional groups. Quantity meters measure successive quantities such as weights and volumes; and are fundamental and basic to the rate meters. Meters of this group have only limited application to rocket testing. Rate meters measure rate of flow in a continuous stream. Meters of this group are in common use in rocket testing and include the orifice meter, the venturi meter and the turbine flowmeter.

a. Orifice Meter. The primary element of an orifice meter is simply a hole in a plate and is placed in the fluid line normal to the direction of flow such that it causes a drop in static pressure to occur while the fluid is passing through and just beyond the hole. The type in most common use and about which the most systematic studies have been made is known as the thin-plate sharp-edged orifice meter. This meter consists of a concentric circular hole in a thin flat plate with a sharp edge at the inlet of the hole. (See Figure IV-12). A rounded-edge orifice meter is less commonly used because it is difficult to specify and reproduce.

The difference in static pressure is measured between an upstream pressure tap and a downstream pressure tap and this differential pressure is correlated with rate of flow. This difference in static pressure is caused by the change of some of the potential energy (static pressure) of the fluid into kinetic energy (velocity) in order to satisfy the general physical laws of conservation of energy and conservation of matter. The Equation of Continuity expresses the conservation of matter and for the steady flow in incompressible fluids, its mathematical form is:

$$A_1 V_1 = A_2 V_2 = Q = \text{constant volume of rate of flow} \quad (15)$$

This equation states that the velocity is inversely proportional to the cross sectional area; therefore, the velocity of fluid has to increase

through the restriction in order to maintain a constant volume rate of flow through every section in the flow system.

The flow equation usable with any restriction in an incompressible fluid flow circuit is:

$$\dot{w} = K_w \sqrt{\Delta P \times \sigma} \quad (16)$$

where $\dot{w}$ = weight flow rate through a restriction (lbs/sec).

K_w = a constant, determined for a given restriction with water flow.

ΔP = differential pressure across the restriction.

σ = specific gravity of the fluid passing through the orifice.

From equation (16) it is realized that flow rate can be determined by measuring the difference in pressure across the orifice.

The orifice flow meter, as well as the venturi and turbine flow meters, are calibrated under laboratory conditions with known flow rates. Flowmeters designed for use with liquids are generally calibrated using water. Correction factors are then applied to the laboratory data to provide calibration data for the other fluids. When the flowmeter is to be used to measure gas flow, nitrogen is generally used for laboratory calibration.

The range using one particular orifice is from 1 to 2.3 up to 1 to 10. Overall accuracy varies from $\pm 2\%$ on a typical test setup to $\pm 0.5\%$ with ideal conditions. Response is sufficiently rapid for steady state flow over 1 or 2 seconds duration but not rapid enough to respond correctly to large flow rate changes within one second.

Differential pressure transducers are used as the secondary elements. The use of full bridge strain gage type pressure transducers permits the recording of flow rate parameters on the strain gage data acquisition channels.

b. Venturi Meter. The primary element of a venturi meter consists of three successive configurations: a converging entrance section, a cylindrical throat section, and a diverging exit section (see Figure IV-13). Each of the three sections are mated to minimize turbulence in the flow stream.

The difference in static pressure is measured between the upstream pressure tap and the throat pressure tap and this differential pressure is correlated with the rate of flow. Each section has a separate effect on the fluid velocity. The purpose of the overall configuration is to quickly accelerate the fluid stream and temporarily lower the static pressure while passing through the throat section, and finally, to decelerate the fluid stream uniformly and with the minimum turbulence so that the outlet static pressure will approach the inlet static pressure as nearly as possible. The venturi meter eliminates some of the disadvantages of the orifice plate by providing gradual changes in cross-sectional area, thus reducing the intensity of turbulence and decreasing the total pressure loss developed by the simple orifice. The venturi may be used for much higher flow rates than the orifice plate when used in the same sized line with the same tank pressures. The venturi has the further advantage of maintaining a more nearly constant discharge coefficient (C_d) than the orifice plate over the flow rate range, which extends its linear range.

c. Flow Nozzle Meter. A brief description of this flow meter is interjected at this point for the overall purpose of pointing out the correct names for each type of head meter. A flow nozzle is simply a venturi without the diverging diffuser section. A throat section ends abruptly with a very sharp 90 degree edge, whereafter, the fluid decelerates in the same turbulent manner as it does after the orifice plate.

The flow nozzle has the large overall pressure loss similar to an orifice plate. Flow nozzles occupy an intermediate position between the orifice plate and the venturi with respect to certain qualities. A flow nozzle is less expensive than a venturi and yet it possesses the better accuracy and linear range of a venturi. Differential pressure transducers are used as the secondary element for both the venturi meter and the flow nozzle meter.

d. Turbine Flowmeter. The primary element of a turbine flowmeter consists of a housing in which a freely rotating bladed rotor is suspended in the fluid passage. In one type of flowmeter a small Alnico magnet sealed inside the rotor induces an alternating electric current in the secondary element which is a pickup coil located outside the housing as close as possible to the rotor (Figure IV-14). In another type, usually

the larger sizes (3" and above), small magnets are mounted in the turbine blades. In still another type the coil is wound around a small permanent magnet and some or all of the turbine blades are made of a magnetic material which causes a signal to be induced in the pickup coil by variable reluctance. It should be noted that in each of these types, the turbine flowmeter is an active type transducer. That is, it generates its own signal without the requirement of exterior excitation.

The fluid flowing through the turbine flowmeter spins the rotor at a speed determined by the fluid velocity. Since the volumetric flow rate through the rotor section is directly proportional to the rotor speed, the output pulse frequency is directly proportional to the rate of the flow of a fluid of constant density through the meter. When this output signal is treated as a train of pulses by a counter, the total number of pulses produced is directly proportional to the total quantity of fluid flow. The turbine flowmeter is inherently linear over most of its range of operation. Some non-linearity will be encountered when operating at minimum flow rates, at which the fluid velocity is not high enough to provide sufficient upstream thrust to overcome the drag on the rotor. The turbine flowmeter can be installed in any position, horizontally or vertically with the flow either upward or downward so long as the flow is in the direction indicated on the housing. However, linearity over the widest possible range of operation will be obtained when the meter is mounted within 15 degrees of the horizontal. Because the rotor spins freely, it responds rapidly to flow changes, indicating fairly large transient changes within the time required for the rotor to make one complete revolution.

Because of the magnetic principle of operation, turbine flowmeters are fabricated from non-magnetic metals. Non-magnetic stainless steel has been adopted as the standard material because of its high resistance to wear and corrosion.

The accuracy of the turbine flowmeter is rated at better than $\pm 0.5\%$ and even on typical test bay installations the overall accuracy is within 1%. Most important, this turbine meter can supply this accuracy in the average liquid flow rate when the flow is pulsating. The ability to respond to pulsating flow rates is one of the chief reasons for the almost universal use of turbine sensing elements in rocket and ramjet testing.

Turbine flowmeters can measure flow rates from 0.01 to over 2000 lbs-per-second of rocket propellants. Flow rates range, using one particular meter, from 1 to 10 up to 1 to 23.

2. Speed Measurements. When the speed measuring transducer can be coupled directly to the rotating shaft, the tachometer is used. The tachometer operates as a miniature generator with a rotor of the tachometer connected to the rotating shaft. As the rotor is turned, an a-c voltage is generated in the stator winding. The frequency of this generated voltage is proportional to the speed of the rotating shaft.

A reluctance pickup is used for applications where a tachometer cannot be connected to the rotating shaft. The reluctance pickup consists of a coil wound around a small permanent magnet. Varying the field of the magnet by movement of an external magnetic body causes a voltage pulse in the coil. The magnetic body can be teeth on a gear or blades on a turbine.

By placing the reluctance pickup next to the teeth on a gear, one pulse will be produced each time a gear tooth moves past the pickup coil. Dividing the total pulses by the number of teeth on the gear gives the rpm measurement.

F. MISCELLANEOUS MEASURING SYSTEMS

1. Valve Position. Position indications are required for both remote shutoff valves (RSV) and analog control valves (ACV).

Indication of the RSV's in both the full open and full closed position is sensed by microswitches mounted on the valve.

The position of ACV's is sensed with linear displacement potentiometers or angular displacement potentiometers as shown in Figures IV-15 A and B respectively. The potentiometer, coupled to the valve stem, is connected into a bridge completion network, located in the signal conditioner as shown in Figure IV-15C. Full open valve position can be detected by microswitches or by an electronic discriminator circuit that conducts at a preset potentiometer output level.

2. Mechanical Displacement. The linear motion potentiometer is used to measure displacement from a fraction of an inch to several inches. Resolution of wire-wound potentiometers is limited by the number of turns

of wire within the slidewire. These units are restricted to low frequencies measurements due to the inertia of the sliding contact arm and contact resistance between the arm and slidewire.

Another device used to measure displacement is the Differential Transformer. It consists of a magnetic core suspended between three coils as shown in Figure IV-16. An a-c voltage is connected to the primary coil. The two secondary coils are connected in series opposition, so that the net output voltage is the difference between the voltages induced in the two coils. The output from each coil is determined by the mutual coupling between the primary core and each secondary coil. With the core centered between the two secondary coils the output voltages cancel and the output is zero. Movement of the core in upward direction from the center increases the coupling between the primary and secondary winding #1, while the coupling between the primary and secondary winding #2 decreases. Movement of the coil in the downward direction from the center produces a similar voltage but with opposite polarity. Both the Differential Transformer and the Potentiometer principles are used in transducers to measure velocity, acceleration, and pressure.

3. Level. Liquid level indicators are required to monitor the level of the LH_2 storage tank and the LH_2 run tank. The level is detected by an electrical capacitance probe. The difference in dielectric constant of gaseous and liquid hydrogen changes the capacitance of the probe as the liquid level changes. Capacitor type liquid level probes are constructed with two concentric tubes, or with two parallel plates which function as the plates of a capacitor. The liquid level probe is connected in a capacitance bridge similar to Figure IV-17. Change in fluid level changes the capacitance of the probe which in turn changes the bridge output voltage.

Level is also detected by pressure measurements. The level of fluids in unpressurized tanks can be determined by measuring the pressure at the bottom of the tank. In pressurized tanks, the difference in pressure between the liquid and gas pressure must be known to determine the level. The gas pressure is detected at the top of the tank and the total pressure is detected at the bottom of the tank. Subtraction of the gas pressure from the total pressure can be accomplished either algebraically or by a differential pressure transducer. Pressure measurements are used to determine the

level in the liquid oxygen storage tank and in the liquid nitrogen storage tank.

4. Vibration. Vibration measurements can be classified as (1) periodic, (2) transient, or (3) random. Frequency, displacement, velocity and acceleration are important in measuring periodic vibrations. In measuring transient vibrations, peak accelerations are of prime importance. In measuring random vibrations, analysis of the frequency spectrum is important.

The basic transducer for vibration instruments is the spring mass system represented in Figure IV-18. The mass element is suspended in the transducer by spring elements. Vibrations of the transducer cause a relative motion between the suspended mass and the transducer case. The sensing element is subjected to forces caused by the relative movement between the case and the mass. Depending upon the design of the transducer displacement, velocity or acceleration can be measured.

a. Acceleration. The mechanical system of the transducer has a natural resonant frequency. Transducers used to measure acceleration are designed with a high natural resonant frequency and are used in applications where this frequency is much higher than the frequency of vibration.

One common type of accelerometer uses a mass suspended on the end of a cantilever. (See Figure IV-19). The mass is restrained to a single degree of freedom. Unbonded strain gage elements are shown mounted on the cantilever, but bonded strain gage elements are also commonly used.

Strain gage accelerometers are available to measure acceleration as large as ± 5000 G, where G is the acceleration equivalent to the earth's gravitational field at sea level. Several types of strain gage accelerometers operate at frequencies up to 5000 cps. These accelerometers are used with strain gage signal conditioning equipment, and strain gage data acquisition channels.

The piezoelectric transducer commonly uses Rochelle salts, or barium titanate crystals, which generate a voltage when subjected to mechanical forces. Construction of a typical piezoelectric accelerometer is depicted in Figure IV-20. The major advantage of the piezoelectric transducers is the high frequency response, in excess of 1,000,000 cps. The

output from the crystal may be as high as 30 volts. But the high impedance of the crystal requires the use of special charge amplifiers, with input impedances above 50 megohms, to condition the signal for use in the data acquisition system.

b. Velocity and Displacement. Transducers using the same mechanical principle as the accelerometers are used to measure velocity or displacement. In order to measure velocity or displacement the transducer is designed with a low natural frequency and is operated in the region where the frequency of vibration is much higher than the resonant frequency of the transducer. Transducers of this type are commonly used in geophysical or seismic measurements.

The basic accelerometer can be used to measure velocity by connecting the output to an electronic integrator. Integrating the acceleration once gives velocity measurements. Double integration of the acceleration gives displacement. The use of the accelerometer for a long-term displacement transducer is limited by the drift and noise of the transducer.

G. RECORDING INSTRUMENTS

1. Graphic Recorders. The engine test data is displayed on strip chart recorders, pen recorders, optical oscillographs, event recorders, and magnetic tape recorders. Recorders are classified as either analog or digital; with the exception of the magnetic tape recorders, the recording instruments listed above are of the graphic analog recorder classification. Magnetic tape recorders are available as analog or as digital recorders. The present text is limited to graphic analog recorders; magnetic tape recorders are discussed in a separate section; and the principles of digital recorders are considered in the digital data systems section.

Graphic recorders contain two major mechanical systems: one system drives the chart paper and the second system places the data information on the chart paper. These graphic recorders are classified by the type of mechanical system that is used to record the data on the chart paper. The recorders used with the ETS-1 instrumentation system are of the following basic types:

- a. Direct Recording Galvanometer
- b. Light Beam Recording Galvanometer
- c. Null Balance Potentiometer Recorder
- d. Events Recorders

2. Definitions. The terms that apply to instrumentation recorders are defined by the American Standards Association and also by the Instrument Society of America. A list of the most basic definitions that are needed to understand the limitations of various recorders are included.

a. Frequency Response. Frequency response is defined as a range of frequencies over which measurements may be taken with a specific accuracy. Examples of frequency response specifications are:

- (1) Flat within $\pm 5\%$ from d-c to 100 cps.
- (2) ± 1 db to 100 cps.
- (3) Flat to 50 cps, 3 db down at 100 cps.

b. Scale Range. The scale range is expressed by stating the largest and smallest readings on the recorder scale. A linear scale may have end values of 0 and 100. If the center of the recorder scale is zero, the end values may be -50 to +50. Logarithmic scales are employed with typical ranges from 1 to 10^5 .

c. Span. The span of a recorder is the algebraic difference between the end values on the scale. For example, recorders with scale ranges of 0 to 100 and -50 to +50 both have a span of 100 scale units.

d. Accuracy. This is defined as the agreement of the indicated reading on the recorder with the true input to the recorder. It is expressed as a percent of span or as a fixed value in the units of the measured quantity.

e. Resolution. The resolution of the recorder is the smallest increment of the quantity measured that can be detected by the recorder. Factors affecting resolution include mechanical limitations of the recorder mechanism, width of chart paper, width of the recorded trace.

f. Response Time. The response time is defined as the time from the application of a step function to the recorder input until the recorder indicator has come to apparent rest. A recorder with a full scale

response time of one second would take one second for the indicator to move from one scale end value to the other after the application of a full scale input voltage.

3. Direct Recording Galvanometer. The direct writing galvanometer consists of a moving coil suspended in a magnetic field. The coil rotation is proportional to the current flowing through the coil, and a stylus connected to the rotating coil records on chart paper. The major components of the direct writing galvanometer recorder are illustrated in Figure IV-21.

The most common methods of recording information on the chart paper are:

- a. Ink pen.
- b. Heated stylus and heat sensitive paper.
- c. Completing a circuit through a metal stylus and electrosensitive paper.
- d. Stylus scribing on pressure sensitive or carbon coated paper.
- e. Chopper bar that presses the stylus against the paper.

The chopper bar recorders are the most economical, but recorders using this technique are limited to frequencies of less than 1 cps. Many of the inking recorders use curvilinear coordinates on the chart because the arc of the pin is a curve. The curvilinear motion of the stylus can be changed to rectilinear motion by mechanical means. Heated stylus and electrosensitive recorders usually use rectilinear coordinates.

The direct writing galvanometer must provide enough force to move the stylus mechanism across the chart paper, and a full scale coil current of 100 milliamperes may be required. An amplifier is necessary to increase the sensitivity of the instrument. Because of the mechanical limitations, the direct writing galvanometer is limited in frequency response to about 100 cps. For displays of data varying less than 100 cps, the direct recording galvanometer is a prime choice.

Examples of direct writing galvanometer recorders include the Bendix Aerovane Wind Recorder and the Beckman Dynograph. The specifications of the

Bendix Aerovane are:

Channels:	Two separate recording instruments in one case.
Writing:	Ink pen.
Chart Paper:	6" wide, curvilinear coordinates.
Chart Speeds:	1½, 3, 6 inches per hour.
Input Level:	0 to 10.56 volts.
Input Impedance:	1,150 ohms.

The specifications of the Beckman model R E Dynograph direct writing recorders are:

Channels:	8 analog channels plus one event channel and one timing channel.
Writing:	Heated wire styli.
Chart Paper:	Each channel 4 centimeters wide, rectangular coordinates.
Chart Speed:	1.0 to 250 millimeters per second in 8 steps.
Input Level:	0 to +5 volts or 0 to -5 volts, differential input.
Input Impedance:	200,000 ohms.
Common Mode Rejection:	120 db at d-c, 100 db at 60 cps.
Frequency:	d-c to 100 cps.
Accuracy:	1%.

4. Light Beam Recording Galvanometer. The light beam oscillograph uses a galvanometer that is much less massive than the direct recording galvanometers. The heavy mechanical stylus is replaced with a mirror mechanically connected to the rotating coil. The coil is a single loop of fine wire suspended in the field of a permanent magnet. A full scale coil current of only a few microamperes is needed to deflect the coil over the full range desired. If the low impedance of the coil does not adversely affect the input signal, these galvanometers can be used without the use of an amplifier.

Oscillograph galvanometers are divided into two classifications: (1) magnetically damped and (2) fluid damped. Damping is important when considering transient response. If the galvanometer is underdamped, a step voltage input will cause the moving system of the galvanometer to over-

shoot the desired deflection and to oscillate at its natural frequency. If the galvanometer is overdamped its ability to follow rapidly changing signals is reduced. Midwestern recommends a damping of 0.65 of critical as the best compromise between overshoot and slow response. Curves showing transient distortion vs. damping are included below:

The magnetically damped galvanometers require an external damping resistor. This resistor is placed in series with the galvanometer when the source resistance is less than the damping resistance or in parallel with the galvanometer when the source resistance is greater than the damping resistance. In the fluid damped galvanometer the coil assembly is suspended in a fluid. The damping is controlled by the viscosity of the fluid and is considered independent of the circuit impedance. The fluid damped galvanometers have a high frequency response, but they require considerably more coil current to provide a given deflection. A table giving the specifications of Midwestern galvanometers is included on the following page.

TYPE	UNDAMPED NATURAL FREQUENCY CPS	FLAT (5%) FREQUENCY RANGE-CPS	SENSITIVITY MILLIAMP./IN.	TERMINAL RESISTANCE OHMS	EXTERNAL DAMPING RESISTANCE OHMS	MAXIMUM CURRENT-MA
102A-40	40	24	.0040	33	350	10
102A-60	60	36	.0070	39	350	10
102A-100	100	60	.0098	34	225	25
102-150	150	90	.021	30	145	25
102-200	200	120	.039	28	100	50
102-300	300	180	.126	24	80	50
102-400	400	240	.226	24	40	50
102-500	500	300	.368	24	20	50
102-900	900	540	3.7	25	Fluid	100
102-1000	1000	600	4.6	25	Fluid	100
102-1500	1500	900	10.7	17	Fluid	100
102-2000	2000	1200	17.5	17	Fluid	150
102-3000	3000	1800	41.0	14	Fluid	150
120B-3.5K	3500	2100	19.4	39	Fluid	100
120B-5.0K	5000	3000	32.2	39	Fluid	100
120B-8.0K	8000	5000	65.0	39	Fluid	100
120B-10.0K	10000	6000	65.0	39	Fluid	100

The oscillograph optical system contains a light source, a lens system to direct the light to the galvanometer mirror, and a second lens system to focus the light beam from the mirror onto the photosensitive paper. (Figure IV-22)

The mechanical specifications of two oscillographs are considered. The Midwestern model 621 accepts a 6 inch wide roll of photosensitive paper 150 feet long. Eighteen chart speeds from 0.2 inches per second to 60 inches per second are provided by a combination of speed selector and range selector switch positions. As many as 14 galvanometer channels are available in this recorder. The Midwestern model 1210 includes up to 50 galvanometers. Chart paper for the model 1210 is 12 inches wide and 475 feet long. Speeds ranging from 0.1 inches per second to 160 inches per second are available from front panel push button control.

The photosensitive paper used with light beam oscillographs is developed by exposure to ultra-violet light or developed and fixed chemically. If the paper is not chemically fixed, continued exposure to sunlight will cause darkening of the record.

Light beam recording oscillographs are used to record data directly during test runs. They are also finding frequent use in recording the output from data reduction equipment and in displaying data originally recorded on magnetic tape.

5. Null Balance Potentiometer. Null balance potentiometer shown in Figure IV-23 contains four major sections:

- a. Slide wire
- b. Bridge circuit
- c. Servo amplifier
- d. Two phase servomotor

The servomotor serves to drive the slide wire which in turn changes the input voltage to the servoamplifier. The two phase motor must have voltage on both windings to operate. One winding is connected to the 60 cycle a-c line. The phase of the current flowing through the second winding is dependent upon the input voltage to the servoamplifier. A positive d-c input to the servoamplifier produces a 60 cycle output current in the servomotor control winding. This current leads the current in the line winding by 90° and causes the servomotor to run in the forward direction, thus moving the slide wire wiper in the up scale direction until the input voltage to the servoamplifier is zero or null-balanced. With no input voltage to the servoamplifier the output current is zero and the servomotor will not run. A negative input voltage at the servoamplifier input produces an output current that lags the current in the line winding by 90° . This causes the servomotor to reverse directions, and the slide wire wiper is moved down-scale.

Mechanical limitations of operating the servomotor, driving the slide wire, and moving the pen mechanism limit the speed response of null-balanced potentiometer recorders to $1/4$ second for full scale pen travel. Thus, null-balanced recorders are limited to recording signals with a frequency of less than 1 cps.

Two advantages are provided by the null-balance potentiometer recorders. First, high sensitivity down to the millivolt region is realized by the inherent amplification of the servo system. Second, independence of lead length is realized since at null-balance no current flows in the input circuit.

The specifications of two null-balance potentiometer recorders are listed below:

The Leads and Northrup Speedomax Type H Strip Chart recorder has the following specifications:

Number of Channels:	1
Full Scale Response:	1 or 5 seconds
Accuracy:	0.3%
Chart Width:	6 1/2 inches
Chart Speed:	1/4 to 60 inches per hour

The Bristol Dynamaster Strip Chart recorder has the following characteristics:

Number of Channels:	1
Full Scale Response:	0.4, 1 or 3 seconds
Accuracy:	1/4%
Chart Width:	12 1/4 inches
Chart Speed:	3/4 to 240 inches per minute

6. Event Recorders. Event recorders are used to indicate one of two fixed positions of the measured parameter rather than to indicate discrete analog levels. These recorders provide a record of the time that each event took place and indicate the sequence of the events.

Event recorders are available with either movable styli or fixed styli. In the movable styli recorders the styli are moved only a small distance usually less than 1/4 inch. The styli may be moved across the chart paper or they may not make contact with the chart paper except when energized by a signal. Movable styli recorders have one to forty channels and are capable of recording between 10 and 100 on-off cycles per second.

The fixed styli recorders employ electric current writing. Each channel indicates the presence or absence of a signal. Fixed styli recorders are available with as many as 650 channels on a twelve inch paper. Signals above 24,000 cps have been recorded on these instruments.

The specifications of the Brush model 14361500 event recorder are:

Channels:	150
Styli:	Fixed
Writing:	Electro-sensitive process
Chart Width:	15 inches with printed channel identification
Chart Speed:	5 to 200 millimeters per second in 6 steps
Input Level:	Not write = 0 to 1 volts, write = +4 to +60 volts, differential input
Input Impedance:	27,000 ohms
Frequency:	Capable of recording 800 event changes per second

Event recorders are valuable in providing a permanent record of valve positions, relay operation, predetermined level measurement, and sequences of operations occurring during test runs.

H. MAGNETIC TAPE RECORDERS

1. General. Magnetic tape recorders have met widespread acceptance in the instrumentation field. Possibly no other recording instrument has affected instrumentation and data processing systems as much as the tape recorder. Two factors are responsible for the wide use of these instruments. First, the tape recorder satisfies the need to record large quantities of measurements at fast rates; and is valuable in reducing the data rapidly to a form that can be utilized efficiently. Second, the tape recorder has several inherent capabilities. Some of the more important inherent capabilities are:

a. Wide frequency range, extending from d-c to over 4 megacycles per second.

b. Wide dynamic range, in excess of 50 decibels from 100% level down to 0.3% level.

- c. Immediate play-back, with no time required for processing.
- d. Repeated play-back capability, the same recording can be played back tens of times.
- e. Ability to alter the time base, allowing multiplication and division of all frequencies involved.

In operation, the tape recorder receives an electronic input signal, amplifies and conditions the signal to produce a current in a recording head coil. The magnetic field from the record head is applied to a magnetic tape as the tape is driven past the record head at a constant speed. This magnetic signal placed on the tape is a permanent record of the input signal. To recover the recorded data, a playback head is used to detect the magnetic information on the tape; the coil in the playback head is connected to an electronic amplifier, which re-creates a signal identical to the original input signal.

Three main types of recorders are utilized in instrumentation systems: direct record, frequency modulation (FM), and digital recorders. All of these tape recorders consist of three basic elements: the record and play-back electronics, the magnetic heads, and the tape transport (Figure IV-24).

2. Tape Transport. The primary function of the tape transport is to move the tape past the record and playback heads at a constant velocity. Standard transport speeds for direct recorders and FM recorders are 60, 30, 15, 7-1/2, 3-3/4, and 1-7/8 inches per second. The digital tape transports operate at 75 ips. The direct and FM recorders require highly constant tape speeds while digital recorders require fast start/stop times.

Basic components of the tape transport are:

- a. Supply Reel. The magnetic tape is fed from the supply reel, across the heads, and to the take-up reel. The supply reel provides hold-back tension to keep the tape in intimate contact with the heads during record or play back. The supply reel provides reverse tape motion to re-wind the tape.
- b. Inertia Roller. The inertia roller functions to smooth out variations in tape speed.
- c. Capstan. The capstan is driven by a synchronous motor and functions to meter the tape at a constant velocity.

d. Pinch Roller. The pinch roller serves to hold the tape against the capstan and to prevent tape slippage.

e. Take-up Tension Arm. The take-up tension arm functions to keep a constant tension on the tape when tape motion is first started.

f. Take-up Reel. The take-up reel provides for tape take-up during normal playing and for fast forward tape motion when shuttling the tape.

3. Magnetic Heads. The magnetic head used for record purposes serves to translate an electrical current into a magnetic field across a gap. The reproduce head translates the magnetic field of the recorded magnetic tape into an electric current. The head contains two identical core halves constructed from thin laminations of a material having high magnetic permeability, low electrical resistance, and good physical wear properties. Coils with equal number of turns are wound on each coil half. Non-magnetic separators are placed between the two core halves to provide front and rear gaps, Figure IV-25A.

The record head must have a gap size long enough to achieve deep flux penetration into the tape, but short enough to obtain sharp gradients of high frequency bias flux. A record gap of 1/2 mil is common. The reproduce gap size is a compromise between high frequency response, dynamic range and long wear properties. A reproduce gap of 1/12 mil is common.

Multiple channel tape recorders are achieved by using multi-track heads. Digital tape recorders utilize a single head stack with as many as 16 tracks displayed on a one inch tape. Direct and FM recorders use either the single head stack or a two head stack. The two head stack uses interleaved tracks, with the even numbered channels on one stack and the odd channels on the second stack. A distance between the center of the gaps in the two stacks is 1.500 ± 0.001 inches, Figure IV-25B. When using interleaved tracks, seven tracks are available on 1/2 inch tape and 14 tracks are available on 1 inch tape. Ampex Corporation has developed a two stack head with 32 tracks for use with 1 inch tape. The 32 tracks are obtained at some increase in cross-talk between tracks and slightly reduced current output of the playback head.

4. Direct Recording. In direct record machines the input signal is amplified, mixed with a high frequency bias, and fed to the record head. The high frequency bias is used to eliminate the non-linearity of the magnetization curve of the head. The amplitude of the bias signal is several times larger than the recorded signal, and the bias frequency is at least 3.5 times the high frequency specification of the recorder.

The bias frequency is too high to be picked up by the reproduce head and does not enter into the reproduce process. The frequency response characteristic of the reproduce amplifier is the inverse of the record amplifier so that the overall tape recorder system has a flat frequency response.

The voltage generated in the playback head is proportional to the rate of change of the magnetic flux. If the frequency of the signal is reduced sufficiently, the signal cannot be differentiated from the noise level. The direct record machines are limited to a low frequency range on the order of 50 cps. Direct record machines are also subject to amplitude instability. Amplitude instability is caused by imperfections in the surface of the magnetic tape and manifests itself in instantaneous loss or reduction in signal amplitude. This instantaneous loss of the signal is referred to as "drop-out."

The direct record mode provides two main advantages over other tape recording modes. These advantages are wide dynamic range and wide frequency spectrum.

5. Frequency Modulation Recording. In the frequency modulation tape recorders a carrier frequency is frequency modulated, or deviated, by the application of an input signal. With zero input signal the carrier frequency is said to be at its center frequency. A positive voltage causes an increase in the carrier frequency while a negative voltage causes a decrease in the carrier frequency. A full scale input voltage deviates the carrier frequency 40% above or below its center frequency, depending upon the polarity of the input signal.

The reproduce electronics demodulates the FM signal and filters out unwanted frequencies to produce an amplitude varying output signal.

Since the input signal is converted from the amplitude domain to the frequency domain, amplitude instabilities have negligible effect on the recorded data. The carrier frequency is present regardless of the amplitude of the input signal; therefore the FM recorder will reproduce d-c levels.

Any variation in tape speed appears as a modulation of the carrier frequency. These tape speed variations place very stringent requirements on the tape transport and limit the dynamic range and accuracy of the FM system. The frequency response of a typical FM recorder operated at 60 ips is 0 to 20,000 cps.

As the tape speed is reduced, the frequency response is reduced in a corresponding manner. For example, at 15 ips the frequency response is 0 to 5,000 cps and at 3-3/4 ips the frequency response is 0 to 1,250 cps. By recording at one speed and playing back at another speed, the time base can be either slowed down or speeded up. With FM recorders, changes in time bases by factors of 1,000 times or more are practical.

6. Digital Recording. Both the Direct and FM recording processes are analog in nature. To use the digital recorder, the information to be recorded must originate in digital form or be converted to digital form before entering the recorder. The input to the recorder consists of a series or a group of binary digits. The binary system uses only two digits - a zero or a one. In digital terms each zero or one is referred to as a "bit." The digital recorder magnetizes the tape to saturation in either of its two possible directions to represent the two digits.

Four basic formats have been used to record the digital data on the magnetic tape:

a. Return to Zero (RZ). In this format the tape is not magnetized between bits. The zero digit is represented by saturation in one direction and the one digit is represented by saturation in the opposite direction. In this format each bit is represented by a pulse.

The series of bits 01001011 recorded in the RZ format is shown in Figure IV-26.

b. Return to Bias (RB). In this format the tape is magnetized to saturation in one direction to represent zero and magnetized in the opposite direction to represent the one. After each bit the magnetization is returned to the bias condition. It must be noted that in this format one of the digits is represented by the bias condition.

c. Non-Return to Zero (Change). In the NRZ(C) format the tape is always saturated in one of the two directions. Reversal of the direction of the magnetization occurs only when the digit changes from a zero to a one or from a one to a zero.

d. Non-Return to Zero (Mark). In the NRZ(M) format the tape is always magnetized in one of two directions. Reversal of the direction of magnetization take place each time a one occurs. The non-return-to-zero formats are more efficient than the return-to-zero or the return-to-bias formats since twice the number of digits are permitted for the same number of reversals of magnetization.

The non-return to zero formats require an external timing pulse to instruct the tape recorder to read the tape at regular intervals. The NRZ(M) format is the most widely used system and offers the best compromise between accuracy, simplicity and reliability.

The digital recorders are sensitive to drop-outs. Imperfections in the tape can cause loss of pulses or spurious pulses. Parity checks and redundancy techniques are used to safeguard against drop-out errors.

In the redundancy technique the same information is recorded on two separate parallel tape tracks. In the parity check technique, one track on the tape is used to check the accuracy of the tape record. A parity pulse is recorded with the direction of magnetization such that the sum of all of the bits including the parity bit will be an even number. The parity check will detect the loss of one or any odd number of bits; an even number of simultaneous errors will not be detected.

The digital recorders have found widespread use in gathering of data, and in preparing data for analysis by computer. With the increasing volume of data for a given engine test, analysis using computer techniques is mandatory.

I. DIGITAL DATA SYSTEM

1. General. For many applications strip chart and oscillograph recorders are adequate. However, when large volumes of data points for a large number of channels must be recorded and processed with accuracies which are close to the limit of present measurement technique and when test to data presentation time is premium, digital data systems have been found optimum.

With a digital data system, the data is recorded in digital form on digital magnetic tape for subsequent use by a computer for tabulations, calculations, and preparation of magnetic tapes for other computers, X-Y plotters, and data storage.

Most transducers produce data in analog form so the data must be converted from analog form to digital form for use by the digital data system. The conversion is accomplished by electronic circuits using relays, flip-flops, or solid state switching devices. Since these elements have only two stable states (on or off) the mathematic system used with these systems contains only two levels and is called binary notation.

2. Binary Numbers. The number of distinct symbols used in a numbering system is called the "radex." In the decimal system the radex is 10 and the symbols are 0, 1, 2, 3, 4, 5, 6, 7, 8, 9. In the binary system the radex is 2 and the symbols are 0 and 1.

The individual symbols used to denote a quantity are called "digits." To write a number one larger than the largest symbol, two digits must be used. For example, in the decimal system 9 plus 1 is 10 or ten and in the binary system 1 plus 1 is 10 or two.

The digits in the decimal system are called the units digit, tens digit, hundreds digit, thousands digit and so on. These digits are also written as 10^0 , 10^1 , 10^2 , 10^3 . In the Binary system the digits are called the: unit digit, twos digit, fours digit, eights digit, and sixteens digit. These digits are also expressed as 2^0 , 2^1 , 2^2 , 2^3 , 2^4 .

The decimal numbers from 0 through 12 and the binary equivalents are listed in Figure IV-27.

Four binary digits are needed to express the equivalent to the decimal nine. Another form of binary notation called Binary Coded Decimal (BCD)

uses a group of four binary numbers to express each decimal digit. The decimal numbers from 0 through 13 and the equivalent BCD numbers are also expressed in Figure IV-27.

3. Analog-to-Digital Converters. The analog-to-digital converter changes the analog input signals into digital signals. This process is called digitizing. The analog-to-digital converters used in the Digital Data System digitizes analog input signals between the limits of ± 5 volts maximum to four BCD digits and sign. The conversion is accomplished by the successive comparisons of internally generated, digitally controlled voltages with the unknown analog input voltage. After 17 comparisons, the digitized output represents the analog input voltages to within one least significant bit.

To describe the successive comparison method of converting an analog signal to a BCD number, the following sequence should be examined for the conversion of a +3.547 volt input signal to BCD format.

Comparison Step	Comparison Voltage	E_s	Digital Controlled Voltage = $\sum E_s$ Retained	BCD Value	Decimal Character
	Retained*	Rejected			
1	0.0000		0.0000	+	+
2		4.0000		$\bar{8}$ **	1000
3	2.0000		2.0000	4	1000
4	1.0000		3.0000	2	1000
5	0.5000		3.5000	1	1000
6		0.4000	3.5000	$\bar{8}$	100
7		0.2000	3.5000	$\bar{4}$	100
8		0.1000	3.5000	$\bar{2}$	100
9		0.0500	3.5000	$\bar{1}$	100
10	0.0400		3.5400	8	10
11		0.0200	3.5400	$\bar{4}$	10
12		0.0100	3.5400	$\bar{2}$	10
13	0.0050		3.5450	1	10
14		0.0040	3.5450	$\bar{8}$	1
15	0.0020		3.5470	4	1
16		0.0010	3.5470	$\bar{2}$	1
17		0.0005	3.5470	$\bar{1}$	1

* Retained when V_i is greater than the summation ($\sum$) of E_s voltages.

** Bar over the number indicates a value of zero.

The comparison voltage (E_s) is compared to the unknown analog voltage, V_i , (3.547 volt) in 17 successive steps. The sum of the retained voltages equals that of the input voltage.

Digital recording of the analog voltage requires the digital equivalent of the analog voltage to be recorded in four columns with the summation of each column representing decimal thousands, hundreds, tens and units counts in descending order. Each column may be weighed from 0 to 9 digital counts.

In the above example, the converted value of 3.547 volts in BCD form is $\overline{8}421$, $\overline{8}4\overline{2}1$, $\overline{8}4\overline{2}1$, $\overline{8}4\overline{2}1$, which is equivalent to a decimal number of +7094. The bar over a number indicates the number value to be zero but is maintained as a place holder.

The system scale is such that 5.000 volts is equivalent to 10,000 counts. Therefore the decimal number of +7094 counts is converted to a voltage by,

$$\frac{+7094}{10000} \times 5 \text{ volts} = +3.5470 \text{ volts}$$

4. Digital Equipment. Both the Binary and the Binary Coded Decimal number systems are used in digital systems. Equipment designed to accept decimal numbers as an input can be built to produce BCD numbers more economically than to produce straight Binary numbers. Examples of equipment producing Binary Coded Decimal numbers are: (1) punched tape produced by electric typewriter, (2) digital indicating devices providing inputs to printers, (3) analog to digital converters. Binary Coded Decimal number systems are rarely used for the calculations within a digital computer. The BCD requires more digits to handle a given decimal number than does the straight binary system. For example, eight BCD digits cannot express a decimal number larger than 99, while eight Binary digits can express a decimal number as large as 255. Binary arithmetic is easier to handle by two state switching circuits than either BCD arithmetic or decimal arithmetic. Although the decimal number system is used by scientists and engineers, the input and output devices used with the digital data systems and computers convert the information to BCD. In the computer the information is converted to binary numbers for arithmetic operations.

Weldable Strain Gage

COURTESY of MICRODOT INC

**Wire Grid and Etched Foil
Strain Gage**

COURTESY of BLH

RESISTANCE STRAIN GAGES
FOR TRAINING USE ONLY

FIGURE IV-1

A WHEATSTONE BRIDGE CONFIGURATION

1. STRAIN GAGE MOUNTED ON TEST ITEM .
2. BRIDGE COMPLETION RESISTOR LOCATED IN ELECTRONIC EQUIPMENT.

B FULL BRIDGE CONFIGURATION

1. ALL FOUR STRAIN GAGES MOUNTED ON TEST ITEM .
- NO BRIDGE COMPLETION RESISTORS LOCATED IN ELECTRONIC EQUIPMENT.

C BRIDGE CALIBRATION CIRCUIT

1. CONNECTING R_C ACROSS R_2 IS EQUIVALENT TO INCREASING THE GAGE RESISTANCE .
2. CONNECTING R_C ACROSS R_3 IS EQUIVALENT TO DECREASING THE GAGE RESISTANCE .

D TEMPERATURE COMPENSATED BRIDGE

1. R_1 ACTIVE GAGE AFFECTED BY TEMPERATURE AND STRAIN.
2. R_4 DUMMY GAGE AFFECTED BY TEMPERATURE ONLY.

FIGURE IV-2

STRAIN GAGE BRIDGE CIRCUITS

FOR TRAINING USE ONLY

ACTION OF A PROVING-RING SENSOR

FIGURE IV-3

TYPICAL TABER PRESSURE TRANSDUCER WITH PROVING-RING SENSOR

FOR TRAINING USE ONLY

FIGURE IV-4

NERVA
TRAINING

FIGURE IV-5

CANTILEVER SENSING ELEMENT ACTUATED BY BELLOWS

FIGURE IV-6

LOAD CELL CHARACTERISTICS

Type: Bonded Strain Gage
Gage: Iso-Elastic Wire
Resistance: 350 Ohms

Range: 50 to 2,000,000 lbs
Excitation: 10v AC or DC
Linearity: 0.25% Full Scale

STRAIN GAGE LOAD CELL
FOR TRAINING USE ONLY

FIGURE IV-7

FIGURE IV-8

BASIC THERMOCOUPLE CIRCUIT

FOR TRAINING USE ONLY

FIGURE IV-8

CRYOGENIC THERMOCOUPLE STANDARD INSTALLATION

FIGURE IV-9

RESISTANCE TEMPERATURE TRANSMITTER STANDARD INSTALLATION

A. THREE-WIRE CIRCUIT

B. DOUBLE BRIDGE CIRCUIT

C. TRIPLE BRIDGE CIRCUIT

D. CONSTANT CURRENT CIRCUIT

FIGURE IX-11

FIGURE IV-12

FLUID FLOW THROUGH A THIN-PLATE ORIFICE
FOR TRAINING USE ONLY

FIGURE IV-12

FIGURE IV-13

GENERAL CHARACTERISTICS

TYPE. Induction, rotating permanent Magnet and Coil.

RANGES. (Flow) .01 lb/sec thru 2,000 lb/sec H₂O

RESISTANCE. (Coil) 75° F approx. 1,000 Ω , -297° F approx. 200 Ω

RESPONSE TIME. 2 to 5 Milliseconds.

TEMPERATURE RANGES. -300° F to 450° F.

LINEARITY. 1/2% over designated ranges.

OUTPUT VOLTAGE. 10 to 2,000 Mv. AC.

NOTES:

1. Large type meters have magnets in the rotor blades.
2. Flowmeter should have 10 line diameters of straight line ahead of installation point for calibration to hold true.

A. TYPICAL LINEAR DISPLACEMENT POTENTIOMETER

B. TYPICAL CONTROL VALVE

C. POTENTIOMETER BRIDGE SCHEMATIC

FIGURE IV-16

DIFFERENTIAL TRANSFORMER OPERATION FOR TRAINING USE ONLY

FIGURE IV-16

FIGURE IV-17

CAPACITOR TYPE LIQUID LEVEL PROBE
FOR TRAINING USE ONLY

FIGURE IV-17,

TYPICAL VIBRATION TRANSDUCER

FIGURE IV-18

STRAIN GAGE ACCELEROMETER

FIGURE IV-19

PIEZOELECTRIC ACCELEROMETER

FOR TRAINING USE ONLY

FIGURE IV-20

DIRECT RECORDING GALVANOMETER
FOR TRAINING USE ONLY

FIGURE IV-21

LIGHT BEAM RECORDING GALVANOMETER
FOR TRAINING USE ONLY

FIGURE IV-22

NULL BALANCE POTENTIOMETER
FOR TRAINING USE ONLY

FIGURE IV- 23

FIGURE IV-24

TAPE RECORDER COMPONENTS FOR TRAINING USE ONLY

FIGURE IV-24

A. HEAD CONSTRUCTION

B. TWO HEAD STACK

<u>DECIMAL</u>		<u>BINARY</u>					<u>BCD</u>							
<u>Tens</u>	<u>Units</u>	<u>16</u>	<u>8</u>	<u>4</u>	<u>2</u>	<u>1</u>	<u>8</u>	<u>4</u>	<u>2</u>	<u>1</u>	<u>8</u>	<u>4</u>	<u>2</u>	<u>1</u>
<u>Digit</u>	<u>Digit</u>	<u>Digit</u>	<u>Digit</u>	<u>Digit</u>	<u>Digit</u>	<u>Digit</u>								
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	0	0	0	0	1	0	0	0	0	0	0	0	1
	2	0	0	0	1	0	0	0	0	0	0	0	1	0
	3	0	0	0	1	1	0	0	0	0	0	0	1	1
	4	0	0	1	0	0	0	0	0	0	0	1	0	0
	5	0	0	1	0	1	0	0	0	0	0	1	0	1
	6	0	0	1	1	0	0	0	0	0	0	1	1	0
	7	0	0	1	1	1	0	0	0	0	0	1	1	1
	8	0	1	0	0	0	0	0	0	0	1	0	0	0
	9	0	1	0	0	1	0	0	0	0	1	0	0	1
1	0	0	1	0	1	0	0	0	0	1	0	0	0	0
1	1	0	1	0	1	1	0	0	0	1	0	0	0	1
1	2	0	1	1	0	0	0	0	0	1	0	0	1	0
1	3	0	1	1	0	1	0	0	0	1	0	0	1	1

FIGURE IV-27