RN-71007

FOLDER 1: TECHNICAL PROPOSAL

DESIGN OF LONG-LIFE, SPACE-MAINTAINABLE
NUCLEAR STAGE REGULATORS AND SHUTOFF VALVES

To GEORGE C. MARSHALL SPACE FLIGHT CENTER

March 1971

MASTER

AEROJET NUCLEAR SYSTEMS COMPANY

A DIVISION OF AEROJET-GENERAL

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TABLE OF CONTENTS

	<u>Page</u>
I. Introduction	1
II. Summary	4
III. Technical Discussion	6
A. Program Objectives	6
B. Problem Areas and Solution	6
1. Sealing and Operating Life	7
2. Thermal	10
3. Deep-Space Pressure (Cold Welding)	11
4. Radiation	12
5. Line Size Variability	13
6. Storage Life	13
7. Vibration	15
8. Remote In-Space Maintenance	16
9. Contamination	17
C. Design Concept Considerations	19
1. Valves	19
2. Regulators	26
3. Remote Coupling and Uncoupling	34
D. Engineering Analysis	36
1. Structural Analysis	36
2. Materials Analysis	39
3. Thermal Analysis	42
4. Probabilistic Analysis and Reliability	43
IV. Program Plan	45
A. Approach	45
B. Program Description	45
1. Phase I - Concept Selection	45
2. Phase II - Preliminary Design	48
C. Documentation	49
V. Program Management	51
VI. Related Experience	67

TABLE OF CONTENTS (cont.)

	<u>Page</u>
VII. Facilities and Equipment	75
A. Sacramento Facility Technical Information Center	75
B. Corporate Technical Information Center	77
C. Computer Facilities	78
D. Facilities for Future Tasks	79
1. Manufacturing	79
2. Testing	80

APPENDICES

A	System Considerations for Remote Replacement of Components
B	SEALCAL Computer Program Description
C	Leakage Data for Various Sizes of Lip Seals
D	Example of Valve Drawing

TABLES

<u>No.</u>		<u>Page</u>
III-1	List of Valve Concepts	20
III-2	Sample - Matrix Selection Chart	21
IV-1	Sample - Nuclear Stage Regulators and Shutoff Valves, Financial Status Report	50
VI-1	Typical Aerojet-General Valves and Components	69
VI-2	Valves Designed for Use on NERVA Flight Engine	73

FIGURES

<u>No.</u>		<u>Page</u>
III-1	Spherical Lip-Type Shutoff Seal	22
III-2	Pressure-Area Force Variation with Valve Diameter	25
III-3	Pressure Regulator Driving Mechanism	28
III-4	Pressure Regulator Regime	30
III-5	Pressure Regulator Building Block Approach	31
IV-1	Program Plan Flow Chart	46
IV-2	Program Schedule and Progress Chart	47
V-1	ANSC Engineering Operations Organization	52
V-2	Program Organization	53

I. INTRODUCTION

This proposal is submitted in response to Request for Quotation No. DCN 1-1-50-13584, dated 18 February 1971, from the George C. Marshall Space Flight Center, NASA/MSFC, Alabama, to design long-life, space-maintainable nuclear stage regulators and shutoff valves.

The Aerojet Nuclear Systems Company (ANSC) proposes to accomplish the program objectives delineated in the RFQ by conducting a 6-month effort, consisting of the following two phases (a final report will be submitted also):

- Phase I - Selection of Most Promising Concepts
- Phase II - Preliminary Design Drawings

The proposed program is fully responsive to the RFQ and features an orderly approach that will consider such significant parameters as performance, life, maintainability, reliability, cost, fabricability, weight, materials, radiation environment compatibility, contamination susceptibility, and engineering experience. Preliminary design drawings of the selected concepts will then be prepared to define the concept and related material requirements.

ANSC will fully satisfy the objectives of this program within the constraints of the proposed schedule and budget because the program is organized to take maximum advantage of successful related technology programs conducted by the Aerojet-General Corporation, such as:

Liquid-metal fast-breeder-reactor valve-technology program.

NERVA nuclear-rocket development program.

More than 500 types of electrical, electromechanical, and mechanical valves and controls designed and developed over the past 25 years.

Such past ANSC programs as NERVA technology development and the liquid-metal fast-breeder-reactor facility maintenance design have contributed to the development of innovations in the fields of remote coupling and uncoupling, remote "changeout" of components and subsystems, and remote checkout and verification of completed maintenance actions. These not only included unique designs for remotely operated electrical, fluid, and pneumatic couplings and associated support equipment but also studies of remote cutting, welding, and explosive bonding techniques. This background provides a sound engineering base to investigate radical departures from these current state-of-the-art technologies.

In addition to Aerojet's pertinent experience, ANSC plans to utilize a functional team of professional personnel. The program manager, L. D. Johnson, has 12 years of engineering experience in valve design and development, including 9 years with the NERVA program (relating to valve, electromechanical actuator, and line design and development) and will ensure maximum incorporation of existing technical experience and current NERVA program data. The appointment of E. A. Shearer as project engineer will ensure that Aerojet's valve design and development experience will be fully integrated into the proposed program. Mr. Shearer has 19 years of valve and control systems experience. During his 15 years with Aerojet, he has directed the design and development of major critical control systems for the Titan I, Titan II, Gemini, M-1, and Transtage engines and has served as project engineer for development of an all-metal, multipropellant-compatible, electric-motor-actuated valve for future deep-space engines. His current assignment is the supervision of NERVA valve design and development.

The proposed organization thus presents experienced leadership and a joining of scientific and engineering disciplines by the personnel that will effectively achieve program objectives within the scheduled time and allocated funds.

The proposed program is detailed in two folders. Folder 1, Technical Proposal, includes the technical discussion, program plan, related experience, project organization, key personnel biographies, and a description of appropriate facilities. Folder 2 is the Business Management Proposal and includes costs. Both folders follow the instructions contained in the RFQ and provide all information requested.

II. SUMMARY

The overall objective of the program is to select during Phase I the most promising concepts of nuclear stage regulators and shutoff valves that can be designed with characteristics which render them suitable for being space maintainable and capable of operation under the conditions set forth in the RFQ. The three most promising valve and regulator concepts selected in conjunction with the NASA project engineer will be subject to further investigation during Phase II and preliminary design drawings of each concept will be developed and submitted.

During Phase I, specific design criteria will be established as the basis for selecting valve and regulator concepts. The concepts selected will take into consideration the problems associated with the selection of materials and design configurations (including tolerances) to ensure that the designs are capable of meeting the performance requirements under specified environmental conditions. Problems associated with leakage, wear and operating life, contamination, storage life, temperature, pressure, radiation, and vibration environments, and remote in-space maintenance will be solved for each concept selected. Reports describing the progress made in the analysis and solution of problems will be submitted monthly.

After obtaining concurrence from the George C. Marshall Space Flight Center that three of the selected concepts for each the valves and regulators (including the methods selected for remote coupling and uncoupling) are feasible for meeting the specified design goals, preliminary design drawings of each concept will be prepared and submitted during Phase II. The drawings and associated analyses will be included in a final report describing overall program accomplishments and recommendations for future effort. The preliminary design drawings will dimensionally delineate the basic valve and regulator concepts and characteristics, including selected materials.

To accomplish the proposed effort, ANSC will use facilities available at the Sacramento Facility. These include an extensive Technical Information Center to facilitate a literature survey needed to aid and support the analytical effort. Also available is a complete digital computing facility. The Sacramento Facility is therefore adequately equipped to execute all tasks required to accomplish the proposed program in a timely and orderly manner during a 6-month program period.

In anticipation that additional effort in the areas of manufacturing and testing will result from this task, this proposal contains a description of facilities available in which this effort can be accomplished.

In view of Aerojet's past experience in the design and development of valves and regulators for several aerospace programs, the available personnel and facilities are considered fully qualified to complete the proposed task, as well as any future tasks that may result from this effort.

III. TECHNICAL DISCUSSION

This section describes the objectives of the long-life, space-maintainable nuclear stage regulator and shutoff valve design study program. To meet these objectives, envisioned problem areas (and their possible solutions), design-concept considerations, and the engineering analysis are also presented.

A. PROGRAM OBJECTIVES

ANSC proposes to meet all objectives of the RFQ without any exceptions to the work statement. The program objective is to develop valve and regulator preliminary designs which have minimum leakage, long life, and a space-maintenance capability. The objective is to be achieved by conducting a two-phase program as follows:

Phase I - Concepts to be studied will be established from available data, past experience, and imaginative design. Included will be radical departures from current state-of-the-art. With a matrix of requirements-versus-concepts the three most-promising concepts of a regulator and valve will be selected for future study.

Phase II - The concepts selected in Phase I will be developed into preliminary design drawings by applying design disciplines supported by engineering analysis.

B. PROBLEM AREAS AND SOLUTIONS

Prior to initiating any component design program it is important to review design requirements, make a determination of the anticipated problem areas, and list the proposed solutions to these problems.

The following section presents a summary of the most important problem areas and proposed solutions with full realization that many more problems will be discovered during the course of the program.

1. Sealing and Operating Life

Every seal design has some potential problems. Only a general discussion of the primary problems and solutions will be attempted here since elaboration would become voluminous. It is assumed that the radioactive environment levels will require the design of all-metal components (including seals).

A general problem-solution discussion of cycle life and fatigue will be covered in this section to describe the design philosophy that can be implemented.

a. Cycle Life and Fatigue

Material wear (either from rubbing or impact) has a major effect upon both seals and any parts having relative motion. Stress levels also must be considered to assure that the design will result in the required life with a high degree of reliability. The effect of thermal stresses will be included in determining the total cycle-life of a particular component.

Liquid lubricants are generally not practical in the presence of liquid hydrogen since they solidify and become brittle at the required operating temperature range. ANSC has experience using dry-film lubricants and interface surface coating combinations in critical areas (such as a gold surface on an electroplated surface). This experience and method of application will be employed in areas in which relative motion constitutes a wear problem.

b. Seal Leakage and Wear

The paramount determinant of valve success is the rate of leakage. Thus, the cyclic life must be considered in terms of resultant leakage. There are many interrelated factors that determine the leakage rate that will be obtained with any sealing arrangement. These must be identified and their relationship structured for proper evaluation. The following sections cover the general category of dynamic seals with respect to cycle life.

(1) Shutoff Seals

The shutoff seal is the heart of the valve. Attainment of 1×10^{-7} sccs helium leakage is a particularly critical problem. High sealing-interface loads will be required to achieve this leak rate; therefore, careful consideration will be given to friction and wear parameter "tradeoffs" to assure that the long-life requirements are also achieved.

Factors that determine the rate of leakage are: (1) pressure differential across the sealing interface; (2) the fluid being sealed; (3) physical material properties of the seal and seat; (4) interface contact length; (5) interface contact width; and (6) surface finish. For the shutoff seal, other factors must also be considered: e.g., interface geometry, constraint of the seal material, peak stresses from impact, and seal stress levels in areas other than the contact interface.

Many of the factors mentioned above are also major determinants of seal wear. To treat these many factors and their interrelationships on an item-by-item basis is impractical. In recognition of this, considerable work has been accomplished in the area of sealing analysis. A computer program (SEALCAL) has been developed by Aerojet to analytically predict leak and wear characteristics. This program, which is discussed in detail in Section III-D, and illustrated in Appendix B, will be a basic tool in solving the leakage and wear problem.

(2) Static Seals

Attainment of low leakage rates will require minimization of the number of flow paths. One way this can be accomplished is to use semi-separable and nonseparable seals at all interfaces other than the shutoff seal. The most critical problem which this approach presents is in the area of remote "changeout" of the component and component parts.

One solution is to use automatic orbital welding of the valve to the inlet and outlet lines to minimize exit and entrance joint leakage. This method is being developed for use on NERVA and has been extensively studied. The main problem area is in the detachment and subsequent reattachment of a replacement module while maintaining system cleanliness. The solution to the problem lies in development of a remote capability for cutting and welding. Other methods pertaining to remote coupling and uncoupling are discussed in more detail in Section III-C-3.

c. Other Elements

Other elements to be considered with respect to wear life are guides, pins, force-transmission links, and travel-limiting devices. The effects of acceleration loads, impact loads, and rubbing also must be considered.

Specific areas of concern are the effects of high rubbing speeds and the cyclic rate. There is evidence that velocity does not affect wear;^{*} however, frictional heating from repeated cycling during preflight check-out may influence wear life. Failure to consider these effects may result in fracture, changes in travel, free play, galling, and generation of contaminant particles. Treatment of these elements is less complex than that needed for seals.

^{*}McGregor, C. W., Editor, Handbook of Analytical Design for Wear, Plenum Press, New York, 1964.

2. Thermal

Thermal gradients during chilldown transients, as well as during nominal steady-state conditions, are potential problem areas because of thermal stresses induced in the components. Although all component parts are subjected to thermal stress, the component housing or body in most designs is the most severely affected. Fluid heating rates, solar heating, nuclear-heating "soak-backs" from adjacent hardware, nonsymmetrical housings, supports, and mechanical restraints all contribute to the magnitude of thermal stresses. These stresses can be sufficiently high to cause severe distortion which may result in seal-seat misalignment, binding of moving parts, and/or opening of leakage paths past seal assemblies.

Solution of the thermal-gradient problem cannot be defined in specific terms. Each design will require evaluation, and the correct approach for one component may not be entirely applicable to another. The general thermal-analysis approaches available are discussed in Section III-D-3.

Thermal cycling over a wide range of temperature is of particular importance to components for extended service. If this factor is ignored, a component that performs well during initial use could fail during extended service.

Solution of the potential problems will rely upon stress analysis in conjunction with heat-transfer analysis and knowledge of material characteristics. General guidelines as to allowable stress levels can be used for the preliminary design work; however, each design will require detailed analysis to assure that desired performance can be maintained for the design life of the component.

3. Deep-Space Pressure (Cold Welding)

One of the primary problem areas of a space environment is cold welding of contacting parts that must have relative movement during use. The adhesion mechanisms are accentuated by increased temperatures, surface-film instability, and increased surface loading. Oxygen and other gas species contribute to the prevention of adhesion of contacting parts designed for relative movement. Adhesion is prevented by the integrity of the surface film upon the contact surface. The sliding of surfaces and other mechanisms disrupt the residual contamination effects of the gas species. Thus, sliding surfaces are more subject to adhesion than "push-pull" contact surfaces. The solid-film lubricants generally used to prevent adhesion have a finite life; however, spacecraft experience justifies the use of MoS_2 and WS_2 for surface preparation. The life of the solid-film lubricant used is dependent on a combination of mechanical, physical, and chemical processes.

Although there is little useful design data available concerning cold welding, limited experimental results indicate that the degree of cold welding is a function of the mutual solubility between contacting materials and the interface stress level. Also, hard materials which have good wear resistance and support of surface-film contamination show good resistance to cold welding.

The primary approach in finding the general solution to this problem will be to select hard materials and/or coatings that have complete insolubility for the contact areas. Pressure welding can be avoided by designing these mating parts with a contact stress less than 50% of yield strength. The one specific area where this approach will be most difficult is the shut-off seat and seal required to meet the 1×10^{-7} sccs helium leakage requirements. However, seal design and test experience has demonstrated that sealing interfaces consisting of gold-plated surfaces in contact with electroplated surfaces will prevent surface adhesion.

4. Radiation

Radiation effects upon fluid control system components present both unique problem areas and some possible beneficial aspects with respect to increased strength. The phenomena can be categorized into areas of gamma dosage or nuclear heating and fast neutron dosage (nvt).

Considerations involving aerospace fluid control system configurations must take into account the results of expected radiation dosage. While gamma rates do not degrade physical properties of metals directly, the resultant molecular excitation increases the bulk temperature of the component or part. Sufficient gamma rates, combined with other sources of heating, can create severe problem areas for sophisticated hardware (e.g., loss of material strength at elevated temperatures, or an excessive expansion of parts, inducing leakage and binding). Large neutron flux dosages (10^{15} - 10^{22} nvt) have a definite effect upon material properties of most metal alloys and organic materials. In general, physical properties of metal alloys (e.g., yield strength, ultimate strength, and shock sensitivity) increase while ductility and fatigue strength decrease, which is very similar to work-hardening of common stainless steels.

Degradation of commonly used elastomers (e.g., Teflon, Kel-F, and Viton-A) has shown these materials to be relatively unsatisfactory in extended radiation environments. However, a comparatively new class of polyimide plastics have shown stable properties at dosages of 10^8 to 10^9 Rads, indicating promise for possible seal and bearing applications.

As nuclear radiation has a definite effect upon the material properties and thermal conditions of components designed for use in a radioactive environment, extreme care must be exercised in the choice of materials used in the design. A thorough nuclear-heating thermal analysis combined with the appropriate stress analyses (as discussed in Section III-D) must be performed to ensure hardware adequacy.

5. Line-Size Variability

Nearly all design parameters and considerations are directly affected by the size of component parts. Therefore, it is of major importance to select component configurations that are not too sensitive to changes in line size. The Phase I approach can be to design the components to meet the specified requirements at the maximum size required (i.e., 20-in. shutoff valve, and 6-in. regulator). Fewer problems will be encountered when scaling to a smaller size than when scaling to a larger size because in most design considerations the size-effects decrease as the part size decreases. For example: (1) distortion and relative motion between mating parts because of thermal cycling, pressure loading, and external loading is greater in a larger valve; (2) meeting the internal and external leakage requirements is more difficult in larger valves where sealing surfaces are larger and distortion is greater; (3) large components require greater actuation requirements to overcome inertia, pressure, and frictional forces; and (4) vibration considerations are more significant in the larger component because the natural frequency of a part decreases as the size increases. However, these design problems can be overcome by careful consideration of the particular concept configuration. For instance, the poppet valve shutoff seal concept discussed in Section III-C results in a component configuration that is applicable to a line size change from 3 to 20 in.

6. Storage Life

Environmental conditions during the storage life of component parts are usually less severe than those imposed during operating life. However, each component should be capable of satisfying all requirements of its controlling specification after being stored ten years in warehouse facilities. Provided that the component has been adequately designed and proper packaging and preservation procedures have been followed, the 10-year storage requirement should present no unusual problems.

A long-storage-life requirement makes it mandatory that the component design incorporate features that will not be affected during long inoperative periods. Two major problem areas that will require design effort are material creep properties and galvanic corrosion.

Creep may be defined as an increase in strain in a material under a constant static load at a given temperature. The total amount of creep varies with time, while the rate of creep is a function of temperature and stress level. Under less severe conditions, material relaxation (i.e., micro-creep) can cause yielding in various critical areas, subsequently resulting in malfunction of the component. For example, the valve seals may be degraded because of a loss of bolt preload at a flange seal or loss of spring preload at a poppet seal.

Since the radiation environment requirement has been assumed to preclude the use of plastic and elastomeric materials, such problems as Teflon "cold flow" and O-ring cure dates will not be a concern.

Solutions of the potential creep problems will rely upon stress analysis in conjunction with heat-transfer analysis and a knowledge of material characteristics. General guidelines concerning allowable stress levels can be used for preliminary design work: however, each design will require detailed analysis to assure that desired performance can be maintained for the designed storage life of the component.

Galvanic corrosion occurs when two dissimilar metals are coupled in the presence of an electrolyte. Galvanic corrosion also occurs when electrodes of the same metal contact different electrolytes, or the same electrolyte, but at different strengths. The extent of galvanic corrosion will depend upon the type of metal, the electrical resistance of the electrolyte, and the duration of exposure. Thus, a material combination which is acceptable for a one- or two-year lifetime may be unacceptable for a ten-year lifetime. The

use of dissimilar metals will be avoided wherever practicable. Where it is not possible, metals will be selected as close together as possible in the galvanic series. During operation and space storage, both liquid water and oxidizer are excluded. In fact, a high concentration of hydrogen in the environment will tend to retard corrosion. Protection must be provided during nonspace storage. The usual method is to employ a more-or-less impermeable seal between contacting interfaces to prevent liquid from reaching the metal surface. The coating (which also prevents cold welding and increases wear life) will be selected to be less subject to corrosion than the base metal.

Where the component can be completely enclosed, another method would be to purge the enclosure of air and moisture and maintain a controlled inert-gas atmosphere in the enclosure during the nonspace storage period.

7. Vibration

Vibration can be introduced in several ways when a component is in use. Flow-induced vibration from cavitation collapse, and vortex shedding must be considered with vibration induced through the structure. Although vibration may not be significant in short-term applications, the effects over three years may be detrimental to component functioning. In addition, vibration levels which may be acceptable in a 1/4-in. shutoff valve or regulator may be detrimental in a 20-in. shutoff valve or a 6-in. regulator. Experience has established that more components suffer reduced performance as a result of vibration testing than in any other form of environmental testing. Common causes of component failures under vibration are: (1) fretting of two interface surfaces, such as a poppet against a seat seal; (2) internal resonance of springs or structural supports, such as sleeve-gate supporting webs; (3) rubbing between springs; (4) physical impact between parts, such as a seal mass supported by a bellows impacting against the mating sealing surface; and (5) flow-induced vibration, such as chattering of flow-control elements in a regulator.

Vibration problems can be avoided through dynamic flow and vibration analyses as discussed in Section III-D. Based upon previous experience, design of vibration-sensitive components will be avoided. When necessary, the component stiffness and configuration will be modified to reduce vibration sensitivity. Examples of methods considered will be: (1) use of unsymmetrical parts, such as five as opposed to four sleeve-element supporting webs to reduce the effects of part resonance; (2) increase stiffness, if required, to increase resonant frequency; (3) use of nested springs to prevent the load from resonating at the same frequency; and (4) the use of parallel-stacked Belleville springs where friction between parallel discs can be utilized to provide spring damping.

8. Remote In-Space Maintenance

As a design goal, the valves or regulators would be designed for long life so maintenance would not be required during the storage life of ten years or an operating life of three years. This would be accomplished by selecting materials which are least affected by nuclear radiation or aging and by providing adequate margins for the as-aged or irradiated condition. A NERVA materials evaluation program has made available an extensive bank of data on the properties of many materials in cryogenic and radiation environments.

Maintenance consists of replacement of the entire valve or regulator or of a component. To obtain an optimum design, the requirements for maintenance or replacement should be considered throughout the development program from conception to application. Consideration of maintainability early in the design process produces an integrated design with an inherent space-maintenance capability.

An important factor to be considered is the level of maintenance. Trade studies can be conducted to compare weight and reliability factors for the case of replacing the components of the valve assembly as opposed to replacing the entire valve-actuator assembly as a unit. The study should be made throughout the specified size range of 1/4 to 20 in. for shut-off valves and 1/4 to 6 in. for regulators.

A study program is presently being conducted at ANSC in support of the design of the NERVA teleoperator*. Developments in space-vehicle remote manipulators produced in that program would be immediately available for application to the remote in-space maintenance problems of the valves and regulators studied during the proposed program.

System considerations in the design of remotely replaceable components are discussed in Appendix A.

9. Contamination

Contamination of some form and degree is always present in fluid systems. To attain a reliable flight system, fluid systems should be cleaned to the most stringent cleanliness level within practical and economical constraints for a given system. This is based upon the numerous variables associated with fluid contamination and upon the lack of adequate information concerning specific effects of contamination upon fluid system components. Only a small amount of data exists on the sealing characteristics of seals and seats in contaminated environments. Most of these data is for a specific system and is based upon broad assumptions and/or limitations in the existing state-of-the-art.

Particulate contaminants found in space-vehicle fluid systems originate from sources that are internal and external to the system. The various sources of these contaminants have been divided into four categories: (1) manufacturing process residuals; (2) operating fluids; (3) system generated; and (4) environmental.

Contaminants remaining from manufacturing operations, (e.g., metal chips, weld splatter, and lapping compounds) are very detrimental to

*NERVA Teleoperator Study, ANSC Report ANSC-TE001-W389f, December 1970.

fluid systems. However, these types of contaminants can be minimized by employment of rigid cleaning and inspection methods during the manufacturing cycle. Fluids used for final testing of a product, as well as operating fluids, are also a source of contamination if adequate filtration has not been provided. Many times test fluids are overlooked as a source of contaminants because they are assumed to be clean. Particles and various contaminants generated within a system as a result of friction, wear, and fluid deterioration are another source of system contamination. These system-generated contaminants are difficult to control since their origin includes the attrition and breakdown processes of all parts of the system after it has been designed, assembled, and tested. The cleanliness of a system can only be as clean as the environment in which it was assembled. Inevitably, airborne contamination will enter a system whenever the system is not adequately protected. A means of controlling this type of contamination is to provide a "clean" room where the air has been filtered to a specified level of cleanliness. The degree of cleanliness required varies for each application, and the contaminants from all four categories must be controlled within limits specified to achieve the desired results.

A possible solution to contaminant-induced problems is to design components to operate in a limited contaminated environment. The typical valve designer usually concentrates his efforts upon classical problems involved in valve and regulator design and assumes that all contaminants will be eliminated by fluid filters. However, by taking an approach that the component must operate at a specific contaminated level, innovations in design concepts can be provided that would assure satisfactory component performance. As an example, a limited contamination test program was completed by ANSC which tested a metal-to-metal valve design concept under the most severe contamination conditions expected to be encountered during actual engine operation. This test program concluded that problems associated with a reasonable level of contamination can be solved satisfactorily by appropriate design techniques.

C. DESIGN CONCEPT CONSIDERATIONS

1. Valves

Valve types to be studied include ball, butterfly, poppet, blade, and sleeve as shown in Table III-1, as well as radical design approaches. The selection of a valve for a particular application is dependent upon many factors as shown in the sample matrix chart of Table III-2. The following requirements have the most influence upon concept selection. The shutoff device: (1) must have optimum seal loading to ensure good leakage control, yet long cycle life; (2) must have minimum seal abrasion during cycling to ensure good leakage control; (3) must have maximum flow area for the valve size and configuration to assure a low pressure drop, a small envelope, and light weight; (4) must use carefully selected materials to ensure propellant and radiation environment compatibility, cold-welding resistance, cycle life, and temperature compatibility; (5) must provide access for removal of the valve element and seat; and (6) must minimize actuator power requirements and response times.

The required leakage rate of 1×10^{-7} scc/sec is a difficult goal to achieve especially in the larger line sizes. The difficulty arises from loading a materially compatible seat-seal combination to the degree required to obtain sealing and yet not overloading the seal to a point where seal life cannot be achieved. The SEALCAL program, will be utilized to determine the seal and seat materials, sealing forces, and surface finishes required to meet the allowable leakage and life requirements.

Spherical poppet shutoff seals have been successfully used by Aerojet in various line sizes. This seal is a hard-on-soft surface metal-to-metal lip type. The basic seal design is shown in Figure III-1. Demonstrated performance data are presented in Appendix C. Poppet-type valves usually provide the best shutoff sealing capability, but actuator loads and pressure drop are high in the larger valve sizes.

TABLE III-1

LIST OF VALVE CONCEPTS

Poppet Valve

 Conventional

 Inverted

 Coaxial

Gate Valve

Blade Valve

Butterfly Valve

Rotating Ball or Visor Valve

Rotating Cone Valve

Rotating Plug Valve

 Tapered Plug

 Cylindrical Plug

 Translating Plug

Sleeve Valve

 Conventional

 Rotating

 Translating

 Angled

 Coaxial

Flapper Valve

Diaphragm Valve

TABLE III-2

SAMPLE - MATRIX SELECTION CHART

		LEAKAGE	CYCLE LIFE	IN-LINE MAINTENANCE	REPLACEMENT MAINTENANCE	SPACE VACUUM	THERMAL	RADIATION	OPERATING LIFE	STORAGE LIFE	SCALING	VIBRATION	ACCELERATION	CONTAMINATION	PRESSURE DROP	ACTION FORCE	RESPONSE	WEIGHT	ENVELOPE	PRODUCIBILITY	INSPECTION	CLEANING				
CONCEPT NO. 1	ADVANTAGES																									
	DISADVANTAGES																									
	SUMMARY																									
CONCEPT NO. 2	ADVANTAGES																									
	DISADVANTAGES																									
	SUMMARY																									
CONCEPT NO. 3	ADVANTAGES																									
	DISADVANTAGES																									
	SUMMARY																									
CONCEPT NO. 4	ADVANTAGES																									
	DISADVANTAGES																									
	SUMMARY																									
CONCEPT NO. 5	ADVANTAGES																									
	DISADVANTAGES																									
	SUMMARY																									
CONCEPT NO. 6	ADVANTAGES																									
	DISADVANTAGES																									
	SUMMARY

SHUTOFF SEALING CONSISTS OF A THIN, SPHERICAL SHELL SEATED IN THE CONICAL SEAT PORTION OF THE VALVE BODY.

DURING CLOSURE THE SEAL CONTACTS AND CENTERS ITSELF IN THE SEAT.

A WIPING OR LAPPING ACTION BETWEEN SEAL AND SEAT PRODUCED MICROSCOPIC CONFORMATION OF THE SEALING SURFACES.

DEFLECTION OF THE SEAL PROVIDES THE SEALING PRELOAD.

EXCESSIVE SEAL DEFLECTION IS PREVENTED BY ACCURATELY LIMITING THE DEFLECTION WITH THE STOP.

Figure III-1 - Spherical Lip Type Shutoff Seal

Materials, seat-seal width, material finishes, load, and pressure determine the internal leakage of valving elements. Long seal life also is dependent upon the use of a valving concept that has a minimum of seal rubbing during actuation. The poppet and diaphragm valves are examples of designs which result in very little rubbing. The "wiping" in ball, plug, and butterfly designs may be eliminated by seal lift-off devices which lift the seal from the rotating member during actuation. However, these devices can introduce complexity and problems of their own.

Pressure drop, flow, and the configuration of the valving elements are interdependent. Ideally, a shutoff device would have no pressure drop when open, in order to reduce system losses to a minimum. Ball, gate, blade, and plug valves have excellent flow characteristics and low pressure drops because these designs have a virtually straight-through flow path in the open position.

The remote "changeout" of the valve element and seal will require the full extent of Aerojet's experience with teleoperators and remote handling of radioactive components and materials. Internally, the task is to provide a removable valve-element cartridge without performance degradation because of the additional static-seal internal leakage paths. Additional design penalties are increased complexity, greater weight, and a larger envelope. The plug-in cartridge approach lends itself to angle valves, such as poppet and sleeve types. In-line valves where this technique can be used are the flapper and gate concepts. With appreciable weight-envelope penalties, the plug and ball concepts also can be used. In-line poppet and butterfly concepts do not lend themselves to a removable cartridge approach.

Valve-actuator power requirements and response are affected by the mass of the moving parts, pressure differential, friction forces, and the valve-element travel. Increasing actuator force or a decreasing actuator load will improve response characteristics. Therefore, the valving element

must be light but sufficiently strong to withstand the differential pressure. The effect of flow forces during the opening cycle can be appreciable upon ball and butterfly valves. For unbalanced poppet-type valves, shutoff sealing forces are in excess of 1000 lb at 100 psid for valves larger than 3 in. (see Figure III-2). Valve concepts which minimize these loads are the sleeve, balanced poppet, and the visor valve. Although the loads at 100 psi are not excessive upon a gate valve, the required envelope is relatively large because of the stroke requirements.

Figure III-2 - Pressure-Area Force Variation With Valve Diameter
for an Unbalanced Poppet Pressurized at 100 PSIA

2. Regulators

a. Introduction

There are many types of pneumatic and liquid systems to regulate pressure and flow utilized in space applications. Each type and its respective components are specifically designed to meet the unique requirements of a specific mission. In the case of the regulators described in the RFQ, critical areas to be stressed are "radical departures from current state-of-the-art in the field of remote coupling and uncoupling, as well as remote change-out of components and component parts," in addition to the other major parameters.

b. Types of Regulators

To study radical concepts, a baseline of the existing "state-of-the-art" is required. The following types of modulating regulators can be encountered in space applications:

1. Pressure-reducing regulators
2. Differential pressure regulators
3. Absolute pressure regulators

c. A Concept Consideration

Radical approaches to regulator design will be considered, as well as the modification of common concepts.

The pressure-reducing modulating regulator is the simplest type of regulator utilized in space applications.

These regulators are normally in combination with shutoff valves that are generally located upstream of the regulators and in the closed position with the system inactive. When the system is activated, the shutoff valve opens to permit high pressure to flow to the inlet port of the regulator. The regulator immediately responds to the step-input pressure and starts controlling downstream pressure to the preset values. If the regulator enters the lockup mode with the shutoff valve open (because downstream system demands) then lockup leakage must be minimum.

This kind of leakage can be achieved by a strenuous force amplification imparted by the sensing-element load and its attendant driving mechanism to generate high seat stresses. A scheme for demonstrating the way in which this may be accomplished is shown schematically in Figure III-3.

Pressure-reducing regulators are generally defined in one of the following categories: (1) direct acting; (2) dome loaded; and (3) piloted assemblies.

The direct-acting pressure-reducing regulator is the simplest unit of the three categories and utilizes the least number of parts. The direct-acting regulator is generally limited to the smaller sizes, depending upon the precision requirement of the regulation band tolerances, required flow rates, and lockup requirements.

The dome-loaded pressure-reducing regulator is more complex than the direct-acting unit. It generally consists of a small direct-acting regulator that loads the dome or sensing element of a larger regulator with a constant reference pressure. Dome-loaded regulators are generally used when increased flow capacities would normally require much larger direct-acting regulators. Large direct-acting regulators yield larger control-band tolerance, sluggish response, and are troublesome in vibration.

Figure III-3 - Pressure Regulator Dirving Mechanism

Piloted pressure-reducing regulators are more complex than either of the direct-acting or dome-loaded types. These units normally consist of a bleed-flow pressure regulator that supplies regulated bleed-flow pressure to the main-stage sensing element. A pilot-valve controller senses regulated pressure and varies the bleed flow from the sensing element with a resultant change in sensing pressure that is proportional to the changes in regulated pressure. Pilot pressure-reducing regulators are used when flow demands are high, inlet pressure variation is high, and when the regulated pressure tolerance is small. Figure III-4 shows the usage regime of each of the three categories of regulators and is generalized for the purposes of this proposal so the three categories of pressure-reducing regulators could satisfy the finalized requirements for the various line sizes as follows:

1. Direct-acting regulator: 1/4 to approximately 3/4 in.
 2. Dome-loaded regulator: approximately 2.5 in.
 3. Piloted regulator assembly: 3 to 6 in.
- d. Building-Block Approach

A building-block approach should be considered to maintain commonality of concepts, as well as a commonality of designed parts. For instance, the building-block study would determine the feasibility of using a direct-acting 1/4-in. regulator as a reference pressure regulator to dome-load the 1- and 1-1/2-in. dome-loaded regulators. Figure III-5 shows the possibilities of the building-block approach, the success of which would greatly enhance the space maintainability of the family of regulators. Figure III-5 also indicates that the larger sizes of direct-acting regulators could possibly be used as the pilot valves for the piloted regulator and (possibly with some major parts of the direct-acting regulator) for the controller pilot. The main valving elements of the dome-loaded regulators and the pilot regulators could be identical in concept and also a family of sizes.

Figure III-4 - Pressure Regulator Regime

Figure III-5 - Pressure Regulator
Building Block Approach

e. General Construction

The regulators would be of all-metallic construction. Materials would be selected that would satisfy the design, strength, and performance requirement, as well as being reasonably impervious to such environments as radioactivity, sublimation in a space vacuum, notch sensitivity in a cryogenic environment, and hydrogen embrittlement. All internal joints subject to external leakage would be of welded or brazed construction. Where necessary for strength purposes, these joints would also be mechanically supported. Minimum internal leakage would be achieved, where required, by mechanisms that create force amplification during the seating process for high seating stresses. To achieve minimum leakage, seating materials and sealing techniques would be selected after theoretical investigations and a search of state-of-the-art information

f. Remote "Changeout" of Component Parts

A strenuous investigation will be performed to determine the most feasible methods, designs, and techniques for remote "changeout" of component parts in the regulator module without removing the entire module from the line and without destroying the leakage or performance integrity of the unit. This investigation will include such items as remotely removing a malfunctioning pilot-valve assembly from a piloted regulator module and replacing it with another precalibrated pilot assembly, including resealing the replacement joint.

The study will also include the possibilities of replacing such items as seating and sealing elements within the malfunctioning pilot assembly, recalibrating the unit, and reassembling the repaired unit into the regulator module. In addition, investigations will include methods of isolating and pinpointing the malfunction or failure so the proper part and procedure can be selected in advance of the replacement or repair.

g. Design Concept Considerations and Problem Areas
to be Studied

1. Investigate valve elements that will yield minimum leakage when they are highly stressed. Problem areas are in the selection of materials that are very hard when in contact with soft metals. Concepts may be conical poppets, optically flat poppets, or spherical poppets. Soft materials must be shielded from erosion caused by flow impingement and hard materials must be sufficiently hard to be impervious to flow impingement.

2. Investigate concepts for the construction of sensing elements which will have low rates and temperature compensation. Problem areas will be leakage through walls, brazed or welded joints, and the selection of metallic materials that will permit fabrication and temperature compensation.

3. Investigate concepts for force amplification to highly stress the seated valving elements. Problem areas include the selection of efficient mechanisms that can take high loads during short strokes. Metallic materials must be capable of high stress levels and thermal expansion coefficients compatible with the rest of the design.

4. Investigate concepts for items 1, 2, and 3 that will lend themselves to a building-block approach for certain elements of the various sizes of regulators (from 1/4-in. to 6-in. line size) to achieve maintainability. Problem areas include sizing of the necessary elements to perform two or more performance tasks.

5. Investigate concepts for modularizing the various elements in the building-block approach so optimum maintainability and the replacement of subcomponents and component parts can be achieved. Problem

areas will include standardization of similar modules and elements that can easily be removed, repaired, and/or replaced without impairing the ability to reseal the replacement joint.

6. Investigate methods and devices for detecting and isolating a malfunction or failure so the proper part and procedure can be selected in advance of replacement or repair. Problem areas will include the development of detecting and isolating devices that will be simple to operate and will not create complexities that can detract from overall performance parameters. .

Concept considerations will not be limited to the six items above.

3. Remote Coupling and Uncoupling

Coupling a valve or regulator to a system or a removable cartridge to a body requires the accomplishment of fluid seals and a means of resisting loads. When coupling and uncoupling is to be performed remotely, the component must then be designed to produce a successful joint when installed by a remote manipulator and under conditions of zero gravity and hard vacuum. The limited dexterity, visibility, accuracy, and tactile feedback of available and expected manipulators requires careful consideration of these factors in coupling design to obtain alignment and prevent damage to seals and other critical surfaces.

A basic approach can be used to create new concepts to solve the problems inherent with remote coupling and uncoupling of components in space. Different methods of solution involving mechanical, electrical, hydraulic (LH_2), magnetic, pneumatic (GH_2 , He), electronic, chemical, thermal, ordnance, or combinations of these means are considered during the synthesizing phase. Available methods of coupling include:

1. For resisting loads:

- a. Bolts or similar fasteners
- b. V-band couplings
- c. Screw couplings
- d. Breach locks
- e. Axial latches
- f. Orbital welding
- g. Quartz-lamp brazing

2. For sealing:

- a. Static seals
- b. Orbital welding
- c. Induction brazing
- d. Quartz-lamp brazing
- e. Fusible seals

Different valve-to-line interface configurations and orientations can be considered as they relate to coupling and uncoupling and the elimination of associated problems. For instance, two external static seals would normally be required to install a valve. However, if the flow is turned 180° and returned through a concentric annular line, then only one external seal is required and the total external sealing length is reduced so the probable external leakage rate is also reduced.

Various coupling configurations (including tube-to-tube, single plane, and cartridge type) are possible. A literature search would aid in the preparation of a detailed list of the specific problems that have been encountered to assist in the conceptual process and, later the evaluation of selected designs.

During the design phase, remote coupling and uncoupling requirements should be considered as one factor in the total system that consists of the remote manipulator, the component, and the spacecraft.

Although metallic seals have been given major attention, developments with radiation-hardened nonmetallics (e.g., the polyimides) have produced materials with radiation resistance comparable to the metals. The nonmetals are softer and competent seals can be obtained with less seal loading, greater tolerances, and rougher surface finishes.

Remote-coupling technology developed for the NERVA engine and during the NERVA teleoperator study program is available and will be utilized in the proposed program.

D. ENGINEERING ANALYSIS

ANSC has at its disposal highly refined analytical techniques to evaluate component and system designs. However, its real strength lies in its experience which permits personnel to properly interpret analytical results and ensure complete coverage of an analytical problem. The degree of investigation and sequence of analysis will vary with each component design; however, there are many developed skills common to nearly all designs. The analytical discipline capabilities available for application to the valve and regulator concepts are presented in the following section.

1. Structural Analysis

A component's structure is analyzed to establish short- and long-term structural integrity in terms of stress levels and magnitudes of distortion. For operating and storage lives of three and ten years, respectively, creep and fatigue problems can often become the critical

criteria. Optimum stress levels in any design are obtained by carefully considering the effects of mechanical loading, thermal profiles, and pressure gradients. If the full design potential is to be achieved, the relationship between these stress contributions must be completely understood. Eventual wall thicknesses in a final design are the result of artful maneuvering about these contributing factors.

ANSC possesses a computer program entitled "Finite Element Stress Analysis Applicable to Compressible Solids with Non-Linear Material Properties", Code No. Ell401. Utilizing a finite-element method of solution, this program calculates stress distributions in any axi-symmetric or plane stress configuration. The boundary conditions are most general and will accommodate thermal, pressure, and mechanical constraints resulting from the external environment. This program will even solve problems that possess significantly large, plastically yielding regions. All types of principal stresses and displacements existing in each element are ascertained. The stress analysis is accomplished on a most expeditious manner, in that the finite-element grid used in the stress analysis is coordinated with the thermal-analysis grid. This procedure results in a minimum of extrapolation of temperature data which are later used in the stress analysis program if thermal affects are of concern.

This program has been successfully utilized to evaluate axisymmetric seal designs.

Natural frequencies and dampening coefficients can be established using a lumped (discrete mass) or continuous (distributed mass) analytical model for comparison with the system environment. If the damping cannot be satisfactorily employed through the use of frictional surfaces or material selection, then the mass distribution can be changed or the structure stiffened to effect an overall shift in resonant point. A configuration alteration is often required.

Structural analysis of a flow component often requires use of potential flow and boundary layer equations. For example, contraction coefficient at vena contracta (important to cavitation phenomena) can be determined by potential flow equations, whereas flow in a separated region downstream of a valve seat can be characterized by using appropriate boundary-layer equations. Since cavitation and vortex-shedding phenomena serve as a forcing function in a fluid-dynamics vibration problem, these analytical tools become important. A knowledge of fluid dynamics can often prevent premature seal and valve element failures.

Valve and regulator designs can be analyzed to determine impulse-momentum problems associated with impact dynamic loading. The moving part (e.g., gate or poppet), has an equivalent momentum prior to impact which must be arrested by the impulse of the resultant force. If the stop (e.g., the seat) is structurally stiff, the impulse duration will be short and the peak force large. On the other hand, a soft structure will spread the load over a larger period of time and, thereby, a lower peak force will be incurred. Often mass-spring-damper models are utilized for this type of analysis. If these loads become excessive because of the valve impact response requirement, the maximum displacement of a seal must often be protected with the aid of a positive stop.

Pressure transients created by rapid valve or regulator response can also be evaluated. These mechanical displacements which generate pressure waves may create substantial fluid changes of momentum against structural members. While the compressibility effects of gaseous fluids certainly reduce pressure spikes and cause rapid damping, large flow areas (such as those in 20-in. valves) produce significant load levels. In cryogenic environments of liquid hydrogen, material impact strength may be greatly reduced and these transient perturbations can cause serious problems.

While compressive loads are generally not regarded as significant, the buckling phenomenon is of unique importance. Often springs of valves and regulators with large strokes suffer from instability problems. Column loading also should be carefully analyzed.

2. Materials Analysis

The most significant types of irradiation in terms of damage to component design are neutron bombardment which downgrades structural materials, and exposure to gamma rays which deteriorates organic substances. Some of the more critical design properties of conventional structural materials which are significantly influenced by nuclear irradiation are:

1. Tensile yield strength can increase by as much as 100% in annealed materials, whereas smaller increases are experienced in metals previously strengthened by cold working or heat treatment.
2. Ultimate tensile strength can increase up to 75% in annealed materials and to a lesser extent in cold-worked metals.
3. Total elongation decreases by as much as one third in annealed metals, and somewhat less in a cold-worked condition.
4. Impact strength decreases and ductile-to-brittle transition temperatures are elevated.
5. Electrical resistivity increases as much as 10%.
6. Creep is affected moderately if material is irradiated while under stress.

7. Dimensional stability can also be moderately affected.

It is significant to note that high-strength alloys and precipitation-hardened alloys may suffer greater loss in ductility than stated above. Notch-sensitive materials are also more severely embrittled than the "tough" structural alloys. Fortunately, material properties (e.g., corrosion resistance and fatigue strength) are affected very slightly by nuclear irradiation.

The primary source of materials properties data available to ANSC personnel is the Materials Properties Data Book*. This document was prepared as a design guide for materials usage within the NERVA program. These data were selected by a critical review of the content of nearly 500 sources and tabulated in two reference volumes. Properties are presented in a statistical manner because of the high reliability goals that had to be met on the NERVA program.

A secondary source of material information is the ANSC Radiation Effects Data Book which contains much information regarding non-metallics.

ANSC has extensive knowledge of hydrogen embrittlement as a result of effort on the NERVA program. The severity of embrittlement is primarily a function of pressure, temperature, material strength and composition, and hydrogen purity. Most current data available have limited usefulness for design guidance in the elastic stress range since the data are obtained mainly in the plastic stress range. While a reduction in the design-load stress and a fracture-mechanics analysis are approaches to combatting this problem, the best solution remains to utilize a nonembrittling material from the start of a design concept.

*ANSC Report 2275

Space welding is also a consideration in material selection. Where leakage constraints are high, stresses between sealing interfaces generally increase. This will promote greater interaction between surface molecules and increase the probability of mechanical bonding. Data from the NERVA program are available to aid in material selections.

The long life and low leakage requirements of Phase I require materials to be resistant to both galvanic and stress corrosion. Of course, these resistant properties are only as valuable as the atmospheric corrosion resistance inherent in the parent material used in the design. Weld joints and highly stressed interfaces are regions which experience has shown to be very sensitive to the corrosive phenomena.

The problem of critical permanent distortions could be very important to a task requiring superior leakage requirements. The phase transformation occurring in some metals that experience cryogenic thermal cycling results in a dimensional change. Special stabilization processes can reduce distortions resulting from residual stresses and stabilize other metallurgical problems.

The proper blending of thermal coefficients of expansion throughout the design will also be of considerable importance since alteration in operational dimensions could seriously jeopardize component performance.

ANSC's experience with the NERVA program has disciplined all personnel to be skeptical of organic materials functioning in a strong nuclear-radiation environment. Polymer chains are often seriously degraded by exposure to gamma-ray bombardment. Normal cold-flow phenomena associated with plastics become a problem for the long-storage requirement and low temperature presents a brittle failure potential. These factors will be considered in material selections for the valves and regulators.

3. Thermal Analysis

a. Steady-State Temperature Profiles

A detailed steady-state temperature profile of any axisymmetric or plane-stress problem can be provided with the aid of ANSC's computer program entitled "Steady-State Analysis of a Two-Dimensional Body", Code No. E12401. This program utilizes the finite element method of solution and will adapt itself to any general boundary conditions that may result from solar and external nuclear heating or convective and conductive cooling resulting from the internal fluids present in a valve or regulator. A knowledge of such a temperature profile of a potential component enables a designer to: (1) select materials compatible with maximum temperatures and to adjust his design-allowable values; (2) readjust material thickness to cope with thermal gradients more effectively; and (3) resize cross sections to maintain reasonable stresses and strains resulting from maximum temperature differences.

b. Transient Temperature Distribution

A detailed temperature distribution generated in any axisymmetric or plane-stress problem can be evaluated with the aid of an ANSC computer program entitled "Transient and Steady-State Analysis of a Two-Dimensional Body", Code No. E12202. This program, which also utilizes the finite-element method, permits direct analysis of thermal-shock problems resulting from sudden exposure to cryogenic fluid flow or caused by large and rapid changes in reactor power and heat-generation rates: e.g., thermal gradients established by these transient conditions can produce internal thermal stresses or significant component distortion, depending upon the boundary constraints of each particular configuration.

4. Probabilistic Analysis and Reliability

Reliability is the probability of maintaining the required performance for the specified duty cycle life. Whether specified as an objective or not, all systems are designed to some level of reliability. The actual reliability of the system cannot be determined exactly but only estimated from test data, analysis, or a combination of the two. To show high reliability as the result of testing, large numbers of tests must be conducted. For instance, to show a reliability of 0.995 at 90% confidence for a system, 460 tests are required without failure. If the system is complicated and/or the reliability requirements are high, it is prohibitive to use system testing alone to show compliance with reliability requirements.

Probabilistic analysis provides the means for estimating the reliability of a system or component. The calculations can include factors to account for unknowns in the required performance and the applicability of analytical techniques, as well as known variations in material properties and manufacturing tolerances. Reliability can be calculated before hardware is fabricated and the results of the calculations used to optimize the design. The calculations illustrate the most important factors which demand closer control, the deficient components that need to be improved or redesigned, and those areas where weight can be reduced or tolerances lessened for overall design improvement.

A reliability calculation consists of determining the probability that the capability of a system or component will exceed the demand placed upon it. For instance, capability may mean burst strength or output torque, then demand would mean pressure or operating torque. To calculate reliability, first an equation is derived which calculates the capability in terms of all the factors which affect that capability. The mean and variability of each of the factors is then determined from the best available source. Similarly for the demand, an equation is derived and

the mean and variability of each of its factors determined. Probability distributions of the capability and the demand are obtained using either propagation-of-variance calculations or a Monte Carlo analysis. The reliability is then determined from these probability distributions by statistical techniques.

Performance characteristics which can be evaluated using probabilistic analysis include:

1. Operating pressure
2. Valve operating torque
3. Cycle time
4. Frequency response
5. Leakage rates
6. Seal wear life
7. Actuator output torque
8. Flow-impedance resolution
9. Pressure regulation
10. Structural loading
11. Bearing life

IV. PROGRAM PLAN

A. APPROACH

The program described in this section has been established to effectively and efficiently provide the technological efforts required to select three design concepts for shutoff valves and regulators and to complete preliminary design drawings of the selected concepts. The program logic shown in Figure IV-1 indicated how basic elements of the program are related. The program has been structured by the tasks defined in the RFQ scope of work and time-phased over the six-month period as shown in Figure IV-2. The time phasing permits an orderly transition from the selection of concepts in Phase I to the preparation of preliminary design drawings in Phase II, including a two-week period for NASA-MFSC approval between tasks.

B. PROGRAM DESCRIPTION

1. Phase I - Concept Selection

Phase I will commence upon contract award with the formulation of a definitive work plan. The important elements of the work plan are shown in Figure IV-2 and are discussed in this section.

The objective of the requirements analysis task is to establish the performance, environmental, and storage requirements which must be met and those design criteria (e.g., materials, producibility, and service) which produce guidelines for design. The information needed to attain this objective will be extracted from existing literature, evaluated, and then combined with the pertinent information from the RFQ scope of work into one suitably organized document for both the valve and the pressure regulator.

Figure IV-1 - Program Plan Flow Chart.

Figure IV-2 - Program Schedule and Progress Chart

The valve data and tradeoff studies covering various concepts are available from extensive in-house studies in support of the NERVA program and from Lewis Research Center design criteria monographs covering valves and regulators. These and similar data minimize the literature search and permit the Task I effort to proceed immediately with the evaluation of candidate concepts, conception and evaluation of unconventional concepts that may offer performance advantages, and the rating of the various candidates. A sample rating sheet is shown in Table III-2. The evaluation will be accomplished by having the assigned design engineers perform a preliminary screening of conventional and unconventional approaches to narrow the field to several prime candidates. The review will then be concentrated upon variations of the prime candidates. During this period, technical specialists in the areas of dynamics, stress, materials, and heat transfer will provide information to aid the evaluation. The major area of interest during Task I will be to determine the manner in which the concept lends itself to remote coupling design and/or to remote maintenance and overhaul. For this reason, a remote coupling activity will be conducted in parallel to support the valve and pressure-regulator design effort. After this activity has resulted in the three most-promising regulator and valve concepts, recommendations for Phase II will be made to MSFC.

2. Phase II - Preliminary Design

For purposes of planning and budgeting, the Task II effort has been defined as a nine-week effort which results in three preliminary valve and pressure-regulator design drawings.

Preliminary design starts with the task of combining subcomponents (i.e., shutoff devices, actuators, and linkages) into assemblies to attain optimization of function, envelope, and weight.

The first analytical task is to establish size by means of a flow analysis. Sketches and "rough" layouts will be made of structural and mechanical elements to aid in a preliminary structural and dynamics analysis to establish valve and regulator proportions and force and power requirements.

Intermeshed with this analysis is the selection of materials for radiation, fluid compatibility, structural strength, corrosion, wear, and friction requirements. The preliminary design configuration becomes defined with the advancement of these studies. As the preliminary-design activity nears completion, the analytical studies are reviewed and design changes are made, as required. The preliminary design will be considered complete with a preliminary design drawing which dimensionally delineates the basic valve and regulator design, including a materials list. An example of the type of drawing planned is shown in Appendix D.

C. DOCUMENTATION

All reports will be submitted in the format and quantities described in Section IV of the RFQ.

Five monthly progress reports will be submitted by the 10th day of the ensuing month as shown in Figure IV-2. These reports will be in narrative form, and will be brief and informal. They will include overall program progress, data as available, problems and proposed solutions, and will describe the planned program for the next reporting period. No report will be submitted during the month when the final report is due.

In addition, the progress report will show the fiscal status of the program. A sample financial report is shown as Table IV-1.

The final report will summarize and document in detail all work performed under the contract. It will be complete within itself and will include appropriate data, analyses, and interpretations, as well as recommendations and conclusions, based upon the results obtained. Detail will be sufficient to explain the results achieved and to be fully utilized in the anticipated future detail design and development tasks.

Within 30 days after completion of Phase II, copies of the final report and the reproducible copies will be distributed.

S A M P L E

TABLE IV-1

NUCLEAR STAGE REGULATORS AND SHUTOFF VALVES

FINANCIAL STATUS REPORT

TASK	CONTRACT TOTAL		ACTUALS				CUMULATIVE BUDGET		ESTIMATE TO COMPLET		ACTUALS + EST. TO COM		VARIANCE		ACTUAL % COMPL	FORECAST % COMPL.
	HRS	\$	HRS	\$	HRS	\$	HRS	\$	HRS	\$	HRS	\$	HRS	\$		
PHASE I																
PHASE II																
PROGRAM SUMMARY																

S A M P L E

V. PROGRAM MANAGEMENT

The Aerojet-General Corporation is incorporated under the laws of the State of Ohio and maintains its corporate headquarters at El Monte, California. As president, J. H. Vollbrecht directs the overall operation of the corporation, divisional companies, principal operating facilities, and subsidiaries. This total complex has a demonstrated capability in all aspects of rocket development, as well as a broad supporting technical base in related fields.

The proposed program will be conducted at Aerojet-General's Sacramento Facility by the Aerojet Nuclear Systems Company, which is under the direction of E. D. Ward who serves as Vice President (see Figure V-1). The project will be assigned to Engineering Operations, which is directed by Dr. C. K. Leeper who has cognizance for all nuclear systems engineering technology.

L. D. Johnson, manager of the module engineering section, reports to Dr. Leeper and has been selected as program manager for the proposed program. His direct line of communication to top-level management facilitates the obtaining of special support if needed. Mr. Johnson will conduct the proposed program on a project basis in which there are clearly-defined areas of responsibility, as well as direct lines of project authority. His functional team is shown in Figure V-2. All personnel named have been selected because of their experience and knowledge in their proposed technological assignments.

Figure V-1 - ANSC Engineering Operations Organization

Figure V-2 - Program Organization

NAME: L. D. Johnson
PROPOSED ASSIGNMENT: Program Manager
TIME ALLOCATED: As Required
CURRENT RESPONSIBILITY: Manager, Module Engineering Section. Mr. Johnson is responsible for providing project design and development engineering effort for radiation-hardened valves, pneumatic and electromechanical actuators (including associated electronics), and interconnecting lines (including remotely actuated line joints).

EXPERIENCE:

Mr. Johnson joined Aerojet-General in 1962 as an engineer in the NERVA project organization. He conducted design analyses on valves, pneumatic systems, and lines. From 1964 until he assumed his current duties, Mr. Johnson served as supervisor of NERVA valve and line design and development of high- and low-temperature, radiation-hardened components for use in the NERVA feed system.

Prior to joining Aerojet, Mr. Johnson spent three years with the Rocketdyne Division of North American Rockwell Corporation where he was a design engineer in the F-1 engine system group.

EDUCATION:

B.S., Mechanical Engineering, 1959, Wichita State University

NAME: E. A. Shearer
PROPOSED ASSIGNMENT: Project Engineer
TIME ALLOCATED: 20%
CURRENT RESPONSIBILITY: As supervisor of the special projects section, Mr. Shearer is responsible for the design and development of the valves for the NERVA flight engine.

EXPERIENCE:

Mr. Shearer joined Aerojet-General in 1956 as a project engineer. He was responsible for the development of hot gas and propellant controls for the pump-drive assemblies of Titan I and Titan II engines. Later, as manager of the mechanical controls department, he directed the design and development of all valves, mechanical controls, and seal programs for Titan II, Gemini, NERVA, and the M-1 engine programs. More recently, he was responsible for the design development of advanced-design sodium valves for the liquid metal fast breeder reactor (LMFBR) program.

Prior to joining Aerojet-General, Mr. Shearer was with the W. R. Whittaker Company where he was responsible for the design, development, testing, and production of aircraft valves.

EDUCATION:

B.S., Mechanical Engineering, 1950, University of California

NAME: J. E. DeKlotz
PROPOSED ASSIGNMENT: Shutoff Valve Design
TIME ALLOCATED: 100%
CURRENT RESPONSIBILITY: Mr. DeKlotz serves as a senior engineer, participating in the design of electrically operated NERVA engine valves.

EXPERIENCE:

From 1949 to 1970, when he joined Aerojet, Mr. DeKlotz served in such capacities for the Whittaker Corporation as design engineer, project engineer, and engineering supervisor in the design, development, and qualification of aerospace fluid controls. Some of the major fluid-control projects to which he was assigned were the 10-in. S-IC liquid oxygen tank vent and relief valve, the 17-in. S-IC liquid oxygen pre-valve, the Agena propellant tank pressurization regulator, and the Agena propellant tank overpressure and differential pressure relief valves. He has also participated in the design, development, and qualification of such components as pneumatic and hydraulic regulators, ball valves, pneumatic and electrically operated gate valves, electrically operated slide valves, squib valves, and solenoid valves for space, missile, and aircraft applications.

EDUCATION:

B.S., Aeronautical Engineering, 1949, Cal-Aero Technical Institute

NAME: T. L. Pattenden
PROPOSED ASSIGNMENT: Pressure Regulator Design
TIME ALLOCATED: 50%
CURRENT RESPONSIBILITY: As a senior engineer, Mr. Pattenden is responsible for the design of cryogenic control valves for the NERVA engine.

EXPERIENCE:

Mr. Pattenden joined Aerojet Nuclear Systems Company in 1970.

With TRW Systems as a member of the technical staff from 1966 to 1970, Mr. Pattenden was responsible for the design and development of several space propulsion subsystems and for the design and development of control valves and regulators for space vehicles.

From 1962 until 1966 he served as a senior engineer with the Rocketdyne Division of North American Rockwell Corporation where he designed fluid-control components, valves, and regulators, for several space propulsion programs. From 1960-1962, as a design engineer with the Missiles and Space Division of Douglas Aircraft, he designed fluid-control components and performed system analysis for the Skybolt program.

From 1955 to 1960 he served as a design engineer for Weston Hydraulics, Ltd., being responsible for the design and development of fluid power controls, pressure regulators, flow control valves, and actuators.

EDUCATION:

Higher national certificates in mechanical and production engineering, 1947, Enfield Technical College, England

NAME: D. W. Pangburn

PROPOSED ASSIGNMENT: Remote Coupling Design

TIME ALLOCATED: 50%

CURRENT RESPONSIBILITY: As a senior engineer in the valve design department, Mr. Pangburn is responsible for design of the electro-mechanical, main propellant shutoff valve for the NERVA engine which incorporates a remotely removable actuator.

EXPERIENCE:

Mr. Pangburn joined Aerojet in 1956. He has participated in the design, development, and testing of mechanical and ordnance devices for the Polaris, Minuteman, and NERVA programs. He has also designed all-metal cryogenic shutoff and control valves for the NERVA engine and has analyzed their performance, using both conventional and probabilistic techniques.

Mr. Pangburn is a Registered Mechanical Engineer in the State of California.

EDUCATION:

B.S., Mechanical Engineering, 1963, Sacramento State College
Graduate Work, Mechanical Engineering, 1967 to present, Sacramento State College

NAME: J. G. Schumacher
PROPOSED ASSIGNMENT: Structural Analysis
TIME ALLOCATED: As Required
CURRENT RESPONSIBILITY: Supervisor of NERVA engine stress analysis activities, Mr. Schumacher is responsible for the detail stress analysis of all NERVA engine components and the provision of stress and dynamics analysis support for engine systems trade studies.

EXPERIENCE:

Mr. Schumacher joined Aerojet-General in 1960. Prior to joining the NERVA project in 1969, he served as manager of structural design and analyses, surface-effect ship division, supervisor of stress analysis for Ares liquid rocket engine program, and supervisor of a special projects group in solid rocket stress analysis. He was manager of corporate research projects concerning graphite failure criteria and aluminum hull structures. He was also responsible for the development of an Aerojet structures manual, and various computer programs concerning nozzle, shell, and propellant-grain stress analysis.

From 1956 to 1959 he was employed as a structures engineer by Convair-Astronautics, where he was engaged in stress analysis of Atlas missile components. In this position, he developed statistical analysis methods for structural loads and was responsible for the development of statistical buckling design curves for thin cylinders.

Between 1952 and 1956 he was a stress engineer for Lockheed Aircraft Corporation, where he performed detail stress analyses of aircraft components.

EDUCATION:

B.S., Civil Engineering, 1952, College of the City of New York
M.S., Aeronautical Engineering, 1959, University of California,
Los Angeles

NAME: D. T. Buchanan

PROPOSED ASSIGNMENT: Thermal Analysis

TIME ALLOCATED: As required

CURRENT RESPONSIBILITY: Mr. Buchanan directs thermal analyses of NERVA components, including conduction, convection, thermal radiation, and nuclear-heat generation in one, two, and three dimensions. Techniques employed include finite-element and finite-difference methods of reducing thermal matrices with boundaries.

EXPERIENCE:

Mr. Buchanan joined Aerojet-General in 1962. He has performed thermal analyses for Minuteman motors, the SNAP-8 power system, and the NERVA engine. For the Minuteman project he developed analog methods for studying tank pressurization and heat-transfer analysis. He also served as a consultant to the SNAP-8 instrumentation section and assisted in the development of high-temperature transducers and instrument calibration techniques. He has been instrumental in developing steady-state and transient finite-element method heat-transfer programs.

From 1959 to 1962 he served as a development engineer for the military design sector of the U.S. Army Corp of Engineers where he designed diverse mechanical systems for military installations.

EDUCATION:

B.S. Mechanical Engineering, 1951, Los Angeles State College

NAME: J. J. Williams
PROPOSED ASSIGNMENT: Gas Dynamics
TIME ALLOCATED: As Required
CURRENT RESPONSIBILITY: As senior gas-dynamics specialist, Dr. Williams performs individual analyses on special problems in the areas of heat transfer, thermal radiation, fluid mechanics, thermodynamics, and material corrosion.

EXPERIENCE:

Prior to 1969 Dr. Williams supervised heat-transfer activities in the research and technology department and the advanced propulsion research section of the Aerojet Liquid Rocket Company. The activities of these groups included performing thermal analyses of such components as structural members, heat exchangers, and elastomeric insulation materials under the influence of transient chemical and thermal environments.

His activities have included: (1) development of a gas-dynamic analysis method for steam ejectors that accounts for steam condensation and real gas properties; and (2) development of differential and integral boundary layer analysis techniques and other gas dynamics analyses procedures. He has published technical papers in several of these fields.

As a group leader in the experimental fluid dynamics section he earlier conducted preliminary system design of a large scale blowdown test facility and performed analytical-experimental gas-dynamic investigations of unconventional nozzle designs.

From 1956 to 1960 Dr. Williams was a senior test engineer at the University of Southern California engineering test center. In this capacity he was responsible for facility design and all phases of evaluation of aerodynamic characteristics of aircraft and air-induction systems. He is a registered mechanical engineer.

EDUCATION:

B.S.M.E., Mechanical Engineering, 1955, University of Santa Clara

M.S., Mechanical Engineering, 1956, Stanford University

Ph.D., Mechanical Engineering, 1969, University of California

PUBLICATIONS:

"Results of a Program for Theoretical and Experimental Evaluation of the Plug Nozzle Concept," co-authored with V. H. Ransom, T. L. DeYoung and S. A. Lorenc, Bulletin of 17th Symposium on Propulsion Design Concepts, May, 1961.

"Annular Flow Nozzles for Solid Propellant Rockets," J. J. Williams and G. B. Hurr, Proceedings of the Fourth Annual Solid Propellant Rocket Conference of the American Rocket Society, Feb. 1, 1963.

"Effect of Exit Cone Gas-Transpiration on Rocket Motor Performance," J. J. Williams, 1965 AIChE Symposium Series on Aerospace.

"Solid Propellant Extinguishment by Water Injection," C. M. Auble, J. J. Williams, E. E. Day, presented at the AIAA Second Propulsion Joint Specialist Conference, Colorado Springs, Colorado, June 12-17, 1966.

"The Effect of Gaseous Film Cooling on the Recovery Temperature Distribution in Rocket Nozzles," J. J. Williams and W. H. Giedt, ASME Paper 70-HT/Spt-42, June 1970.

"The Radiative Contribution to Heat Transfer in Metalized Propellant Exhausts," J. J. Williams and D. P. Dudley, Proceedings of the Fifth (ASME) Symposium on Thermophysical Properties, 1970.

"The Chemical Erosion of Fibrous Graphite Composite by Hydrogen Gas at Surface Temperatures Between 2000 Deg R and 4000 Deg R," J. J. Williams, O. J. Demuth and J. O. Sane, in preparation.

NAME: D. R. Rogers
PROPOSED ASSIGNMENT: Nuclear Analysis
TIME ALLOCATED: As Required
CURRENT RESPONSIBILITY: As supervisor of the nuclear analysis and shielding group, Mr. Rogers is responsible for analyses to define the induced radiation environment throughout the NERVA system, including engine components, the propellant module, and payload.

EXPERIENCE:

He has established the requirements for shielding in both manned and unmanned applications of NERVA, determined optimum locations and weights of shielding, and provided support to studies of candidate propulsion modules and payloads.

Previously he was employed at Aerojet-General Nucleonics where he engaged in the development of shielding for the ML-1 mobile, gas-cooled reactor program. His responsibilities included shield design and determination of radiation environment, using both analytical and experimental techniques.

EDUCATION:

B.S., Engineering Physics, 1958, University of California
M.S., Nuclear Engineering, 1959, University of California

PUBLICATIONS:

"Radiation Environment for Rendezvous and Docking with Nuclear Rockets," D. R. Rogers, E. A. Warman, and B. A. Lindsey, National Symposium on Natural and Manmade Radiation in Space, March 1971
"Shielding Requirements for Manned and Unmanned NERVA Missions," Transactions American Nuclear Society, 13 (2), 441 (1970), E. A. Warman and D. R. Rogers

"Operating Radiation Environment of Nuclear Rocket Systems,"
Transactions American Nuclear Society, 12 (2), 416 (1969),
E. A. Warman, D. R. Rogers, and J. C. Courtney

"Radiation Exposure Limitations for Shielded NERVA Engine Components,"
Aerojet-General Corporation, RN-S-0557, April 1970, E. A. Warman,
D. R. Rogers, J. C. Courtney, C. E. Dixon, J. R. Smith, and
J. Conant

"Shielding Trade Study Interim Status Report: Tasks 2 and 2A and
Related Studies," Aerojet-General Corporation, RN-TM-0584, May 1969,
K. O. Koebberling, D. R. Rogers, B. A. Lindsey, and J. C. Courtney

"Nuclear Analyses in Support of E/STS 2-3 Preliminary Design,"
Aerojet-General Corporation, RN-S-0423, August 1967, E. A. Warman,
D. R. Rogers, D. L. Foreman, and H. O. Whittum

"Preliminary Evaluation of the ML-1 Shutdown Shield Performance,"
Transactions American Nuclear Society, 6 (2), 429 (1963), D. R. Rogers
and H. O. Whittum

NAME: C. E. Dixon
PROPOSED ASSIGNMENT: Materials and Processes
TIME ALLOCATED: As Required
CURRENT RESPONSIBILITY: As supervisor of the advanced materials group, Dr. Dixon is responsible for evaluating all phases of material research and development in the NERVA program.

EXPERIENCE:

His assignments have included reactor-materials liaison with the Westinghouse Astronuclear Laboratory and cryogenic and high-temperature irradiation research in structural alloys, polymers, and elastomers.

Earlier (1951 - 1953) he was employed by Atomics International where he conducted radiation-damage research on materials, research and development of high-temperature reactor materials (with emphasis on graphite and refractory oxides), and basic research on lattice imperfections and the mechanical properties of materials.

EDUCATION:

B.S., Physics, 1942, Washington State University
M.S., Physics, 1948, Washington State University
D.Sc., Physics, 1951, Carnegie Institute of Technology

PUBLICATIONS:

Cryogenic Radiation Effects on NERVA Structural Materials, ASTM Publication STP 426 (ASTM, 1967), page 625

Cryogenic Radiation Damage in Structural Polymers, Transactions, American Nuclear Society, November 1966

High Temperature Radiation Embrittlement of Hastelloy X, Inconel 625 and AISI 347, Transactions, American Nuclear Society, June 1967

Radiation Effects of High Energy Electrons in Metals, Progress in Nuclear Energy, Series V, Volume 2 - Metallurgy and Fuels (Pergamon Press, 1959), page 475

Generalities of Radiation Damage, Reactor Handbook, Volume I, Materials, (Interscience 1960) page 40

Internal Friction and Shear Modulus of Thorium at High Temperatures
Proceedings of 2nd Nuclear Engineering and Science Conference,
Paper 57-NESC-6, 1957

Interstitial and Vacancy Migration in Copper and Cu_3Au , Acta Metallurgica, Volume 2, page 636, 1954

VI. RELATED EXPERIENCE

Aerojet Nuclear Systems Company personnel have had extensive experience in valves and fluid controls. This experience encompasses initial conceptual design efforts, design tradeoff studies, final design definition, valve fabrication, valve development, and valve qualification. ANSC personnel have designed and developed more than 500 types of electrical, electromechanical, and mechanical valves, as well as controls to satisfy requirements that included both unconventional materials and operating conditions. These devices are used in liquid, solid, and nuclear rockets. They vent propellant tanks, relieve system pressure, bleed and shutoff propellant tanks and feed lines, control gas and liquid flows, detect system malfunctions, gimbal engines, and control engine thrust. As a result, competence has been gained in designing to extreme temperature (-425°F to 6000°F), wide pressure ranges (hard vacuum to 10,000 psi), zero gravity to hundreds of g's, corrosive fluids, near-zero leakage, exacting response times, and other stringent conditions.

The design knowledge gained in the aerospace industry has led ANSC to place increased emphasis on the analytical phase of valve and controls design. It is firmly believed that the cost of an extensive analysis of the design requirements and the potential design approaches early in a program is more than justified by its elimination of problem areas prior to hardware fabrication. An example of a thorough design evaluation conducted to best select a valve design approach for a specific application is available in Report 7-733-1F, "Study of Bipropellant Shutoff Valves", as prepared under NASA Contract NAS 7-733. The approach of emphasizing preliminary design analysis was utilized during the design of an improved Apollo SPS bipropellant valve under Contract NAS 9-8317. By conducting a detailed analysis of sealing requirements and conditions, a design was defined which greatly increased seal life and performance. The analysis included the use of SEALCAL, a computerized method of seal design developed by Aerojet.

The value of the analytical phase of design is greatly affected by the amount of actual experience and test data available. Almost all of the primary factors considered in a trade-off study or performance calculations are influenced by the judgement and experience of the designers. ANSC is especially qualified for this activity through its extensive valve design and development background. Some of the specific valves designed, fabricated and tested are presented in Table VI-1. Valves for cryogenic fluids were designed for Titan I (butterfly, poppet, and contoured poppet valves for liquid oxygen), M-1 (poppet valves and sleeve valves for liquid oxygen and liquid hydrogen), and NERVA (butterfly and poppet valves for liquid and high-temperature hydrogen). Valves for storable propellants were designed for Titan II and Gemini (butterfly and poppet valves for N_2O_4 and A-50). Valves for hot gases were designed for Titan I (butterfly and poppet). Valves for high-pressure helium and gaseous nitrogen systems were utilized in the Titan, Gemini, and Apollo programs. In addition to this major aerospace program experience, ANSC personnel have accumulated valve experience with liquid fluorine, diborane, chlorine trifluoride, and other less commonly used fluids in smaller, government and company-sponsored programs.

Table VI-2 identifies the valves currently planned for use on the NERVA flight engine. Preliminary designs for these valves have been completed by ANSC personnel. The designs have resulted from a comprehensive trade-study of various concepts that were initially considered suitable for the specific applications, and included concepts for remote coupling and uncoupling. The analyses performed during these trade studies show conclusively that the designs selected are capable of performing the required functions in a radioactive environment with liquid hydrogen under the conditions shown in Table VI-2.

Not readily apparent from the table is the extensive experience gained by ANSC personnel in developing unique electromechanical actuators for controlling the positioning of various valves in response to control system

TABLE VI-1

TYPICAL AEROJET-GENERAL VALVES AND COMPONENTS

<u>Valve Name</u>	<u>Type</u>	<u>Line Size</u>	<u>Medium</u>	<u>Flow Rate</u>	<u>Oper Press. psi</u>	<u>Actuation Method</u>
<u>TITAN I 1st STAGE</u>						
TCOV	Butterfly	5.00	LOX	400 #/sec		Mech linked to TCFV
TCFV & Actuator	Butterfly	4.00	RP-1	200 #/sec	850	Hyd Press. from PSV
TCFV	Butterfly	4.00	RP-1	200 #/sec		"
PSV	Slide	.5	RP-1	11.0 #/sec	850	Fuel Press.
GGOV	Poppet	1.25	LOX	50 #/sec	900	Pressure
GGFV	Poppet	1.75	RP-1		900	Pressure
Density Compensator Valve	Butterfly	4.00	RP-1	187 #/sec	500	Manual
Oxidizer Bleed Valve	Poppet	1.5	LOX		150	Gas Press.
N ₂ Start Valve	Poppet	2.5	N ₂	40 #/sec	3000	Gas Press.
<u>TITAN I 2nd STAGE</u>						
TCOV	Butterfly	4.00	LOX	200 #/sec		Mech linked to TCFV
TCFV & Actuator	Butterfly	3.00	RP-1	100 #/sec		Hyd. Press. from PSV
TCFV	Butterfly	3.00	RP-1	100 #/sec		"
PSV	Slide		RP-1			Fuel Press.
GGOV	Poppet		LOX	.50 #/sec	800	Pressure
GGFV	Poppet		RP-1	11 #/sec	800	Pressure
Density Compensator Valve	Butterfly	3.00	RP-1	82 #/sec	500	Manual
Oxidizer Bleed Valve	Poppet		LOX			
HGDV Assy	Poppet	2.50	Hot Gas	6.3 #/sec	600	Gas Press.
<u>NIKE</u>						
Nike "B" Hercules Gas Reg.				1.65 #/sec	440	
Nike Ajax Gas Regulator		1.00	GN ₂	.37 #/sec	440	

TABLE VI-1 (cont.)

<u>Valve Name</u>	<u>Type</u>	<u>Line Size</u>	<u>Medium</u>	<u>Flow Rate</u>	<u>Oper Press. psi</u>	<u>Actuation Method</u>
<u>TITAN II 1st STAGE</u>						
TCOV	Butterfly	5.00	N ₂ O ₄	552.6 #/sec	962	Linked to TCFV
TCFV & Actuator	Butterfly	4.00	A-50	275 #/sec	1410	Hyd Press. from PSV
PSV	Slide	.5	A-50	1.88 #/sec	1410	Fuel Press.
GGOV	Poppet	.38	N ₂ O ₄			Pressure
GGFV	Poppet	.38	A-50			Pressure
<u>TITAN II 2nd STAGE</u>						
TCOV	Butterfly	4.00	N ₂ O ₄	2.08 #/sec	1094	Linked to TCFV
TCFV & Actuator	Butterfly	3.00	A-50	111.2 #/sec	1189	Hyd Press. from PSV
PSV	Slide	.5	A-50	2.97 #/sec	1189	Fuel Press.
GGOV	Poppet	.38	N ₂ O ₄	.45 #/sec	652	Pressure
GGFV	Poppet	1.00	A-50	10.98 #/sec	750	Pressure
GGOV	Poppet	.38	N ₂ O ₄	1.9 #/sec	1000	Pressure
GGFV	Poppet	.75	A-50	5.08 #/sec	716	Pressure
<u>M-1</u>						
GGV Pilot Valve		.25	GN ₂	2.7 #/sec	1800	Pressure
GGOV	Poppet	1.75	LOX	49.1 #/sec	1685	Gas Press.
GGFV	Poppet	2.500	LH ₂	61.3 #/sec	1608	Gas Press.
PU & By-Pass Valve	Sleeve	5.00	Hot Gas	21 #/sec	1070	Elect. Motor
He Start Valve	Poppet	3.00	Helium	81 #/sec	3500	Gas Press.
Poppet TCOV	Poppet	10.0	LOX	2951 #/sec	1200	LOX Press.
Poppet TCFV	Poppet	10.0	LH ₂	590 #/sec	1200	LH ₂ Press.
Sleeve TCOV	Sleeve	10.0	LOX	2951 #/sec	1200	Gas Press.
Sleeve TCFV	Sleeve	10.0	LH ₂	590 #/sec	1200	Gas Press.
Pump Circulating Valve	Sleeve	6.00	LH ₂	K _w 5624	1881	LHe Press.

TABLE VI-1 (cont.)

<u>Valve Name</u>	<u>Type</u>	<u>Line Size</u>	<u>Medium</u>	<u>Flow Rate</u>	<u>Oper Press. psi</u>	<u>Actuation Method</u>
<u>NERVA</u>						
Tank Shutoff Valve		8.0	LH ₂	75 #/sec	50	GHe Press.
TSOV-Remote Disassembly						
TSOV-Pilot Valve						
Reactor Cooldown Valve	Poppet	2.50				Elec. Motor
Turbine Power Control Valve	Butterfly	4.00	Hot Gas	7 #/sec	550	GH ₂ Press.
<u>ARES</u>						
Suction Valve	Visor	3.50	N ₂ O ₄ or A-50	300 #/sec	550	Hydraulic or Elect. Motor
Prim.Comb.Fuel Control Valve	Sleeve	1.00	A-50	20 #/sec	6000	Hydraulic or Elect.Motor
Sec.Comb. Fuel Control Valve	Sleeve	1.75	A-50	85 #/sec	4000	Hydraulic or Elect.Motor
<u>TITAN III 1st STAGE</u>						
TCOV	Butterfly	5.00	N ₂ O ₄	547.2 #/sec	1042	Mech.linked to fuel vlv.
TCFV & Actuator	Butterfly	4.00	A-50	284.5 #/sec	1342	Fuel Press.
PSV	Slide		A-50			Fuel Press.
GGOV	Poppet	.38	N ₂ O ₄	1.02 #/sec	783	Oxid Press.
GGFV	Poppet	1.00	A-50	12.01 #/sec	830	Fuel Press.
<u>TITAN III 2nd STAGE</u>						
TCOV	Butterfly	4.00	N ₂ O ₄	207.3 #/sec	1098	Mech.linked to fuel vlv.
TCFV & Actuator	Butterfly	3.00	A-50	115.1 #/sec	1180	Fuel Press.
PSV	Slide		A-50			Fuel Press.
GGOV	Poppet	.38	N ₂ O ₄	4.32 #/sec	765	Oxid Press.
GGFV	Poppet	.75	A-50	4.91 #/sec	670	Fuel Press.
<u>TRANSTAGE</u>						
Bipropellant Valve	Poppet	1.75	N ₂ O ₄ or A-50	18/9 #/sec	150	Fuel Press.

TABLE VI-1 (cont.)

<u>Valve Name</u>	<u>Type</u>	<u>Line Size</u>	<u>Medium</u>	<u>Flow Rate</u>	<u>Oper Press. psi</u>	<u>Actuation Method</u>
APOLLO Bipropellant Valve	Ball	2.00	N ₂ O ₄ or A-50	38/24 #/sec	175	Gas Press.

CODE FOR ABBREVIATIONS:

TCOV - Thrust Chamber Oxidizer Valve
TCFV - Thrust Chamber Fuel Valve
PSV - Pressure Sequencing Valve
GGOV - Gas Generator Oxidizer Valve
GGFV - Gas Generator Fuel Valve
HGDV - Hot Gas Diversion Valve
LOX - Liquid Oxygen
RP-1 - Petroleum Base Fuel
GN₂ - Gaseous Nitrogen
N₂O₄ - Nitrogen Tetroxide
A-50 - AeroZINE 50 - (50% UDMH & 50% Hydrazine)
LH₂ - Liquid Hydrogen

TABLE VI-2

VALVES DESIGNED FOR USE ON NERVA FLIGHT ENGINE

<u>Name</u>	<u>Type</u>	<u>Line Size (in.)</u>	<u>Medium</u>	<u>Flow Rate (lb/sec)</u>	<u>Operating Pressure (psi)</u>	<u>Actuation Method</u>
PSOV	Poppet	10	LH ₂	75	30	Electromechanical Actuator
PDKV	Flapper	5	LH ₂	75	1500	
PDBV	Ball	5	LH ₂	85	1450	
PDCV	Visor	5	LH ₂	85	1450	
BBV	Ball	4	GH ₂	16	1150	
BCV	Visor	4	GH ₂	16	1150	
TBV	Poppet	7.5	GH ₂	50	1150	
TDBV	Poppet	7.5	GH ₂	50	750	
SSBV	Ball	4	LH ₂	6	1460	
SSCV	Visor	4	LH ₂	6	1460	
CSOV	Poppet	3	LH ₂	4	30	
CSCV	Poppet	3	LH ₂	4	30	

CODE FOR ABBREVIATIONS:

PSOV - Propellant Shutoff Valve

PDKV - Pump Discharge Check Valve

PDBV - Pump Discharge Block Valve

PDCV - Pump Discharge Control Valve

BBV - Bypass Block Valve

BCV - Bypass Control Valve

TBV - Turbine Discharge Block Valve

SSBV - Structural Support Block Valve

SSCV - Structural Support Coolant Valve

CSOV - Cooldown Shutoff Valve

CSCV - Cooldown Supply Control Valve

demands. A wide range of variations in the design of ac motors relative to variations in the design of electronic module control circuitry provides a capability of utilizing a single mechanical gear transmission system for a wide range of valves and their associated operating loads. Through research, the technology of ensuring reliable operation of electronic components in a radiation environment of high intensity has been developed. This technology is available for direct application to the development of a valve-actuator system under the scope of "Future Tasks".

VII. FACILITIES AND EQUIPMENT

The Aerojet Nuclear Systems Company has available to it all of the facilities located at the Sacramento Facility, which represents an Aerojet-General Corporation investment in excess of 82 million dollars and a Government investment of over 132 million dollars. These facilities support all of the divisional companies located at Sacramento as well as all programs; NASA, Air Force, Navy and Army. They will contribute and provide special benefits to the proposed program.

Administrative and engineering personnel are located in the main Administrative Area building complex. Office space of approximately 650,000 sq ft is available for engineers engaged in the development of rocket propulsion systems and for personnel manning the administrative support functions. These facilities are located close to the manufacturing shop, computer facilities, laboratories and technical library situated in this complex.

Only those facilities that will be utilized directly for the proposed program are briefly described herein.

A. SACRAMENTO FACILITY TECHNICAL INFORMATION CENTER

Aerojet-General maintains a well-equipped technical information center staffed by 8 employees, including four professional librarians. The center collection provides an extensive coverage of the following fields: mathematics and the physical sciences, engineering, rocketry, and aerospace technology. Materials in other fields (i.e., accounting and business) are acquired as needed.

Holdings include over 25,000 books, 3000 bound periodicals, and over 100,000 technical reports. The center subscribes to 600 technical journals and has excellent working relationships with many large research libraries for inter-library loans. In addition to its collection of printed reports, the library maintains files of NASA, AEC, and DDC microfilms.

A comprehensive collection of vendor catalog information is also maintained on microfilm for the use of design engineers. The VSMF supplier Microfilm File, together with a reader-printer, is available to locate and reproduce pages of product information.

Military and federal specifications, standards, military manuals, technical orders, and regulations are also handled by the Technical Information Section. Extensive files of these items are maintained and as new ones are automatically received from the military and other agencies, they are distributed.

All of the external and internal technical reports in the Center's collection have been indexed. This literature retrieval system is stored on magnetic tape and used on an IBM computer. A literature search on the computer can accommodate 52 separate coordinations at a time.

To supplement the literature retrieval systems produced by Aerojet-General, the Information Center utilizes magnetic tape reels containing the NASA literature retrieval system. Searches are supplied by NASA's Scientific and Technical Information Center, Bethesda, Maryland on request. The Sacramento Plant is thus afforded rapid literature searching in depth for literature abstracted in NASA's Scientific and Technical Aerospace Reports and in AIAA's International Aerospace Abstracts. In addition, searches can be obtained from the Defense Documentation Center (DDC) as needed.

The professional librarians assist personnel in making searches using the computer retrieval systems, as well as in searching the open literature. The Information Center maintains current and retrospective files of the pertinent published indexes. In addition to the indexes noted, the following are some of the more important indexes maintained and utilized:

- Applied Mechanics Reviews
- Applied Science and Technology Index
- ASM Review of Metal Literature
- Chemical Propulsion Abstracts
- Engineering Index
- Nuclear Science Abstracts
- Technical Abstract Bulletins
- Technical Translations

The Information Center also has more specialized indexes and a large collection of subject bibliographies.

B. CORPORATE TECHNICAL INFORMATION CENTER

The Corporate Technical Information Center (CTIC) was established as a means for providing ready-access to all technical information generated within any of Aerojet-General's several plants. The CTIC has the responsibility for indexing each technical document in depth.

Documents are indexed by means of descriptive terms selected by professionally-trained experts in each field of technology.

Documents are retrieved through the use of an inverted index system. Thus, each document can be retrieved through the use of technical terms as well as by other characteristics, such as the plant of issue, the author, contract number, and date of issue. The descriptive terms used are selected with great care and are constantly being revised to reflect new technology.

The instant accessibility of the index system, together with a priority telephone linkage, permits searches to be made and inquiries satisfied in a matter of minutes regardless of the plant originating the inquiry. The CTIC works through the library of each facility.

C. COMPUTER FACILITIES

Of particular interest to the proposed program are the existing digital computing facilities available at the Aerojet Sacramento Facility. These facilities provide the following capabilities:

1. IBM 360/65 Large Scale Computer

An IBM 360/65 with 756K bytes of core storage is located in Building 2001. The operating system provides for multiprogramming with variable tasks (MVT) which provides for several jobs to operate concurrently for more efficient utilization of computer resources. Additional equivalent capability can be made available on terminals if required.

2. Computing Services

Computing services provides ANSC users Timesharing Services with the following:

1. G.E. Mark I and II BASIC
2. UNIVAC

Services under (1) are obtained from teletype terminals located in Building 2019A1. The UNIVAC 1108 is accessed via a terminal located in the Aerojet Solid Propulsion Company's part of Building 2019.

3. ANSC Computing Services Emulation Capability

For those programs written for the IBM 7094, and too costly to convert to the IBM 360, Computing Services provides processing service through Greyhound Computing Corporation. Emulation jobs are submitted in Building 2001 where they are distributed by 5 pm daily and returned to the requestor by 11 am the following day.

D. FACILITIES FOR FUTURE TASKS

The following facilities and their capabilities are available for use in the fabrication and development of hardware under the scope of "Future Tasks".

1. Manufacturing

Depending on the schedule and quantity of hardware required, should the analysis result in a "Make" decision, an advanced technology shop is available at Aerojet for use in fabrication of prototype hardware.

This shop is unique in that special procedures, facilities, and personnel are utilized to meet the fabrication needs of exploratory research and advanced development programs. Staffed with skilled machinists, the shop can produce unique experimental hardware from a sketch or a print. The routing of hardware through work stations, inspection, and manufacturing processes is accomplished by indicating the sequential station number on shop orders.

The shop has been in existence since 1963. It has achieved quality fabrication of one-of-a-kind experimental hardware at substantial savings in cost per machine hour on a unit basis as compared with production-mode fabrication. Work produced in this shop is competitive with "outside"

concerns in cost and has been equal or superior in quality. Actual machining is started within one day after the release of the shop-order package containing the routing, drawings, quality control instructions, hydraulic testing instructions, and material.

The shop occupies approximately 10,000 square feet. It is equipped with general-purpose machine tools and equipment, including lathes, milling machines, horizontal and vertical boring machines, drills, grinders, shapers, hones, and sawing and filing machines. Internal production control, assembly, dispatch, and stores areas also are provided.

The overall manufacturing capabilities of the Sacramento Facility, as well as those of other Aerojet Facilities also are available to support fabrication requirements. The manufacturing complex consists of: four major shop buildings with one million feet of floor space; a foundry; a heat treat facility; laboratory support operations; and a machine shop.

2. Testing

a. Cryogenics Laboratory

The Cryogenics Laboratory is the prime facility required to develop and test the hardware in the anticipated development program. It is a remotely located test facility, designed specifically for performing hazardous component testing, using actual cryogenic propellants including liquid oxygen and liquid hydrogen under the pressure requirements of this program.

The facility is divided into a number of test bays for the purpose of performing several tests simultaneously. The largest test bay is equipped with a 10-ton bridge crane to facilitate handling of large test specimens. Available in one test bay is a chamber for simulating space

environment. The chamber, providing an interior work space 6 feet in diameter and 9 feet long, is designed for sustained operation at simulated altitudes to 750,000 feet (1×10^{-6} Torr), and has liquid-nitrogen-chilled walls. Each test bay is equipped with a complete fluid and gas distribution system and electrical power outlets that provide 440 and 110 VAC and 28 VDC. Instrumentation input panels in each bay can accommodate up to 178 data channels.

Thirteen thousand gallon LH_2 and LN_2 storage vessels are available with 3600 psi, 650 cubic foot GH_2 and 650 cubic foot GH_2 receivers. A 6000-gallon run vessel and four 450-gallon run vessels are also available. Disposition of large quantities of gaseous H_2 is safely accomplished by use of a burn pond. This pond can handle flows up to 20 lb/sec.

Three liquid-to-gas converters permit cascade pumping from ambient pressure to 3600 psig in approximately 180 minutes.

A complete data acquisition center is located within the laboratory building. A system of patch panels permits use of any combination of recording, monitoring, and control instrumentation for the space chamber, as well as the other test bays. End recording instrumentation includes direct writing strip charts, paper tape printouts, oscillographs, and magnetic tape. Test data can also be transmitted to a data center for on-line computer processing and tabulated printout. Forty-eight high level and forty-eight low level analog-to-digital conversion channels are available, providing sampling rates of 10,500 and 3,750 bits per second, respectively.

Testing capabilities are further enhanced by a materials laboratory housed in three closed test bays and equipped with a separate control room. Equipment includes a 120,000-lb BLH tensile machine, a 1000-lb Instron tensile machine, and a 10,000-lb Wiedemann Sonntag fatigue machine. Cryostats are provided on all machines to permit testing of materials at liquid hydrogen temperatures.

Two precision assembly rooms with a total working area of approximately 2000 square feet are available for preparation of test specimens. Room air is conditioned to 75°F, 50% RH, and filtered to 2 microns (95%). Circulation systems provide 20 complete air changes per hour. Clean rooms are also available for support of cryogenic test operations.

A vibration system equipped with an 80-channel automatic equalization console, and capable of 1200 lb force at frequencies up to 10,000 Hz, is available within the laboratory.

A completely equipped machine shop is also available within the Cryogenics Laboratory for fabrication and assembly of test fixtures and other test supporting hardware.

b. Mechanical Development Laboratory

This laboratory consists of several areas, each containing specialized equipment for a particular phase of the assembly, development, and testing of mechanical controls, including valves, seals, filters, and actuators. Physical areas are devoted to environmental and servo system testing, to water flow calibration, and to compressible fluid testing.

(1) Component Build-Up and Assembly

This area contains benches, tools, jigs, and fixtures for the assembly, disassembly, and testing of controls components and control systems as well as chambers wherein valves, seals, and actuators are burst, proof, and leak tested with both liquids and gases. There are two chambers available for this type of testing; one measuring 5 ft by 5 ft by 8 ft high and the other 40-in. by 42-in. by 8 ft high. A one-ton Bridge Crane serves a large area of this laboratory.

(2) Cryogenic Testing

The two test chambers described above, as well as a 20 ft by 20 ft Compressible Fluids test cell, are equipped for liquid nitrogen flow and pressure testing. Liquid nitrogen is supplied from a 3000 gal storage vessel and gaseous nitrogen is supplied by a liquid-to-gas converter system. A continuous flow rate of 2 gpm at 50 psi is available while flow tests at 1500 psi and 2 gpm can be attained for short durations. Pressure tests can be conducted up to 3600 psi.

(3) Machine Tool Area

Fabrication and modification of engineering development test hardware are performed in a modern 800 sq ft laboratory machine tool area. Immediately adjacent to this area is a convenient storage space for materials and supplies. An adequate supply of raw stock (e.g., bar, round, and sheet in many sizes and materials) is maintained.

c. Electrical/Electronic Development Laboratory

This laboratory is fully equipped for the testing, evaluation, and qualification of experimental, prototype, and deliverable components, as well as subsystems utilizing electronic, solid-state, and integrated components. Breadboard systems are assembled and tested. Experimental components are developed to meet any program requirements. Typical systems are servo controls, ignition systems, malfunction detection systems, engine sequence and protective controls, and ground support equipment. Skilled laboratory engineering and technical personnel, using the latest test equipment, are fully experienced in the development and testing of complex solid-state electronic controls.

(1) Electrical/Electronic Measuring Equipment

The laboratory is completely equipped for precision measurement and analysis of all electrical/electronic test parameters, such as voltage, current, resistance, impedance, and frequencies.

(2) Environmental Facilities

The laboratory maintains test facilities for conducting vibration, humidity, salt spray, high, low, and cryogenic temperature tests as well as for operational testing at simulated altitudes of 3×10^{-12} Torr.

(3) Instrumentation

Complete data acquisition systems are available utilizing X-Y recorders, oscillographic, and magnetic tape recorders for recording of test parameters. These systems are in portable consoles and can be quickly set-up and calibrated in place for the recording of system pressures, temperature, flow, position, Kw, voltage, current, and time. Direct writing oscillographs can be used for a "quick look" at data, or the photographic-type oscillograph can be used where a more permanent type record is desired. Magnetic tape records of data can be made simultaneously, if desired, for automatic data reduction.

(4) Radio Frequency Screen Room

A radio frequency screen room, certified to MIL-STD-285 and MIL-D-2947A, is equipped with precision measuring equipment capable of performing conducted and radiated interference (EMI) testing and measurement throughout the frequency range of 30 Hz to 10 GHz in conformance with Specifications MIL-STD-826 (USAF, Category A), MIL-I-6181D (DOD, Category A), and AGC-46784.

Current capabilities of conducted and radiated susceptibility testing also are in conformance with the above specifications through the frequency range of 30 Hz to 10 GHz. Sweep generating and spectrum analysis equipment operating up to 10 GHz are available plus RF power measurement meters and wave analyzers.

This facility is one of the most complete radio interference screen rooms. It meets the stringent requirements of EMI testing per the above specifications.

(5) Electro-Mechanical Servo Room

A separate facility is available for the development and operation of electro-mechanical servo systems. This facility is equipped with special test equipment designed to provide input signals to and analyze signals from servo-actuated systems. The equipment can be used to ensure that materials, parts, components, and subassemblies for airborne control systems and ground support systems meet specification requirements. A special console provides test signals to command the system in various patterns, either manually or from a program tape, for the purpose of gathering open-loop and closed-loop transfer-function data quickly and accurately. Signal analysis equipment has the capability to measure, compute, and record data pertinent to transient analysis, velocity error, position error, and frequency response testing. Data are displayed in analog and digital form in addition to being permanently recorded on punched paper tape. Digital printout and analog plots are made by utilizing an automatic program reader that controls the equipment in precisely the type of operation that is on the program tape.

Program tapes can be made quickly by utilizing the test equipment itself. The over-all capability of this facility is such that it can meet the precision measurement requirements of servo-system development or acceptance test programs.

(6) Assembly and Evaluation Area

A portion of the laboratory is devoted to fabrication processes and quality evaluation of developed or procured electronic components to achieve as well as maintain a high state of reliability. High and low temperature conditioning chambers, vibration equipment, altitude simulation chambers, and other miscellaneous equipment also are located in this area, along with the tooling necessary for experimental fabrication, repair, and modification of electrical and electronic controls.

d. Measurement Standards Laboratory

This laboratory provides primary calibration standards traceable to the National Bureau of Standards. It gives a common reference for all calibrations and measurements within the operating laboratories throughout the Sacramento Facility.

e. Instrument Laboratories

This major in-house laboratory provides instrument and equipment repair as well as calibration support to the Development Laboratories. Servicing of all equipment is performed on a scheduled Recall and Calibration System to ensure equipment accuracies as well as the integrity and reliability of data.

f. Transducer Laboratory

Aerojet maintains a Transducer Laboratory which provides the necessary facilities and standards for periodic calibration of pressure, force, temperature, and flow transducers.

APPENDIX A

System Considerations for Remote Replacement of Components

APPENDIX A

SYSTEM CONSIDERATIONS FOR REMOTE REPLACEMENT OF COMPONENTS

Remote replacement of nuclear stage components within the hostile environments of both space and radiation will require special attention, design consideration, and interface coordination in the following general areas:

1. Accessibility
2. Visibility
3. Alignment and orientation
4. Flange-joint design
5. Fasteners
6. Seals
7. Standardization
8. Inspection and qualification
9. Component power connections
10. Manipulator-teleoperator interfaces
11. Auxiliary handling equipment
12. Materials selection
13. Component contamination

A. GENERAL

Actual experience and knowledge of remote handling operations in space are quite limited and nonexistent for conditions involving replacement of components within a radiation environment. Fortunately, however, there is a vast background of useful information available from the nuclear industry which has been remotely disassembling and reassembling radioactive systems for many years. As a direct result of actual remote component replacement operations on the NERVA engine at the Nuclear Rocket Development Station, for instance, many basic fundamentals of remote handling design were developed to permit efficient and reliable methods of remote "changeout".

Not only must it be possible to replace a component but, in addition, verification or requalification of the total system must be performed to confirm that the remote replacement operations meet all system specifications. Therefore, pre-inspection of mating interface flanges also must be made to insure that sealing surfaces have not been damaged during removal of the faulty or malfunctioned component. The removal and replacement of nuclear stage components other than valves and regulators should incorporate certain commonalities or standardization of design to allow multiple use of manipulator tools. Examples of this are standardization of flange designs, seals, and electrical disconnects to component actuators. In the same manner, coordination of all systems requiring remote replacement operation should be evaluated and designed in parallel with the manipulator-teleoperator system design.

B. ACCESSIBILITY

Effective operations involving remote replacement of components is directly dependent upon the degree of accessibility provided. Components requiring removal should not be located behind fixed structural members or rigid piping systems. Likewise, the component must be located to provide ease of inspection to ascertain possible malfunctions by visual methods, perform leak detection, examine for flaws and cracks, or observe its failure to operate. Auxiliary tools and fixtures often must be used to assist in the replacement and qualification operations and they, too, must have access to the failed part. In general, components requiring frequent remote handling or inspection should be located and designed for optimum replacement and must be compatible with the remote manipulator-teleoperator system to be used and associated tools and fixtures.

C. VISIBILITY

Not only must components be accessible for remote replacement but also must be located and positioned to provide optimum viewing of the

operations being performed at all times. The radiation environment dictates that remote viewing devices will be required (e.g., a television system). Current technology extends from reliable two-dimensional black-and-white systems to advanced research in the area of three-dimension color television. The radiation environment will require that the television cameras be positioned by manipulators-teleoperators to provide complete coverage at all times. Stationary cameras anchored to the teleoperator structural system will permit overall viewing of the entire operation and permit the teleoperator actuator arms to perform the replacement operations. It is also entirely possible that tethered cameras could be positioned at strategic positions to observe operations. Designs of the interfacing flanges, therefore, must be compatible with inspection by television systems. High-intensity lighting systems will be a necessary subsystem of the total television system, including directional and light-intensity control.

D. ALIGNMENT AND ORIENTATION

Alignment and orientation of the components relative to the interfacing flanges or joints is a primary design consideration. Components being replaced should ideally be designed with parallel parting planes for the flange interfaces. This type of orientation requires only a single motion by the manipulator to locate the component with relation to interfacing flanges of the system. Guide pins or rabbet-designed flanges are recommended to assist in locating and aligning the interfacing flanges. Visual markings on the sides of the flanges also have proven to be of great assistance to provide a sense of component orientation to the operator.

E. FLANGE-JOINT DESIGN

The use of flange-type joints has proven to be the most successful means of joining piping system remotely. The mating surfaces of the flanges can be either flat or rabbeted, and may incorporate the use of pilot pins.

Guide pins permit early engagement of the two mating flanges and, when used with a rabbeted joint, a high shear-strength joint is achieved. Rabbets as well as pilot pins should be tapered to assist in initial flange engagement. Flange faces must be fabricated accurately and with parallel faces if they are to be successfully and easily rejoined. Grooves milled into opposite sides of the flange have proven to be desirable to assist in separating flanges that have warped or corroded. Special tools inserted into the grooves allow the flanges to be removed. At times it may be required to provide alignment fixtures to realign the interfacing pipe flanges if distortion has occurred because of temperature, vibration, or other operational problems. The use of bellows in the pipe sections has been successful but rigid pipe systems are the most reliable. Commercially available remote cutting and welding tools permit removal of components and rewelding.

F. FASTENERS

The joining of mating flanges has been most successfully achieved by use of captive nuts and bolts. Captive studs with removable nuts have also been used extensively but are more difficult to handle than captive types. V-clamp flanges, such as Marman-type couplings, have also been used. The Marman coupling flange requires a special rigidly mounted clamp assembly with a dual-screw drive. Auxiliary tools for driving the screws simultaneously to a predetermined torque have already been highly developed and refined. While the standard hexagon machine bolt is available, it also requires the greatest tool clearance. The best type of bolt head is the 12-point head since it is easier to handle remotely. Because of its shape it also has the least weight and is smallest in size. Socket-head cap screws have been used but it is extremely difficult to insert the tool and tighten the bolt.

G. SEALS

Metallic seals will be required to meet the environmental conditions of high radiation levels and broad temperature limits imposed by the specifications and to contain liquid hydrogen and inert gases at both vacuum and pressure ranges with minimal leak rates. The metal seal should be made captive to the replaced component to minimize or eliminate remote placement or removal of the seal. Special attention should be given to the inspection of the mating flange seal face prior to replacement to insure that damage has not incurred to the mating flange during removal operations. Special tools may be required to remachine flanges if they have been damaged.

H. STANDARDIZATION

Standardization of bolt heads, flange design, pilot-pin design, seals, and auxiliary tools should be coordinated to minimize the number of special tools and fixtures required for the system. Torque requirements, bolt sizes, flange diameters, and clearances between components should be coordinated in parallel with teleoperator and tooling engineers.

I. INSPECTION AND QUALIFICATION

While the remote replacement of a component may appear to be the most difficult task of remote maintenance, the task remains incomplete until the replaced component has been qualified following replacement. Means for leak testing, checking electrical continuity, and operation of the valve actuator according to specification must be accomplished prior to returning the system to operation. Therefore, the design of components must include special fittings, flanges, or pads that will be required for requalification testing.

J. COMPONENT POWER CONNECTORS

The actuator system of the component generally includes electrical power connectors and instrumentation. Remote electrical disconnection and reconnection of electrical lines can be made using multiple-pin disconnect couplings. Most standard commercial connectors are too fragile for remote operations and many do not lend themselves to manipulator operation. The most successful remote connector that has been used in the nuclear industry is the self-aligning contact pin connector developed by the Cole Electric Company. This type of connector is extremely easy to engage and disengage and is very rugged. However, it does require a larger connector and is more costly than other types.

K. MANIPULATOR/TELEOPERATOR INTERFACES

Components requiring remote replacement must be designed to be handled by the available manipulator-teleoperator system. Manipulator interfaces should be considered during the design of the component; i.e., location, accessibility, stability, and allowance for slight deviations of alignment between the replaced component and the mating system. Smaller components can generally be handled by the standard manipulator hands but larger components will require special adaptors. Handling points should be evaluated in regards to the ease of viewing during operations. Poorly designed manipulator interfaces can easily cause damage to both the replacement component and the system when the component is being engaged.

L. AUXILIARY HANDLING EQUIPMENT

Remote replacement operations will require a variety of remote-handling auxiliary equipments. Special manipulator hands, zero-reaction torque tools, alignment fixtures, gages, and inspection equipment are but a few of the

anticipated tools that might be required for remote component replacement. Every effort should be made to coordinate component design to insure compatibility with the available teleoperator system and thus achieve an economical plan of remote repair.

M. MATERIALS SELECTION

Selection of materials for component replacement hardware should follow the general rules used in the nuclear industry. Special coatings and paints should be avoided since they are subject to deterioration in a radiation environment and will peel and perhaps cause serious damage to the interior of the system being repaired. Aluminum or stainless steel have been universally used in nuclear disassembly operations. In space, the hardware should be as light as possible and still resist the highest anticipated inertial forces that might be imposed.

N. COMPONENT CONTAMINATION

It must be assumed that a failed component in space may be required to be examined to determine the failure mode. Likewise, it must be assumed that the component has become either radioactive or contaminated with radioactive particulates. In either case, decontamination of the component to remove surface contaminants will reduce the radiation level and either permit contact examination or reduce the amount of shielding required for storage. Therefore, it is recommended that decontamination methods and storage provisions be considered as part of the total component-replacement study.

APPENDIX B

SEALCAL Computer Program Description

APPENDIX B

SEALCAL COMPUTER PROGRAM DESCRIPTION

The SEALCAL dynamic seal analysis program uses the basic models proposed by Bauer⁽¹⁾ for leakage and sealing parameters and the IBM models^{(2),(3)} for zero and measurable wear. The inputs required for the program are; test fluid properties and conditions, interface contact geometries and configuration, materials properties data, design loads, allowable leakage, and life factors. The program predicts the allowable loads for zero wear life and the leakage with these loads, and will predict the wear scar depths and the amount of leakage for a number of cycles with a design load greater than the allowable load. The formulas used and the input and output data are described in the following paragraphs.

A. LEAKAGE AND SEALING PARAMETERS

The leakage predictions are gained from the basic formula:

$$Q_L = \frac{(P_1^2 - P_2^2)}{24 \mu_T P_o l} w (h^3) \left[1 + 6.39 \epsilon \frac{\lambda_{TP}}{h} \right] \quad \text{EQ. (A-1)}$$

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- (1) Bauer, Paul, An Investigation of Leakage and Sealing Parameters, AFRPL-TR-65-153, IIT Research Institute, Aug 1965
 - (2) McGregor, C.W., Ed., Handbook of Analytical Design for Wear, Plenum Press, New York, 1964
 - (3) Bayer, R.G. and Wayson, A.R., Designing for Measurable Wear, Machine Design, August 7, 1969

where:

Q_L = Leakage flow across the interface ($\text{in.}^3/\text{sec}$)

P_1 = Inlet (or high) pressure (psia)

P_2 = Outlet (or low) pressure (psia)

P_o = Atmospheric pressure
(14.7 psia)

μ = Viscosity of the fluid at the temperature being analysed
(Reyns -lb-sec/in.^2)

w = Length of the interface normal to flow (in.)

ℓ = Width of the sealing interface in the direction of flow (in.)

h^3 = Flow conductance parameter (in.^3) = the cube of the
equivalent channel clearance between the interfaces.

h = Equivalent channel clearance (or height) (in.) = $\sqrt[3]{h^3}$

ϵ = Correction factor for gasses = .9 for a single gas

λ_{TP} = Mean molecular free path of the gas at temperature being
analyzed and a mean pressure = $(P_1 + P_o)/2$

This equation provides for flow in the laminar, transition, and molecular flow modes. The first part of the equation is essentially the viscous flow equation and the term $(1 + 6.39\lambda_{TP}/h)$ is a modified molecular flow correction factor. When this term is essentially equal to 1 (i.e., $\lambda_{TP}/h < .01$), viscous (laminar) flow predominates and will produce the largest leakage flow. Between the values of approximately 1 and 7 (i.e., $\lambda_{TP}/h = .01$ to 1.0), both laminar and molecular flow (transition flow mode) exists in the channel. Values above 7 (i.e., $\lambda_{TP}/h > 1.0$) indicate that the predominant flow mode is molecular.

The leak channel (or fluid barrier) geometry are described in the formula by w , h^3 (or h) and ℓ . The length of the channel (w) normal to the flow direction is determined from the size of the seal required to meet other criteria (i.e.: allowable pressure drop through the valve at specified

propellant flow rates). The leak path length (ℓ) in the direction of flow depends on the seal interface geometry (conforming or non-conforming) and also depends upon the applied load and seal material in the case of non-conforming geometries (i.e.: wedge or cylinder impressed on a flat surface). The leak path length (ℓ) is predetermined by the designer for conforming geometries (i.e.: flat-on-flat), but must be calculated for non-conforming geometries. Typical examples of non-conforming seal geometries are shown on Figure 1. The length (ℓ) would be calculated for the 60° and small radius seal from:

$$\ell = \frac{L}{C \sigma_m} \quad \text{EQ. (A-2)}$$

where:

L = Applied load intensity (lb/in)

σ_m = Meyer Hardness of the seal material (psi)

C = Constant

This formula is based on the assumption that a condition of constant average stress occurs at the interface as the wedge is deformed. This implies plastic flow of the material or:

$$L/\ell = S_n = \text{Constant} \quad \text{EQ. (A-3)}$$

The average normal stress (S_n) is related to Meyer Hardness by:

$$S_n = C \sigma_m,$$

where C is a constant that depends upon the wedge geometry and is approximately 0.5 for the 60-degree wedge and approximately 0.8 for the small radius seal.

Figure 1 Typical Non-Conforming Seal Configurations

The Hertz formula for the maximum stress imposed by pressing a cylinder against a flat plate is used in calculating the maximum stress in the large radius seal up to the compressive yield strength of the wedge material:

$$(S_c)_{\max} = 0.798 \sqrt{D \left[\frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \right] \frac{L}{D}} \quad \text{EQ. (A-4)}$$

where:

- $(S_c)_{\max}$ = Maximum Compressive Stress Induced by Pressing the Cylinder Against the Plate (lb/in.²)
- D = Diameter of the cylindrical wedge (in.)
- v_1 & v_2 = Poisson's ratio for the seal and mating surface respectively
- E_1 & E_2 = Young's modulus of the seal and mating surface respectively (psi)
- L = Applied load per inch of seal circumference, (lb/in.)

The load at which the induced compressive stress equals the compressive strength of the seal is calculated from:

$$L_{\text{CRIT}} = \left(\frac{\sigma_m}{.798} \right)^2 D \left(\frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \right) \quad \text{EQ. (A-5)}$$

where:

- σ_m = Meyer hardness of the seal material (psi)

Load-area relationships are calculated using the integral:

$$L = \int_{-b}^b S_c \, dx, \quad \text{EQ. (A-6)}$$

where:

S_c = Compressive stress at any point along the contact interface.

For an applied load (L) less than the critical load (L_{CRIT}), a parabolic stress distribution over the contact area is assumed as shown in the following sketch:

$$S_c = (S_c)_{\text{max}} \left[1 - \left(\frac{x}{b} \right)^2 \right] \quad \text{EQ. (A-7)}$$

Substituting Equation (A-6) into Equation (A-7)

$$L = (S_c)_{\text{max}} \int_{-b}^b \left[1 - \left(\frac{x}{b} \right)^2 \right] dx$$

$$\text{or } L = \frac{2}{3} (S_c)_{\text{max}} \cdot 2b$$

Since $2b = l$

$$L = \frac{2}{3} (S_c)_{\max} l \quad \text{EQ. (A-8)}$$

This relationship holds for $(S_c)_{\max} \leq \sigma_m$. The contact length (l) is an elastic deformation. Then

$$L_{\text{CRIT}} = \frac{2}{3} (\sigma_m) l \quad \text{EQ. (A-9)}$$

For an applied load (L) greater than the critical load (L_{CRIT}), the parabolic stress distribution flattens at the compressive yield strength of the material as shown below. The stress parabola is then displaced outward in the x-direction.

$$\begin{aligned}
L &= \int_{-(b+\beta)}^{b+\beta} S_c \, dx \\
L &= \int_{-\beta}^{\beta+b} S_c \, dx + \int_{-\beta}^{\beta} S_c \, dx + \int_{-(\beta+b)}^{-\beta} S_c \, dx \\
L &= \frac{2}{3} \sigma_m \cdot b + \sigma_m \cdot 2\beta + \frac{2}{3} \sigma_m \cdot b \\
L &= \frac{2}{3} \sigma_m \ell + \sigma_m \cdot 2\beta \\
2\beta &= \ell' \text{ and } \frac{2}{3} \sigma_m \ell = L_{\text{CRIT}}, \text{ so} \\
L &= L_{\text{CRIT}} + \sigma_c \ell'
\end{aligned}$$

EQ. (A-10)

where:

ℓ' = Plastically deformed contact width, in.

$\ell' = A' =$ Apparent contact area, (in.²/in. of seal circumference)

This plastically-deformed contact width is, in essence, the width of the leak path through which any leakage must pass. In this plastically-deformed contact area, the stress level in the seal is close to the Meyer hardness of the material. Thus, the seal plastically flows in this area and conforms to any asperities in the mating surface. The surface contact in the elastically deformed region is quite close. The stress level is somewhat less than the Meyer hardness of the seal and the contact between the seal and seat is less intimate. Therefore, the resistance of the leak path is less in this region.

To develop the load-area relationships for the various materials and configurations being considered, L_{CRIT} is first calculated for the seal material and diameter using Equation (A-9) Then ℓ' is calculated from Equation(A-10) as a function of the applied load, L .

The values for (h^3) depend upon the net applied load, apparent contact area, the Meyer Hardness (σ_m) and Meyer Index (n') of the seal material and the peak-to-valley (PTV) surface roughness of the harder interface material. Empirical values for h^3 have been derived⁽⁴⁾ from tests and are shown on Figure 2. This figure represents the data collected for surfaces lapped and polished to the peak-to-valley roughness (PTV) heights shown on the curves. The modified stress ratio must be initially calculated using the relationship:

$$R = \frac{W^{2/n'} / A_a}{\sigma_m} = \frac{L^{2/n'} \ell}{\sigma_m} \quad \text{EQ. (A-11)}$$

R = Modified Stress Ratio

W = The net applied load (lbs)

L = The applied load intensity (lbs/in of seal length)

Aa = Apparent Contact Area (in²)

σ_m = Meyer Hardness of seal material (psi)

n' = Meyer Index Number

The h^3 required to meet a specified gaseous leak rate (at specified conditions of pressure and temperature) for a particular seal configuration is gained by rearranging the flow formula (A-1):

$$h^3 \left(1 + 6.39 \varepsilon \frac{\lambda_{TP}}{\bar{h}} \right) = \frac{24 Q_L P_o \ell \mu_T}{(P_1^2 - P_2^2) \omega}$$

or:

$$h^3 + 6.39 \varepsilon \lambda_{TP} h^2 = \frac{24 Q_L P_o \ell \mu_T}{(P_1^2 - P_2^2) \omega} \quad \text{EQ. (A-12)}$$

⁽⁴⁾ Bauer, Paul, op. cit.

Figure 2

Design Criteria for Lapped and Polished Surfaces with
Surface Roughness Shown as a Parameter
(Reference Footnote 1)

The required value of h^3 with respect to the leak path (ℓ) is obtained by inserting known values into the formula which reduces to:

$$h^3 + C_1 h^2 = C_2 \ell$$

Typical calculated values for the h^3 required with respect to ℓ (for a specific seal configuration and pressure and temperature conditions) to meet 100 cc/hr leak rate are shown on Figure 3.

ANSC experience in the Design of seals has shown the practical limit for the seal interface width to be approximately .020-in. Other investigators⁽⁵⁾ have reported that a minimum width as low as .012-in. was practical for good sealing. However, these values may be impractical for very small shut-off elements, particularly with metal-to-metal seals. Investigations are made during the initial design phase to establish a minimum (ℓ) for a particular application.

The required modified stress ratio (R) is determined from the relationships derived by Bauer (see Figure 2), and the required loading is determined by rearranging formula (A-11).

$$W = (R \sigma_m A_a)^{n'/2} \quad \text{EQ. (A-13)}$$

$$\text{or } L = (R \sigma_m \ell)^{n'/2}$$

Figure 4 depicts the effect of mating (harder) surface roughness on the load required to meet a specified leakage for a particular seal configuration.

(5) Bauer, Paul, op. cit.

Figure 3

Typical Sealing Load vs Mating Surface Roughness

FIGURE 4

B. WEAR PARAMETERS

When rubbing occurs between the interface surfaces under load, the problem of sealing is much more complex. By definition, good sealing practices require that the intimate contact between mating surfaces be undisturbed to maintain the initial seal. Also the best seal is attained when the gasket is compressed to a stress level above the yield (in the plastic range) of the material. However, for good wear, the interface stress levels must be in the elastic range of the materials and the permissible normal stress level is dependent upon the amount of rubbing that occurs during the desired life of the interface.

Extensive investigations ⁽⁶⁾ have shown that the "zero-wear" life of the rubbing interfaces primarily depends upon the actual shear stress at the interface and the shear yield strength of the interface materials. "Zero-Wear" is defined as a wear scar depth no greater than approximately one-half the initial PTV surface roughness (only the peaks are removed from the surface asperities). It is reasonably assumed that within the zero-wear criteria, leakage would remain the same or possibly decrease because of the reduction in surface roughness height. The empirical relationship for "zero-wear" obtained from these investigations is:

$$S_s \leq \left[\frac{2000}{N} \right]^{1/9} GY \quad \text{EQ. (A-14)}$$

- where:
- S_s = the actual shear stress level at the interface (psi)
 - N = the number of passes experienced during the life of the interface and is related to the amount of rubbing experienced by each of the two surfaces.
 - G = a form of a stress concentration factor that depends on the two materials and the lubricants used, if any, and is best determined by actual test.
 - Y = the yield strength in shear of the materials used (psi)

(6) McGregor, C W, op. cit.

The number of passes (N) is a unit of sliding that can be applied to all types of motion in the wear analysis. The normally specified lifetimes (cycles, strokes, months) is converted to the number of passes by:

$$N = nZ \quad \text{EQ. (A-15)}$$

where:

n = the number of passes experienced for each member in one operation (stroke, cycle, revolution)

Z = number of operations required for the life of the members.

Since the seal is always the softer (lowest strength) of the two contacting members and experiences the most wear, the number of passes per operation is:

$$n = \frac{d}{\ell} \quad \text{EQ. (A-16)}$$

where:

d = the length of the sliding distance the seal experiences in one operation (cycle, revolution)

ℓ = width of the contact area in the direction of sliding.

Two typical examples (figure 5) are used for illustration. If the desired life of the sliding shaft seal is 1000 cycles. Then the number of passes per cycle:

$$\begin{aligned} n &= \frac{2d}{\ell} \\ \text{and} \quad N &= n \times 1000 \end{aligned}$$

If the desired life of the rotating shaft seal is 1000 hours and the shaft turns at the rate of 10 RPM.

SLIDING SHAFT SEAL

ROTATING SHAFT SEAL

Figure 5 Typical Seal Configurations

$$d = \pi D \text{ and } \ell = \pi D$$

$$\therefore n = 1/\text{revolution}$$

$$\begin{aligned} \text{and } N &= 1 \times 10 \text{ RPM} \times 60 \text{ min/hr} \times 1000 \text{ HR} \\ &= 60,000 \end{aligned}$$

The value of n will always be a minimum of $n = 1$, because any change in direction or any loading or unloading of the seal implies one pass.

For unlubricated interfaces, G can be only one of two values: 0.20 for interface material combinations with a high susceptibility to transfer, or 0.54 for interface material combinations with a low susceptibility to transfer.

The maximum permissible shear stress ($S_s \text{ max}$) can be assumed equal to the value: $\left[\frac{2000}{N} \right]^{1/9}$ GY, and can be calculated for various values of N if the value of G is known for the particular material combination, and the shear yield strength "Y" is known for the seal material.

The maximum permissible normal stress, S_n , is related to the shear stress by:

$$S_{n(\text{max})} = \frac{S_s(\text{max})}{K \sqrt{1/4 + f^2}} \quad \text{EQ. (A-17)}$$

where:

$S_{n(\text{max})}$ = maximum permissible normal stress (psi)

$S_s(\text{max})$ = maximum permissible shear stress previously calculated (psi)

K = stress concentration factor

f = friction factor and is dependent on the two materials in contact and the lubricant, if any.

The stress concentration factor (K) depends upon the sharpness of corners and edges in the direction of sliding.⁽⁷⁾ For well-rounded corners, the value of K is approximately 2. For sharp corners, K can be as high as 1000. The value

of K is best determined by actual test, but preliminary estimates can be made based upon data collected by McGregor.⁽⁸⁾ The friction factor, f, is also best determined by test of the particular material combination, but preliminary estimates can be made from the McGregor data.

Measurable (or non-zero) wear is defined as a wear scar depth greater than approximately 1/2 the initial PTV surface roughness and occurs when:

$$S_S > \left[\frac{2000}{N} \right]^{1/9} \text{ GY} \quad \text{EQ. (A-18)}$$

or $L > L_A \text{ and } N > N_o$

where:

L = Actual load applied to the seal.

L_A = Allowable load for zero wear for the desired number of passes (N).

N = Desired number of passes for the lifetime of the seal.

N_o = The number of passes permissible for zero wear.

The amount of wear that occurs between N_o and N is dependent upon the type of wear encountered, the seal/mating surface geometry, materials, material properties, lubrication, and other considerations. IBM has developed relationships⁽⁹⁾ for determining the amount of wear based on the two basic wear modes; variable energy and constant energy. For the variable energy mode the governing equation is:

$$d \left[\frac{A_S}{(S_S (\text{max}) \times \ell)} \right]^{9/2} = C d N \quad \text{EQ. (A-19)}$$

where: A_S = cross-sectional area of the wear scar taken perpendicular to the direction of sliding (in^2) (the material volume removed for 1 unit of sliding)

(8) McGregor, C.W., op. cit.

(9) Bayer, R.G., op. cit.

- $S_S(\text{max})$ = Maximum shear stress in the contact region (psi)
- l = length of the contact area in the direction of sliding (in.)
- N = No. of passes above zero wear passes (No)
- C = A constant for a given seal/mating surface configuration, materials, etc.

For the constant energy mode:

$$dA_S = CdN \quad \text{EQ. (A-20)}$$

The wear mode encountered is only dependent upon the combination of seal/mating surface materials and the lubricant used, if any. The type of wear encountered is best determined empirically with the material combination and lubricant to be used, but preliminary estimates are made based on the data provided by Bayer and Wayson⁽¹⁰⁾ and McGregor⁽¹¹⁾.

The more conservative constant energy mode is assumed where empirical data is not available. IBM has performed the integration of the two equations for different interface geometries and presents relationships which define the amount of wear encountered with an applied load greater than the allowable zero wear load. There are two basic seal/mating surface geometries: Conforming and non-conforming. The SEALCAL Program uses two conforming geometries (flat-on-flat and radius-on-radius) and two non-conforming geometries (radius-on-flat and parallel radii). These geometries describe most seal interface configurations. Other geometries will be added to the program as needed.

(10) Bayer, R.G., op. cit.

(11) McGregor, C.W., op. cit.

C. PROGRAM REQUIREMENTS AND DATA

The input requirements for the program are divided into four basic groups; fluid properties and conditions, geometric data, materials properties, and design requirements or criteria.

The fluid properties and conditions required are:

μ_o = viscosity of the leak test fluid at STP
(Reyns - lb-sec/in²)

C_v = Sutherland's constant for the leak test fluid

λ_o = Mean free path of the leak test fluid @ STP (in)

P_o = Standard pressure at which μ_o and λ_o are determined
(i.e.: 14.7 psia)

P_1 = Inlet (or high) pressure of test fluid (psia)

P_2 = Outlet (or low) pressure of test fluid (psia)

T_o = Standard temperature at which μ_o and λ_o was determined (°R)

T = Test Temperature (°R)

E = Constant = .9 For Pure Gases

The test pressures (P_1 and P_2) and the range of test temperatures (T) are specified in the design requirements for the valve. The fluid viscosity (μ_T) at test temperature (T) is calculated by Sutherlands⁽¹²⁾ equation:

$$\mu_T = \mu_o \left(\frac{T}{T_o} \right)^{1/2} \left(\frac{1 + C/T_o}{1 + C/T} \right) \quad \text{EQ. (A-21)}$$

The mean free path of the test fluid at temperature (T) and mean pressure ($\frac{P_1 + P_2}{2}$) is calculated by:

$$\lambda_{TP} = \lambda_o \frac{2P_o T}{(P_1 + P_2) T_o} \quad \text{EQ. (A-22)}$$

The geometric data required are:

CCN = Contact control number. Each number (from 1 to 4) describes the geometry of the seal/mating surface interface

(12) Dushman, Saul, Scientific Foundations of Vacuum Technique, John Wiley & Sons, Inc., New York, 1955

C, Program Requirements and Data (cont.)

- ℓ = The interface contact width (for conforming geometrics only (in))
- C = Shaft, ball, or poppet diameter (in)
- D = Mean interface contact diameter (in) ($w = \pi D$)
- K_s = Stress concentration factor for determining the relationship between normal interface compressive stress and shear stress
- θ = Angle of contact with respect to the direction of load application (degrees)
- H_f = Initial PTV roughness of seal and mating surface (in)

The contact control number (CCN) is simply a number (integer) that defines which of four sets of equations for interface geometries (conforming or non-conforming with variations) to be used in calculations. The contact width (ℓ) is required only for conforming geometries and is defined (at least for first estimate) by the seal design. The mean contact diameter (D) is also defined by the particular design from other design requirements (i.e: shaft size needed for loading). The seal radius (r) is required only for non-conforming geometries and is also defined (preliminarily) by the designer. The stress concentration factor (K_s) is estimated depending on the sharpness of corners and edges in the direction of sliding. The contact angle (θ) is set by the design and is simply the angle between the applied load direction and the resultant normal load at the seal interface. The normal load is related to the axial load by:

$$L_n = L_a / \sin \theta$$

The initial PTV roughness of the seal and mating surface is specified and is determined by the analysis previously described (see Eq.(A-12) and (A-13) and Figure 4.

The materials properties data required are:

- G = Material Transfer susceptibility factor for Zero Wear (.54 or .20) for the particular material combination
- f = Friction Factor for the particular material combination
- Y_1 = Shear Yield strength of the seal at temperature T
- Y_2 = Shear Yield strength of the mating surface material (psi) at temperature T
- F_c = Compressive yield strength of the seal at temperature T
- V_1 = Poisson's Ratio for Seal Material
- V_2 = Poisson's Ratio for Mating Surface Material
- E_1 = Modulus of Elasticity of Seal Material (psi) at temperature T
- E_2 = Modulus of Elasticity of Mating Surface (psi) at temperature T
- σ_m = Meyer Hardness of seal material at temperature T
- n' = Meyer Index No. for seal material
- M_w = Wear Mode for the particular material combination (1 = constant energy, 2 - variable energy)

The wear factor (G) will be one of two values (.54 or .20) depending upon the two materials in contact and the lubricant used, if any. The value used will be taken from the IBM data, ANSC data, or (if not available for the particular material combination) the .20 value will be used for preliminary estimates. The friction factor (f) will be taken from the IBM data or ANSC test data for the particular material combination. The shear yield strengths (Y), compressive yield strength (F_c), Poisson's ratio (v), and the modulus of elasticity (E), will be taken from the IBM data, ALRC data, or numerous other references for preliminary estimates. These values would be corrected when actual data is available on the two materials. The

Meyer hardness and Meyer Index number is available for many materials, but preliminary hardness estimates can be made for other materials from Rockwell, Brinell, or other hardness values. These values would be modified when actual data becomes available. The wear mode (M_w) for the particular material combination is best determined by test. However, preliminary estimates can be made from IBM data and some ANSC test data. If data is not available for the particular material combination, the more conservative constant energy mode will be assumed. The input simply instructs the computer as to which of two sets of equations are to be used in the measurable wear calculations.

The design requirements data are:

N_1 = The number of passes the seal experiences for one operation

N_D = The number of passes required to meet the life requirements

Q_D = The maximum leakage permitted per design specifications (STD in³/sec)

L_D = The load applied to the seal as estimated by the designer for other requirements (lb/in)

The number of passes the seal experiences for one operation is hand calculated using:

$$n = \frac{d}{\ell}$$

where: d = the length of the sliding distance in one operation (stroke, cycle, revolution)

ℓ = the width of the contact area in the direction of sliding

Since: $N = nZ$

where: Z = total number of operations the seal must withstand

N = total number of passes for "Z" operations

Then: N for one operation = n

The design number of passes (N_D) is also calculated from the above equation for the number of operations required by specifications. The maximum allowable leakage (Q_D) is specified in the design requirements. The design load (L_D) is specified by the designer if it is defined by some other requirement for the design.

D. OUTPUTS

The program first calculates the load required (L_R) to meet the specified leakage (Q_D) from:

$$h^3 + 6.39 \varepsilon \lambda_{Te} h^2 = \frac{24 Q_D P_o l h_T}{(P_1^2 - P_2^2) \omega}$$

$$\therefore h^3 = C$$

Since: $h^3 = f(R)$

then: $R = f(h^3)$ (see Figure 3)

and: $L_R = (R \sigma_m l)^{n'/2}$

The program then calculates the number of zero wear passes and the leakage at the required load (L_R) or design load (L_D), if specified. The program then calculates the allowable load (L_A) and the equivalent leakage (Q_L) for the given passes for one operation (N_1). It repeats this calculation for $N \times 10$, $N \times 10^2$, $N \times 10^3$, -----, $N \times 10^6$. The predictions gained from this portion of the program are shown on Figure 6. If the number of zero wear passes (N_0) at required load (L_R) is less than $N \times 10^6$, the program then calculates the wear scar depth (H_w) and the equivalent leakage for the number of passes from N_0 to $N \times 10^6$ with the load (L_R) applied. This is done in increments of 500 passes. The predictions gained

LEGEND:

- Zero-Wear Life Curve
- Leakage Curves
- 1 Material Combination No. 1
- 2 Material Combination No. 2

Typical Applied Sealing Load vs Zero-Wear Life and Leakage for Specified Surface Roughness

FIGURE 6

from this portion of the program are shown on Figure 7. These predictions are compared with the requirements for the design (leakage, life). If necessary, geometric data or other parameters are modified to meet the requirements and the program re-run with the new data. In addition, starting friction loads for shafts are estimated from the required normal loads and friction coefficient used.

LEGEND:

- Wear Scar Depth Curves
- Leakage Curves
- 1 Material Combination No. 1
- 2 Material Combination No. 2

Typical Number of Cycles vs Wear-Scar Depth and Leakage
When Design Sealing Load is Greater Than the Allowable Zero Wear Load

Bibliography

Bauer, Paul, An Investigation of Leakage and Sealing Parameters,
AFRPL-TR-65-153, IIT Research Institute, August 1965

Bayer, R. G., et al, "Designing for Measurable Wear", Machine Design,
7 August 1969

Dushman, Saul, Scientific Foundations of Vacuum Technique, John Wiley
& Sons, Inc., New York, 1955

McGregor, C. W., Ed., Handbook of Analytical Design for Wear,
Plenum Press, New York, 1964

APPENDIX C

Leakage Data for Various Sizes of Lip Seals

APPENDIX C

LEAKAGE DATA FOR VARIOUS SIZES OF LIP SEALS

The information is presented with the intent of indicating the state-of-the-art capability of Aerojet-General in the area of designing and fabrication of lip seals. All configurations are angle poppet valves. The seal geometry is a soft-metal spherical shell seal guided onto a hard conical seat. Test data indicate a characteristic, monotonically decreasing leakage rate asymptotically approaching a constant leakage rate after a few hundred cycles. This "seating in" is a characteristic of a seal with long cycle life capability.

Table C-1 furnishes both a brief description of the valve and seal configuration of three Aerojet lip seals and leakage information.

TABLE C-1

SUMMARY OF VALVE CONFIGURATION AND LEAKAGE DATA
FOR AEROJET ANGLE POPPET VALVES WITH METAL LIP SEALS

<u>Valve Configuration</u>	<u>Leakage Data</u>
1. Space Storable Oxidizer Valve (See Figure C-1) Seal Dia: 1.70 in. Cycle Life: 1000 cycles Phosphor-Bronze Seal/14 PTV ¹ finish Gold Plated CRES Seal/14 PTV ¹ finish Electrolized Inconel 718 Seat/14 PTV ¹ finish	See Figure C-2
2. Bipropellant Valve (See Figure-C-3) Seal Dia: 0.650 in. Cycle Life: 1000 cycles minimum Beryllium Copper Seal/2 RMS ² finish Beryllium Nickel Seal/2 RMS ² finish Electrolized Inconel 718 Seat/3 to 4 AA ³ finish	Summarized in Table C-2
3.Cooldown Supply Control Valve (Test Valve, See Figure C-4) Seal Size: 3.75 in. Cycle Life: 5000 cycles, minimum Phosphor-bronze Seal/4 AA finish Electrolized Inconel 718 Seat/4 AA finish	See Figure C-5

¹ Peak to Valley -- in micro-inches

² Root Mean Square -- in micro-inches

³ Arithmetic Average -- in micro-inches

TABLE C-2

BIPROPELLANT VALVE PRIMARY DESIGN CRITERIA
AND TEST DATA

<u>Parameter</u>	<u>Design Goal</u>	<u>Demonstrated</u>
Internal Leakage	1.75×10^{-4} scc/sec GHe at 200 psig	4.68×10^{-6} scc/sec; BeNi 4.98×10^{-7} scc/sec; BeCu
External Leakage	1×10^{-7} scc/sec GHe	1×10^{-7} scc/sec
Pressure Drop	25 psid, max	10.3 psid
Travel Time	0.005 to 0.015 sec open and close	0.007 sec open 0.008 sec close
Temperature	-230 to +300°F	-320 to +70°F

Figure C-1 - Space Storable Oxidizer Valve

Figure C-2 - Comparison Between Actual and Calculated Leakage Rates,
Phosphor-Bronze/Inconel 718, All-Metal Lip Seal

Figure C-4 - Cooldown Supply Control (Test) Valve

	<u>Design Goal</u>	<u>Measured Value</u>
Internal Leakage	13.7 sccs @ 30 psia and 39°R	Less than 0.10 sccs @ 30 psia and ~ 40°R

Figure C-5 - Ambient Leakage Data for Cooldown Supply
Control Test Valve, Phosphor-Bronze/Inconel 718,
All-Metal Lip Seal

APPENDIX D

Example of Valve Drawing

NOTES:

VALVE DATA

1. INTERPRET DRAWING PER MIL-D-1000 FORM 3
2. THIS VALVE ASSEMBLY IS DESIGNED TO MEET THE REQUIREMENTS OF COMPONENT SPECIFICATION EC9025R DATED 8 JULY 1970 AS MODIFIED BY STEADY STATE POINTS DATED 18 NOVEMBER 1970
3. THE FOLLOWING OPERATING CONDITIONS WERE CONSIDERED IN THE DESIGN OF THE VALVE:
 - A. NORMAL ENGINE OPERATION
 1. INLET TEMPERATURE 40°R
 2. INLET PRESSURE 30 PSIA
 3. PRESSURE DIFFERENTIALS 30 PSID
 4. VALVE POSITION CLOSED
 - B. SHUTDOWN OPERATION
 1. INLET TEMPERATURE 40°R
 2. INLET PRESSURE 30 PSIA
 3. PRESSURE DIFFERENTIALS 30 PSID TO 150 PSID
 4. FLOW RATES 2.00 LBS/SEC
 - C. HYDROTEST PROOF PRESSURE 940 PSIA VALVE OPEN
 - D. HYDROTEST PROOF PRESSURE 940 PSIA VALVE CLOSED (TEST TO INLET)
 - E. HYDROTEST BURST PRESSURE 2700 PSIA VALVE OPEN
4. MAXIMUM FLOW RESISTANCE IN THE FULL OPEN POSITION IS BASED ON A INLET LINE FLOW AREA OF 5.42 IN²
5. FULL VALVE STROKE EQUALS 1.0 INCHES
6. MAXIMUM ALLOWABLE INTERNAL LEAKAGE IN THE FULLY CLOSED POSITION IS 0.005 CM³/MIN AT 30 PSID AND 6000 SCMH/IN² AT INLET AT 30 PSIA TO 150 PSIA
7. THE VALVE IS REQUIRED TO OPEN BETWEEN .5 SECONDS AND 1.0 SECONDS ESTIMATED OPENING TIME .750
8. THE VALVE IS REQUIRED TO CLOSE BETWEEN .5 SECONDS AND .8 SECONDS UPON RECEIPT OF AN EMERGENCY CLOSING COMMAND SIGNAL VALVE WILL CLOSE IN .5 SECONDS MAXIMUM

9. RANGE OF VALVE'S VARYING CONTROL ELEMENTS IS 4 LB-FT
10. MECHANICAL STOPS PROVIDED FOR FULL OPEN AND CLOSE POSITIONS AS INDICATED

SPRING RATE (LBS/IN), ENERGY ABSORPTION (IN-LB), ENERGY ABSORBED (IN-LB)

OPEN STOP	2000 IN/IN	100	.0028
CLOSED STOP	2000	75	.0028

11. TORQUE REQUIREMENTS AT AN INITIAL MAXIMUM DIFFERENTIAL PRESSURE OF 30 PSID, MAXIMUM OVERLOAD (30% OVER) INCLUDED IN THE OPERATING TORQUE REQUIREMENTS

12. ESTIMATED WEIGHT
 1. VALVE 23.23 LBS
 2. ACTUATOR 25.00 LBS
 3. TOTAL 48.23 LBS

13. ESTIMATED DESIGN VIBRATION LEVEL 20% 50 TO 2000 Hz IN THREE MUTUALLY PERPENDICULAR DIRECTIONS

14. BASED UPON VALVE FLOW AREAS AND TYPICAL ANGLE POPPET VALVE CURVE FROM AFC REPORT U3180.FIG 38#39

15. FLANGES FOR VALVE PROOF TEST AND ACCEPTANCE TEST, THE TEST FLANGES ARE TO BE CUT OFF PRIOR TO VALVE AUTOMATIC WELDING INTO NEXT ASSEMBLY (MODULE).

MOTOR AND ELECTRONICS DATA

26. ELECTRICAL OPERATING CONSTRAINTS ON MOTOR
 - A. VOLTAGE AVAILABLE AT VALVE INTERFACE 28 ± 2 VDC
 - B. MAXIMUM ALLOWABLE CURRENT DURING THE DESIGN ELECTRONIC LOADS PER PHASE
27. OPERATING TEMPERATURES TO BE EXPERIENCED BY MOTOR -416°F TO 140°F
28. DUTY CYCLE
 - A. AT AMBIENT CONDITIONS THE MOTOR CAN OPERATE FOR ONE FULL VALVE CYCLE (OPEN & CLOSE) AND THEN IT MUST BE DE-ENERGIZED FOR A MINIMUM OF 10 MINUTES.
 - B. AT -320°F THE MOTOR CAN BE OPERATED CONTINUOUSLY.
 - C. MAXIMUM HOLD IN TORQUE OF 5 LB IN. CAN BE HELD FOR 1 MINUTE AT AMBIENT AND INDEFINITELY AT CRYOGENIC TEMPERATURES.
29. MOTOR DESCRIPTION
 - A. TYPE AC INDUCTION, 6 POLE, CONTROLLED
 - B. ROTOR INERTIA 0.3 LBM IN² IN
30. POSITION INDICATION WILL BE ACCOMPLISHED IN THE FOLLOWING MANNER
 1. TYPE: ROTARY POTENTIOMETERS
 2. QUANTITY: 3 GANG POTENTIOMETER
 3. LINEARITY OF OUTPUT: .25%
 4. STROKE: 200°
 5. POWER REQUIREMENT: 10 WDC
 6. RESISTANCE: OPEN: 700 OHMS CLOSED: 700 OHMS

31. DISCRETE POSITION INDICATION WILL BE ACCOMPLISHED IN THE FOLLOWING MANNER
 1. TYPE: LIMIT SWITCHES
 2. QUANTITY: 4
 3. PURPOSE:
 - (1) TO SIGNAL END OF OPENING STROKE AND SHUTOFF MOTOR
 - (2) TO SIGNAL FULL OPEN POSITION
 - (3) TO SIGNAL END OF CLOSING STROKE AND SHUTOFF MOTOR
 - (4) TO SIGNAL FULL CLOSE POSITION
 4. PRE TRAVEL .085 IN. MAX
 5. DIFFERENTIAL TRAVEL .019 IN. MAX
 6. OVERALL TRAVEL .115 IN. MAX
 7. BRAKE DISTANCE .011 IN. MAX

TRANSMISSION DATA

51. COMPOUND DIFFERENTIAL PLANATARY GEAR TRAIN YIELDS A SPEED REDUCTION OF 86:1
52. OVERALL EFFICIENCY OF TRANSMISSION 76%
53. BACK DRIVING EFFICIENCY THROUGH TRANSMISSION 59%
54. TRANSMISSION INERTIA (AS SEEN BY MOTOR) .02 LBM-IN
55. MECHANICAL BACKLASH FROM MOTOR TO VALVE ATTACHMENT POINT IS .004 RADIANS
56. SLIP BRAKE DESCRIPTION:
 - A. TYPE MULTIPLATE FRICTIONAL BRAKE
 - B. LOCATION HOLDS SECOND DIFFERENTIAL RING GEAR
 - C. CRACKING TORQUES 5.00 LB-IN TO 7.00 LB-IN

4.1.4 FLOW CONTROL CHARACTERISTICS

VALVE FLOW AREA

VALVE REQUIREMENTS TO OPEN

MOTOR TORQUE SPEED CHARACTERISTICS

FOR RECORD ONLY DO NOT FABRICATE TO THIS PRINT.
☒ RETAIN ORIGINAL VELLUM.
☐ DESTROY ORIGINAL VELLUM
AUTHORIZED CHECKER: [Signature]

QTY REQD		CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL / SPECIFICATION	ITEM NO.
WEIGHTS		UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES		CONTRACT NO. SUR-1		AEROSPACE CORPORATION
STRESS		TOLERANCES DECIMALS ANGULAR .XX ± .03 .XXX ± .010 DO NOT SCALE DRAWING		DRAWN: [Signature] DATE: [Date]		
MATERIALS & PROCESSES		TREATMENT		DESIGN: [Signature]		TYPICAL PREDESIGN VALVE DRAWING
MANUFACTURING ENGNG		FINISH		DESIGN ACTIVITY		
QUALITY ASSURANCE		PARTY NEXT FINAL		CUSTOMER		E 34632 APPENDIX D
ADDITIONAL APPROVALS		DATE		APPLICATION