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WANL-TNR-206

PROGRAM REPORT ON THE
ANTI-CRITICALITY POISON WIRE
SYSTEM

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ABSTRACT

This report documents the status of the development program for the Anti-Criticality Poison Wire System (ACPS). The need for an in-flight poison wire system for maintaining the NERVA reactor sub-critical from assembly to operation in space was realized early in the NERVA program.

At the present time, a shipping type of poison wire is in use. However, its use for space operation is limited due to material rigidity, excessive weight and neutronic values. It was therefore necessary to develop a flexible poison wire capable of being extracted from the reactor core and through the nozzle throat for system storage or ejection.

The system design is based on criteria derived from normal and accidental environmental conditions which might conceivably be encountered during assembly and space flight. In addition to listing the criteria upon which the ACPS system is based, a description of the entire system, operational sequences, and control features is provided. Reliability has been stressed and is reflected in the conceptual design of each component.

Problems of hardware availability, manufacturing technique, and material selection have been substantially resolved. Fabrication and successful testing of key sections of the ACPS have been accomplished.

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FOREWORD

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SUMMARY

The Anti-Criticality Poison Wire System has been designed to meet the need for safeguarding the NERVA engine from the time of assembly to its eventual use in outer space. Poison wires are uniformly distributed throughout the core cross section in axially aligned coolant channels. Consequently, the wires must be bent during the withdrawal process in order to pull them through the nozzle throat which has a maximum diameter less than the diameter at which most of the wires are inserted. This feature has led to the development of a flexible wire which will not impose damaging forces upon the reactor and nozzle components during a withdrawal process.

Accident situations, orbital flight, and flight termination possibilities dictate the conditions that must be withstood by the materials and structure of the wires. These conditions include the resistance to high temperatures to inhibit poison removal during a plausible fire; pliability at ultra-low temperatures to facilitate wire removal under orbital flight conditions; and a high degree of insolubility to sea water to prevent poison removal over long periods of immersion following re-entry and ocean impact.

The element boron showed the greatest promise as a neutron absorbing ingredient of the poison wire. To provide adequate resistance to deterioration and dissipation under credible situations involving fire and water immersion, the boron is combined into a suitable chemical compound. The chemical compound chosen was boron carbide (B_4C) since it is highly stable, the properties are well known, and it is readily available.

To reduce the weight of the poison wire system for space flight, B_4C prepared from boron highly enriched with the isotope of atomic weight 10 should be used. If boron enriched 80 to 90 percent with boron 10 is employed, the number of wires required to obtain a given poisoning effectiveness is approximately one-third of the number as compared to the use of natural boron.

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To provide flexibility in the poison wire, a technique was developed to break the hard ceramic boron carbide sticks comprising the core of the wire into short pieces, each nominally 1/8 inch in length. Further assurance of wire flexibility was obtained by utilizing fiberglass braid in the poison stick encasement as a means of transmitting tensile forces through the length of the wire. Fiberglass braid is not only flexible and strong, but it is also resistant to high temperature.

The outer surface of the prototype poison wire is a Teflon sheath which is shrunk over the fiberglass braid. The low friction coefficient of Teflon minimizes resistance to forces applied during withdrawal of the poison wire from the reactor.

Approximately 400 wires were fabricated in accordance with the construction described above. These were bundled near one end to form groups of ten wires per bundle. The nuclear poison of these wires was simulated by the use of properly dimensioned pencil lead material. Various quantities of these wires were pulled from an arrangement of NERVA reactor dummy fuel clusters to determine withdrawal forces required for flexible wires.

The apparatus used to withdraw the wires from the dummy fuel clusters was designed and constructed to demonstrate principles and techniques that could be employed to withdraw the wires during flight of the NERVA engine. In essence, the wires were terminated at a retractor head positioned near a simulation of the throat of the engine nozzle. A stainless steel tape connected the retractor head unit to a spool on the shaft of a pneumatic motor. Upon admission of air to the motor, tape was wound on the spool, and the wires connected to the retractor head were withdrawn from the dummy fuel clusters.

A load cell in series with the tape and retractor head was used to measure the pull forces. Average force under sliding friction conditions (the measured force divided by the total number of wires pulled) was determined to be 0.122 kg per wire. Peak average force is estimated to be higher than this by a factor of 1.25. On this basis, a withdrawal system capable of exerting approximately 310 kg is required to remove 2000 wires, which are uniformly distributed throughout the core cross section, from the reactor.

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The neutron absorbing poison requirements of the wires were dictated by the necessity of assuring subcriticality under the worst conditions that can be postulated (i.e., a complete immersion and water flooded reactor). An analysis was performed to determine the reactivity effects of changing $B_{4}^{10}C$ density, wire diameter, wire length, and the number of wires. The following information summarizes results that were obtained for a fully flooded reactor.

- 1) The reactivity of the fully flooded non-poisoned reactor is $1.59 K_{eff}$.
- 2) Reactivity variation is relatively insensitive to $B_{4}^{10}C$ density over the range 80 to 90 percent theoretical.
- 3) A 10 percent change in the number of wires in the range of 2000 to 2200 wires results in about a 0.04 reactivity change.
- 4) A change in wire diameter from 0.137 cm to 0.157 cm results in about 0.08 reactivity change.
- 5) Two thousand wires, containing 85 percent theoretical density $B_{4}^{10}C$ of 0.147 cm diameter, uniformly distributed throughout the core are adequate to maintain the fully flooded reactor at or below a reactivity of 0.95.

$B_{4}^{10}C$ material containing boron of 70 to 80 percent isotope 10 enrichment was prepared in powder form, extruded, and sintered to obtain cylindrical sticks. Approximately 90 wires using these sticks were fabricated for the purpose of evaluation in the PAX critical assembly.

PAX reactor critical tests were conducted to determine the worth of the poison wires. The $B_{4}^{10}C$ diameter averaged 0.1416 cm and its specific gravity averaged 1.87 gm/cc. Experimentally determined wire worth at the center of the reactor was 1) 5.3 cents to 6.0 cents each with a dry reactor, and 2) 9.2 cents to 13.9 cents each for a water flooded reactor (water simulated with polyethylene rods). The calculated worth of the poison wires in the same location in the reactor core was 1) about 4.0 cents each in a dry reactor and 2) 6.9 to 9.3 cents in a flooded reactor. These test results indicate that 2000 wires are more than adequate to maintain a water flooded core subcritical.

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For purposes of perspective and future reference, a preliminary wire withdrawal actuator design was prepared. This concept provided the basis for analysis of the action involved in withdrawal of poison wires and in ejection of the ACPS from the nozzle. This analysis confirmed that an ACPS was feasible, and that its operation was compatible with flight vehicle staging and NERVA engine startup.

Since the poison wire is the essential component of the ACPS, criteria, fabrication, and qualification of the wire are discussed in the beginning of the report. The next section is devoted to criteria that the ACPS fulfills. This is followed by results on analytical and experimental investigations of the neutron absorbing worth of the prototype wire and the neutronic effectiveness of an installation of poison wires. The closing sections of the report provide a conceptual description, a review of plausible system operation, and a qualitative reliability evaluation.

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CONCLUSIONS

An installation of poison wires is the only conceivable countermeasure for which the following benefits are concurrently obtained.

- 1) Poison wires are immediately in effect upon installation without further implementation of additional measures or procedure.
- 2) Since a potential hazard is completely eliminated, operations involving the NERVA engine and the vehicle on which it is installed may be conducted in a manner similar to those employed with chemically fueled engines and vehicles.
- 3) The nuclear reactor presents no additional hazard in any accident or situation associated with rocket vehicles and their launch facilities.

The neutron absorbing capability of a poison wire configuration has been proven by experiment. It has been established on the basis of these experimental results that the number of wires (2000) required for an ACPS system is reasonable and compatible with the means of removal and the nozzle dimensions. The neutron absorbing poison, boron-10, is available. Boron-10 can be combined into a compound, $B_4^{10}C$, which is producible in a dimensionally suitable form with the desired density.

The wires can be fabricated with flexibility suitable for use with the reactor and nozzle components. The materials fabricated into the wires combine satisfactory tensile strength with adequate resistance to water immersion and high temperatures to which they might be exposed in accident or flight termination situations. The wire materials also retain flexibility at low temperature, and therefore they are suitable for removal following an extended time in orbit. Since the wire construction contains no metal, the burden, with respect to weight, is minimized.

An ACPS can be designed which will withdraw the wires from the reactor and remove itself and the wires completely from the nozzle. Based on the analysis performed, these actions can be accomplished without damage to the nozzle or to the reactor. ACPS operation with respect to the time required to complete the sequence of action is compatible with programming of flight vehicle staging for either suborbital or orbital start.

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CHAPTER I

INTRODUCTION

A countermeasure device which eliminates the possibility of an accidental NERVA reactor criticality is presented and analyzed in this report. In various conceivable accident situations the NERVA reactor would not be maintained in a subcritical state by the control drum system which is utilized in normal operations.

The control drums do not contain enough neutron absorbing material to prevent a nuclear excursion if, for example, the reactor is submerged in water or if hydrogenous rocket propellant of high density enters the reactor core. Furthermore, during the period preceding launch and flight, it may not be desirable at all times to maintain the control drums in an inoperable condition by using positive mechanical lock techniques to prevent rotation of the control drums from the least nuclear reactive position (maximum neutron absorbency of the drums). For instance, it may be desirable for check-out and launch preparation purposes to exercise the drum rotation of a complete NERVA engine.

For these reasons, a method which supplements the control drums is required to guarantee subcriticality of the reactor. This guarantee should be maintained until capability of the reactor to operate is brought about by a deliberate sequence of actions following the launch of a flight vehicle carrying the NERVA engine.

The means proposed to guarantee subcriticality of the reactor is the Anti-criticality Poison Wire System (ACPS). Prominent features of the system are shown in figure 1-1. In essence, anti-criticality poisoning consists of special neutron absorbent wires manufactured for insertion into the coolant channels of the reactor core. A sufficient number of these wires prevent attainment of a self-sustaining nuclear fission reaction within the reactor fuel by

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absorbing neutrons required in the reaction. The neutron absorbent material of the wires is boron, the "poison".

To prepare the reactor for operation in flight the wires must be removed from the reactor core. Consequently, another essential feature of the ACPS is a wire withdrawal mechanism. The wire withdrawal mechanism may be installed in the throat and divergent portion of the NERVA engine nozzle. Following withdrawal of the poison wires from the reactor core during flight, the entire ACPS will be ejected from the nozzle prior to starting the NERVA engine.

With the ACPS installed, activities associated with the NERVA engine need not differ greatly from those associated with chemically fueled propulsion engines. Precautions during ground handling situations and during launch and orbital operations of the NERVA engine will be quite similar to those of chemical propellant engines.

The ACPS is conceived as a highly self-contained system. Therefore, withdrawal of the wires from the reactor core is dependent, to a minimum extent, upon actions and fulfillment of conditions external to the system. For this reason, the ACPS may be used on a flight in which either orbital startup or suborbital startup of the NERVA engine is programmed since withdrawal of the wires requires only an appropriate actuating signal.

According to the ACPS design, there is no difference between the NERVA I engine and the larger NERVA II engine, except in scale. As a result of the change in scale, a change in the dimensions of the wire and in the number of wires may be required. In this event the wire withdrawal mechanism of the system will be larger and somewhat heavier. Since the changes are of a dimensional nature, the ACPS design would be applicable to the NERVA I or the NERVA II engine.

The currently conceived ACPS, as illustrated in figure 1-1, consists of an arrangement of flexible poison wires inserted in the reactor coolant channels and connected to a mechanical withdrawal actuator contained in a pair of concentric cylinders approximately 7.0 feet in length. The system is seated in the throat region of the nozzle and is braced in the divergent section.

Installation or removal of apparatus can be conducted without jeopardizing the integrity of the nozzle. This conclusion is supported by the consideration that during preparations for

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each of the current series of reactor ground tests, a plug is installed in the nozzle throat to permit reactor assembly pressurization. Use of this device has not caused damage to any of the nozzles.

With regard to operation of the system, the poison wires are withdrawn into the inner guide cylinder retainer upon transmission of the actuating signal. In order to assure that a premature ejection does not take place, another separate signal initiates the system ejection procedure following separation of the preceding stage of the flight vehicle from the nuclear stage. Ejection of the complete system, including the nozzle protective foam, is conducted in a manner independent of external means. The ACPS has the following distinct advantages:

- 1) It is self contained and independent.
- 2) The reactor is positively poisoned, and no portion of the core can be formed into a critical mass under accident conditions as long as the wires are in place.
- 3) The ACPS will not damage the reactor, the engine, or other components of the flight vehicle.
- 4) The ACPS will maintain reactor subcriticality from the time of reactor assembly to the time of wire withdrawal in flight.

It was recognized that a flexible poison wire must be developed in order to make the ACPS a reality. Concentrated studies of wire development problems, in addition to the revision of previously proposed withdrawal and ejection techniques, have resulted in an ACPS concept that is feasible. Many features of the poison wires and many system operating principles have been proven from the fabrication and trial of prototypes.

As currently fabricated, the prototype flexible poison wire consists of encased boron carbide (B_4C) cylindrical granules. The B_4C can be manufactured with boron enriched with the isotope of boron 10 (B^{10}). The encasement is comprised of a plastic granule retaining tube enveloped by a flexible fiberglass braid and an outer sheath of Teflon. The pliability which results from this construction of the flexible wire reduces the possibility of damage to reactor or nozzle parts.

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Upon review of various nuclear poisons reported in Reference 1, it was concluded that the element boron, especially the isotope B^{10} , showed the most promise as a neutron absorbing ingredient for the poison wire. Adequate resistance of the nuclear poison to deterioration and dissipation under credible accident situations involving fire and water immersion is required. For this reason the boron contained in the poison wire is combined into the chemical compound boron carbide which is highly stable. As a benefit, with respect to increasing flight payload, a system weight reduction results upon utilizing boron carbide prepared from boron enriched 80 to 90 percent with B^{10} . The number of wires required to obtain a given effectiveness is approximately one-third the number used when employing natural boron.

Previous investigations² demonstrated that Teflon sheathed flexible wires could be withdrawn from the core coolant channels without damaging reactor core components. These investigations also showed that the use of Teflon as an outer sheath was beneficial in reducing withdrawal resistance.

Measurements of the neutron absorbing capability of the wires indicate that 2000 wires will be more than adequate to maintain the desired subcriticality. A review of geometrical arrangements indicated that 3000 wires could be withdrawn readily through the throat of the NERVA I nozzle.

The insertion of poison wires into the coolant channels of the reactor core is a practical and proven means for maintaining subcriticality. With respect to all NERVA reactors manufactured and under construction, this method of obtaining the desired degree of subcriticality has been incorporated and utilized in the reactor assembly procedure, the preparations for

¹WANL-TME-603, Selection of Material, Number and Distribution of Poison Wires for the Anti-Criticality Poison Wire System, November 1963 (CRD)

²WANL-TNR-155, Status Report on the Anti-Criticality Poison Wire System, March 1964 (CRD)

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reactor transportation, and the shipment of the NERVA reactor to testing installations. A complement of 6800 wires is installed in a reactor for the purpose of transportation or shipment. This large number of wires is required since the neutron absorbing chemical element of the wires is manufactured with a mixture of natural boron which is not as effective as the boron 10 isotope.

These wires used for shipment purposes are stainless steel tubes filled with B_4C and encased in polyethylene. Wires of this type are inserted during reactor assembly and removed immediately prior to attachment of the nozzle to the reactor. This procedure is satisfactory for the reactors used in the NRX ground test series; however, the shipping wires are not flexible enough to permit the removal of most of them through the nozzle. Therefore, the shipping type wires cannot be employed during preparations for engine flight following attachment of the nozzle to the reactor. Nevertheless, the shipping type wire has provided a sound basis for development of the flexible wire since extensive experience was obtained on poison wire neutronic computational methods,³ and insight was gained on wire fabrication techniques.

The need for maximum reliability in all ACPS components has influenced the direction of all investigations. It has been kept in mind that the ACPS is an absolute safeguard in principle since no circumvention can obtain reactor operation if the poison wires are in place. Consequently, a method of maximum dependability is required to withdraw the wires. Furthermore, it has been realized that the ACPS cannot jeopardize the integrity of the reactor and nozzle components.

³WANL-TME-1172, Status Report on the Flexible Poison Wire Development, May 1965.

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Figure 1-1. Anti-Criticality Poison Wire System.

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CHAPTER II POISON WIRE DESIGN AND CONSTRUCTION

A. FUNCTIONAL CRITERIA

An intrinsic advantage of the poison wire concept, in comparison to other safeguard concepts, is its passive character. Upon installation of the poison wires, the safeguarding capability is immediately in effect. Safeguard devices of an active nature that might be employed in place of poison wires require steps of activation, other than installation, in order to bring them into effect.

The decision to utilize the poison concept eliminates much of the exhaustive effort in hazards analysis which is required to determine, in minute detail, all possible situations in which criticality could accidentally occur. Furthermore, the utilization of poison wires makes it possible to conduct activities which would not be desirable, under other circumstances, or would require the establishment of prolonged safeguard procedures.

A nuclear incident is not possible during the engine assembly period if the wires are in place. Furthermore, the nuclear engine may be handled in the same manner as a chemical propellant engine at the vehicle assembly location. Transportation of the nuclear engine to the launch pad will involve only conventional methods. Even in the event of a flight cancellation, due to storm or hurricane, the complete vehicle may be readily returned to weather protective enclosures and facilities by means customarily available. Also, the need for a special or remotely isolated launch pad is no greater with a poison wire equipped nuclear engine vehicle than that involved with chemical propellant vehicles.

The poison wire system, as proposed, presumes removal of the poison wires following most or all staging of the nuclear engine vehicle during flight. Therefore poison wire equipped nuclear engine vehicles do not present greater hazards than chemical engine vehicles with respect to reaction time required to activate a destruct system at launch or as a result of deficiencies of tracking systems in detecting early flight path deviations.

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The launch pad hazard level is not raised as a result of nuclear moderating properties of liquid hydrogen and hydrogen containing petroleum based fuel since the possible presence of these materials has been considered in establishing the number of wires to be inserted into the nuclear reactor. For the same reason, no hazard exists for the possibility of complete water immersion. In the event of a drop from a considerable height or in the event of an explosion, it is not plausible that the wires would become separated from the nuclear fueled mass due to the impact or crushing action alone.

The development of the flexible poison wire is based, in part, on the poison wire used at the present time for reactor shipping purposes. Although the shipping type of poison wire is adequate for its purpose, the particular features and requirements for its manufacture prevent it from being a desirable component for reactor flight applications. The shipping type poison wire consists of a B_4C powder compacted into a stainless steel tube. The final diameter is obtained by swaging the powder-filled tube to the appropriate size.

Bending is required in order to withdraw the wire from the reactor core via the nozzle throat. The metal tube encasing the poison wire is susceptible to buckling which produces sharp corners and edges. The swaging process inhibits the flexibility of the poison wire as a result of work hardening of the metal wall.

Consequently, features incorporated in the current wire design have been derived primarily from efforts to increase wire flexibility and to lower the risk of producing changes in the wire cross-sectional geometry as a result of crushing or buckling of the wire. Accordingly, the margin has been increased, with respect to maintaining the integrity of the reactor core components which contact with the wire.

The current conception of the poison wire has been established to fulfill the accident requirements listed in table 2-1. The poison wires must provide a neutron absorption capability sufficient to prevent reactor criticality under credible situations of potential hazard with an adequate margin of safety. It has been judged that a maximum reactivity of 0.95 under the

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TABLE 2-1

CAPABILITIES REQUIRED IN THE POISON WIRE AND SYSTEM DESIGN

Water immersion and hydrogenous material accident requirements:

- 1) With the core completely immersed and flooded with water or hydrogenous propulsion engine propellant, the poison wire system must be capable of maintaining $0.95K_{eff}$ with the control drums in the most reflective position.
- 2) Under conditions of accidental discharge of liquid hydrogen through the reactor, the system must prevent the ejection of the wires and retard hydrogen flow by throttling at the nozzle throat.
- 3) The wires must not be affected by water corrosion and erosion.
- 4) The wire poison and encasement materials must be non-soluble in water.

Fire and explosion hazards:

- 1) AEC regulations, with respect to reactor shipment containers, shall be fulfilled.
- 2) Reactor subcriticality shall be maintained in the event of vehicle and launch pad fire and explosion.

Impact and compaction hazards:

- 1) Wires to be designed to stay in the reactor as long as the pressure vessel and nozzle are basically intact.
- 2) Any attitude of the engine at the time of impact shall tend to produce embedment of the wires into the reactor core.

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most unfavorable combination of circumstances will provide a conservative margin of safety without incurring excessive secondary penalties such as large poison system weight. A reactivity of 0.95 means that the neutrons produced from a given number of nuclear fissions (and therefore available for further reactions) is 95 percent of the neutrons which entered the reactions. It follows that a reactivity less than 100 percent results in a decay of the number of fissions per unit time.

Factors which influence and determine wire design specifications are listed in table 2-2. These conditions establish strength requirements as well as dimensional limitations. Wire life, durability, and flexibility requirements are also implied in this information.

B. POISON WIRE CONFIGURATION

1. Dimensions and Weight Distribution

Figure 2-1 represents a cross section of the neutron absorbing portion of the poison wire. Dimensions of this illustration are based on maximum values expected. Typical longitudinal dimensions are indicated in figure 2-2 which illustrates the prototype poison wire construction. The weight distribution of basic wire components is presented in table 2-3.

2. Wire Components

The major wire component groups are the:

- a) Center poison granules
- b) Encasement
- c) Segregation and support elements
- d) Termination

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TABLE 2-2

POISON WIRE DESIGN AND OPERATING CRITERIA

Environmental Conditions

- 1) 795 mm Hg to 10^{-8} torr
- 2) 71°C to -55°C
- 3) Acoustical vibrations 160 db
- 4) Acceleration 6.0 g longitudinal, 1.8 g horizontal
- 5) Steady state vibration 7 g, 14 g transient
- 6) Local shock 2.5 g longitudinal, 1.8 g horizontal
- 7) Storage life 2 years
- 8) No radiation environment

Materials Requirements

- 1) Minimum weight for function
- 2) Bend radius of 2.54 cm
- 3) Outside cover TFE or FEP Teflon
- 4) Neutron poison material B_4^{10}C
- 5) Elongation 0.5% between 21° and 71°C
- 6) Minimum tensile strength of wire 0.9 kg
- 7) Double encasement seal for B_4^{10}C

System Functional Requirements

- 1) Pull rate, 15 to 25 cm/sec
- 2) Maximum time for wire extraction, 10 seconds
- 3) Maximum peak pull force for any wire, 450 gm
- 4) Bundling rigidity sufficient to retain wires
- 5) Functionally removable from reactor and nozzle
- 6) Flexible attachment to retaining device.

Mechanical Limitations

- 1) Diameter of wires, 0.219 cm at maximum operating temperature and minimum pressure
- 2) Practical upper limit of wires, 3,000
- 3) Finished outer coating must be smooth
- 4) Minimum active B_4^{10}C length in core, 131 cm
- 5) Maximum permissible penetration in core, 137 cm
- 6) Wire tips designed to minimize peak extraction load
- 7) Wires capable of use at least five times

Neutronic Requirements

- 1) Wires must be capable of 0.95 k_{eff} shutdown with control drums at 180° minimum neutron absorber position and complete immersion in water

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Figure 2-1. Characteristics of Prototype Poison Wire

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Figure 2-2. Typical Longitudinal Dimensions and Components of the Poison Wire

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TABLE 2-3

WEIGHT DISTRIBUTION OF ACTIVE-POISON LENGTH OF
POISON WIRE PROPOSED FOR FLIGHT APPLICATION

	Weight per Unit length, gm/cm	Proportion of Total Weight, %
Center Poison Material 89.5 w/o B ₄ ¹⁰ C 87.5% theoretical density	0.0358	42.2
Mylar Plastic, poison sheath	0.0039	4.6
Fiberglass sleeve	0.0240	28.3
Teflon outer sheath	0.0211	24.9
TOTAL	0.0848	100.0

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The center portion contains the neutron absorbing ingredient, elemental boron, which is chemically combined in B_4C . The encasement prevents the loss of core material, but primarily it compensates for strength and property deficiencies of the core material.

The segregation elements determine the particular wires which are grouped together or fastened to a given connector. Since a member may combine the function of segregation with wire retention and support, these parts are treated under a single classification.

The termination of the wires, or of a wire bundle, on the end attached to the pull actuator may take several different forms. The form of termination is not entirely dependent on the bundling or support members with which it is associated; however, it is dependent on the nature of the interface with the pull actuator. Consequently, the termination is a separate item in establishing the major wire components.

3. Wire Center Composition

The B^{10} isotope contained in the central poison material is the active ingredient effective in absorbing neutrons. Since B^{10} does not occur naturally separate from boron eleven (B^{11}), some of the latter is always present despite processing undertaken to increase the proportion of B^{10} .

Pure boron, regardless of the isotopic proportions, is not acceptable as a poison material. Under conditions of high temperature, pure boron oxidizes to form water soluble compounds. In a situation involving a fire followed by water submergence, formation of boron oxide with subsequent dissolving and removal is a plausible result.

To enhance temperature resistance of the poison material and to reduce water solubility, the boron within a boron compound is utilized to obtain adequate neutron absorbing capability. Table 2-4 compares the various boron compounds considered. B_4C was chosen since its effectiveness in neutron absorbing capability ranks high. More important, B_4C is readily available, and processing techniques are well established compared to those required for the other boron compounds.

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TABLE 2-4

COMPOSITION OF VARIOUS BORON COMPOUNDS

Compound	Natural Boron (18.8% Boron 10)							
	Molecular Weight	Specific Weight gm/cc	Specific Boron Weight gm/cc	Boron Percent	Specific Weight Boron 10, gm/cc	Boron Atoms cc $\times 10^{-23}$	Boron Atoms cc $\times 10^{-23}$	Relative Boron 10 Effectiveness
Boron (B)	10.82	2.34	2.34	100	0.44	1.30	0.26	0.22
Boron Carbide (B_4C)	55.3	2.52	1.97	78.3	0.37	1.10	0.22	0.18
Silicon Carbide (B_6Si)	93.0	2.47	1.72	69.8	0.32	0.96	0.19	0.16
Aluminum Carbide ($B_{12}Al$)	156.8	2.58	2.14	82.8	0.40	1.19	0.24	0.20
Boron Nitride (B N)	24.8	2.20	0.96	43.6	0.18	0.54	0.11	0.09
Compound	Enriched Boron (92% Boron 10)							
	Molecular Weight	Specific Weight gm/cc	Specific Boron Weight gm/cc	Boron Percent	Specific Weight Boron 10, gm/cc	Boron Atoms cc $\times 10^{-23}$	Boron Atoms cc $\times 10^{-23}$	Relative Boron 10 Effectiveness
Boron (B)	10.10	2.18	2.18	100	2.01	1.30	1.20	1.00
Boron Carbide (B_4C)	52.4	2.39	1.84	77.0	1.69	1.10	1.02	0.85
Silicon Boride (B_6Si)	88.7	2.34	1.59	68.0	1.46	0.96	0.88	0.73
Aluminum Boride ($B_{12}Al$)	148.2	2.44	2.00	82.0	1.84	1.19	1.10	0.92
Boron Nitride (B N)	24.1	2.14	0.90	42.0	0.83	0.54	0.50	0.42

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two Russian investigators.⁴ on the resistance of refractory compounds toward chemical reagents. These results show that the dissolving of boron carbide cannot be detected with certainty following one and one-half weeks of immersion in concentrated hydrochloric, sulfuric, and nitric acid solutions. Since these experiments could not conclusively provide evidence of boron carbide solubility in high hydrogen ion concentrations, it is reasonable to presume that no solubility exists for sea water in which the hydrogen ion concentration is relatively low.

The B_4C material has a number of characteristics which are incompatible with the removal action in which the poison wires are involved. The final form of the B_4C for the application is a sintered stick which is manufactured from a finely divided powder. In the final form the B_4C is hard and brittle and, like most ceramics, fractures under low tensile stress.

Table 2-5 summarizes the results of a B_4C processing development which was conducted at WANL. The sintering temperature is extremely critical since proper sintering occurs in a range which is only one-half of 1.0 percent of the centigrade temperature level. Particle size of the B_4C powder entering the process has a pronounced effect on sintering. Selected additives influence the sintering process in a desirable manner by lowering processing temperature and by inducing a higher density in the finished core sticks. Selection and processing of B_4C is discussed in detail in Reference 3.

4. Poison Encasement

a Functional Basis

The encasement performs several functions:

- 1) Prevents the escape of poisoning material.
- 2) Maintains the circular configuration of the poison wire cross section.
- 3) Transmits and absorbs tensile forces during removal of the poison wires.
- 4) Minimizes frictional interaction between the wire and contacting

surfaces of reactor components.

4 G. V. Samsonov, Handbooks of High-Temperature Materials, Volume 2 -Properties Index, Plenum Press, New York, 1964

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TABLE 2-5
BORON CARBIDE SINTERING DEVELOPMENT

1) Laboratory samples produced 80 to 90% density B_4C .

2) Organic binder affects :

extrusion capabilities
green strength
sintered density

3) Sintering temperature requirements for B_4C .

2250°C	B_4C does not sinter
2260°- 2270°C	B_4C even sintering
2280°C	B_4C eutectic melting

4) Particle distribution for B_4C sintering .

10 to 45 microns	poor sintering
5 to 20 microns	improved sintering
1 to 10 microns	good sintering

5) Natural impurities, no significant effects.

6) Added Impurities:

Increase B_4C sintered density
Lower sintering temperatures

7) Cover gases control :

oxidation
void formation
sintering process

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5) Permits translation of the wire through a curved path without damage to any part of the wire.

6) Maintains poison wire integrity and resists deterioration in the presence of extreme environmental and emergency conditions.

In order to maximize performance of these functions and to provide a reasonable bending durability for repeated use and handling, a flexible encasement construction is required. In numerous electrical applications the flexible construction is obtained by means of a woven braid surrounding the central conductor or tube. The material from which the braid is woven is varied to suit various environmental and strength requirements. Utilization of this principle for poison wire encasement was selected because of its applicability and because it is well proven in other applications.

b. Material Selection for Braided Sleeve Encasement

Both metallic and nonmetallic materials may be utilized to form braid. Small diameter wire of almost any material may be woven into a braid. The use of a metallic braid is one means of maximizing resistance to high temperatures. A disadvantage of the metallic braid is the greater weight penalty in comparison to the use of nonmetallic material of which fiberglass is typical. Compared to the value of 0.024 gm/cm with respect to fiberglass sleeving from table 2-3, type 304 stainless steel wire of 0.0101 cm diameter which is braided with maximum surface coverage directly onto poison material sticks, weighs 0.038 gm/cm which is 50 percent heavier. Consequently, in using this type 304 stainless steel, 0.0101 cm diameter wire braid in place of fiberglass braid in figure 2-1, the weight of the poison wire would increase from 0.085 to 0.099 gm/cm or 16.5 percent. A further weight penalty is associated with the metallic braid. Braid openings through which core material might migrate leave approximately 25 percent of the surface uncovered. The weight of the sealant required to fill these openings is not included in the above values.

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Fiberglass is a nonmetallic material which is in common use for electrical conductor braided sleeving. It has high strength coupled with high temperature capability. The common electrical or E-type fiberglass can sustain a weight load up to 650°C. Special fiberglass S-type which has a weight load carrying ability up to 870°C is also available and is suitable for braiding. The use of the S-type glass in the poison wire braided sleeving enhances the temperature resistance of the poison wire. Figure 2-3 shows a strength comparison of the E and S glass fibers. This figure is based on Owens-Corning Fiberglass Corporation Circular NY-AD-64-3A. Values are based on the strength of very small 0.0075 cm diameter filaments.

Table 2-6 provides a comparison of sleeving braided with each type of glass. Braids 1 through 4 have the same weave pattern. Although braids 1 through 5 are all suitable dimensionally, braid 5 will be employed since it provides a surface texture less rough than other braids which were evaluated.

It is apparent upon examination of table 2-6 that room temperature tensile strength of fiberglass braid decreases upon exposure of the braid to high temperatures. This reduction in strength probably results from the volatilization of starches and other organic treating obtained without further conditioning, subsequent to braiding, is stronger than conditioned braiding.

Complete surface coverage is not a problem with fiberglass sleeving since this is the usual characteristic of stock fiberglass braiding. The numerous fine fiberglass filaments composing each strand of the sleeving permit the crossed strands to flatten, bend, and conform to each other. Upon pulling or drawing of the braid, apparent closure of all openings in the braid occurs as conforming actions of the strands produce contact between adjacent filaments. Fiberglass braided sleeving is available in an extremely wide variety of braid patterns, yarn sizes, and electric conductor sizes, and also, it appears to be adequate from the standpoint of tensile strength and temperature resistance; therefore, it will receive first consideration with respect to construction of a flexible poison wire.

c Braid Coating and Outer Sheath

Coating or sheathing of the braid is desirable from two standpoints:

- 1) It serves as a seal to prevent loss of the poisoning material through the openings in the braid wall.

Figure 2-3. Comparison Between Strengths of E and S Types of Fiberglass

TABLE 2-6

FIBERGLASS SLEEVING TENSILE BREAKING STRENGTH

Braided Sleeving Designation	Type of Glass in Yarn	Treatment Subsequent to Braiding	Average Breaking Strength (Two Specimens), kg		
			Unheated	Heated One Hour at 427°C	Heated One Hour at 538°C
1	E	None	26.6	14.1	6.6
Variation			22.4 - 30.9	12.9 - 15.4	5.7 - 7.6
2	E	Normalized and Treated	14.0	12.2	7.4
Variation			11.8 - 16.3	10.6 - 13.9	3.9 - 10.9
3	S	None	43.5	18.1	8.7
Variation			41.6 - 45.4	15.5 - 20.8	8.2 - 9.2
4	S	Normalized and Treated	15.3	13.3	7.2
Variation			12.7 - 17.9	13.0 - 13.7	5.0 - 9.6
5	E	None	31.4	12.4	8.8
Variation			28.0 - 34.7	10.4 - 14.4	7.6 - 10.1

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2) It serves as a means of reducing frictional resistance during poison wire removal from the reactor core.

Since a characteristic of fiberglass braid is 100 percent coverage, application of a special coating to seal braid openings is not mandatory. However it may be desirable to decrease the macroscopic roughness of the braid. This may be accomplished by employing a filler to reduce the depth of "valleys" between "peaks" which are produced by the lay of the wire or yarn. Based upon preliminary investigations, room temperature curing silicone rubber seems quite suitable for the purpose of filling the braid openings. This type of material is useful from -55° to more than 260°C . Throughout this temperature range the silicone material remains flexible and would not be displaced from the braid openings by flexing of the poison wire.

In order to minimize frictional resistance and to minimize mechanical interaction of irregularities of the braid and the reactor core coolant channel surfaces, both fiberglass-braided and metal-braided poison wires may be inserted into a Teflon sheath. The Teflon sheath is tubing which is shrunk onto the exterior of the fiberglass sleeve for the purpose of obtaining a smooth outer surface on the poison wire. The sheath also serves to prevent passage of core material through the braid wall. Teflon sheath wall thicknesses of 0.010 to 0.015 cm may be attained.

d Tip Requirements

The tip of the wire attains the greatest insertion depth into the reactor and requires a special construction. The wire tip portion is approximately 1.2 cm in length and it:

- 1) Prevents the loss of core material through the end of the encasement.
- 2) "Smooths" and "rounds-off" the end of the encasement to eliminate contact of sharp edges with the coolant channel wall.
- 3) Provides a transition length to reduce gouging action and large localized forces on the coolant channel exit surfaces as the wire leaves the channel.

The objectives of 1) and 2) are obtained by molding into place the desired configuration from material with appropriate adhesive characteristics. Objective 3) is realized by selection and combination of materials to shape the resistance which the tip plug presents

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to a specific type of poison wire bending couple. This type of couple appears if the tip plug made from material of selected elasticity and resilience deflects and deforms upon application of the bending couple. This deformation causes more of the tip cylindrical surface to contact the channel wall resulting in less force per unit area. Consequently, there is less likelihood of the tip penetrating and chipping the coating of the coolant channel wall.

C. POISON WIRE MANUFACTURING

1. General Approach

Approximately 400 simulated poison wires have been constructed to a demonstration design for utilization in the poison wire and withdrawal system evaluation tests. In many respects these demonstration wires are similar to the representative wire design of figure 2-2. The wire of figure 2-2 represents the results of an approach which satisfies poison wire criteria but permits manufacture by simple means. Flexibility is thereby intrinsic with respect to future modification of the design and manufacturing techniques.

A group or bundle of the demonstration wires is shown in figure 2-4. In these wires special lead material of the proper diameter was substituted for the B_4C indicated in figure 2-2. Since the wires were utilized only for tests of a mechanical nature, the pencil lead substitution provided a means for economy of material. Furthermore, the metal wire extension of figure 2-2 was not included in the fabrication of the wires of figure 2-4. Since precise ACPS specifications have not been prepared, no sufficient basis exists for establishing the characteristics desired in the section of the wire extending from the reactor core. The manner in which the metal wire may be utilized is discussed later in this report.

2. Fabrication

The following information describes some of the methods used in making poison wires. The first step in manufacturing a poison wire consists of insertion of cylindrical poison pieces, 0.142 to 0.147 cm in diameter, into a thin walled plastic tube. Upon insertion, the poison pieces are butted end-to-end in contact with each other. The thin walled plastic tube unites numerous poison pieces into a single element of the desired length. Construction of the poison

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Figure 2-4. Demonstration Wire Bundle

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wire is therefore facilitated since only a single unit must be manipulated. To minimize encasement wall thickness the thin plastic tube has a maximum thickness of 0.0075 cm after shrinkage onto the poison pieces.

As an example of the design flexibility, metal wire has been incorporated into the illustration of figure 2-2. The metal wire is utilized in this application to prevent collapse of the encasement and to stiffen the wire throughout the length which cannot be inserted into the reactor core. Substituting material other than poison material into the wire center provides a means of changing wire characteristics without incurring an abrupt discontinuity in the encasement.

The central, sheathed poison unit is slipped into a braided fiberglass sleeve to complete the next step of the poison wire construction. It is expected that the encasement thickness contribution of the fiberglass sleeve will be no greater than 0.013 cm.

Insertion of the fiberglass enclosed unit into a Teflon sheath is the next step of the process. The application of heat to shrink the Teflon tube tightly onto the fiberglass completes the encasement of the poison wire. The Teflon sheath, subsequent to shrinkage, will contribute approximately 0.015 cm to the encasement thickness.

For purposes of production of a large number of wires the operations identified above may be mechanized. For instance, insertion of the poison sticks into the sheathing could probably be accomplished by utilizing a vibratory feeder in conjunction with appropriate holding fixtures. The latter would compensate for spooling curl by aligning the tubing and funnel the sticks, fed one at a time, into the tubing entrance.

Wire units which are encased in unshrunk tubing can be conveyed past heating elements to obtain shrinkage of the tubing. Figure 2-5 is a photograph of the apparatus which has been successfully employed. In order to obtain shrunken tubing surfaces of uniform, satisfactory texture, the combination of velocity past the electric heating elements and the shrinking temperature must be closely controlled to predetermined levels. The necessary precision feed-control of the wire units to the heating elements has been accomplished by an electric motor driven apparatus. Desirable combinations of feed and temperature are established by varying the settings of an autotransformer which provides current to the heating elements and by varying the speed of the motor driving the conveyor.

Figure 2-5. Shrinkable Tubing Conveying Apparatus

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The B_4C poison as produced consists of sticks 7.5 to 15 cm in length which are inserted into the sheath. To obtain the flexibility characteristics required of the wire, the sticks must be broken into short pieces, 0.3 cm or less in length after the sheath is shrunk into place. Severing of the sheath during fracturing of the poison sticks should be prevented since the purpose of the sheath is to reduce the number of pieces which must be manipulated during subsequent encapsulating operations.

A method which produces fracturing consists of passing the sheathed poison unit through a mill consisting of a rubber roll which compresses, during rotation, against a driven steel roll. The rubber deforms to accommodate the intrusion of the wire poison unit. During rotation, the compressed rubber springs back as contact with the steel roll diminishes. As the original shape is restored, the rubber applies a bending force to the portion of the poison unit which has passed the nominal line of maximum compression between the two rolls. This extension of the sheathed poison unit is bent in cantilever fashion against the curved surface of the steel roll until fracture occurs. Figure 2-6 shows the apparatus which was successfully employed following construction in accordance with the principle described.

Upon completion of individual wires, specific numbers of them are brought together to form bundles. Bundles will be formed to:

- a) Facilitate the installation of wires
- b) Aid in maintaining a specific position of the wire insertion
- c) Provide a structurally self supporting configuration to permit elimination of support accessories.
- d) Reduce the number of connections to be made at the interface with the pull actuator.

Figure 2-4 represents a typical bundle of wires to be utilized in wire and actuator feasibility trials.

D. POISON WIRE QUALIFICATION

1. Direction of Qualification Effort

All wire designs for the ACPS will be mechanically qualified to establish confidence that no credible loading will compromise wire functions and that durability margins are adequate.

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Figure 2-6. Poison Material Fracturing Mill

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High margins of various types of capability assure satisfactory endurance of the poison wire to manipulation and handling stresses. In the event a reactor shipment wire is based on the ACPS design, high margins of capability will increase life expectancy. Exceedingly high strength, compared to the loads that will be applied, increases the number of times that the wires can be used. Therefore, the testing and qualification efforts of the ACPS wires should be expended in establishing the primary wire function listed as follows:

- a) Insertion of the wires in the core is maintained until positive action is taken to remove the wires.
- b) The wires withdraw unequivocally upon actuation of the wire withdrawal system.
- c) The wires in no way jeopardize the integrity and operability of the reactor and nozzle as a result of either installation or withdrawal.

2. Wire Qualification Criteria

Tables 2-1 and 2-2 give the accident and operating conditions which the wires must be capable of withstanding. Table 2-2 provides tensile pull strength related to various temperatures which will be useful in evaluating the capability of the wires to withstand the conditions stated in tables 2-1 and 2-2. Table 2-7 shows that the wire pull strength is far greater than adequate from temperatures lower than -167°C to those up to 204°C . The wire is a composite of various materials; therefore, the results of a particular test cannot be attributed entirely to one element of the wire since the wire elements interact to influence one another. For this reason arbitrary and non-standard demonstrations must be conceived in order to prove that the wire properly qualifies.

A number of wires should be tested to prove that the arbitrary demonstrations are valid. A major criteria determining test validity is the completion of a test without any undesirable change in the characteristics of the wires. During these tests most of the effort should be directed to determining the following qualities and capabilities:

- a) Roughness and texture
- b) Flexibility
- c) Tensile pull strength
- d) Dimensional changes, breaks, or cracks in any of the wire elements

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TABLE 2-7

VARIATION OF POISON WIRE BREAKING STRENGTH WITH TEMPERATURE

Temperature	Breaking Strength of Individual Test Specimen (kg)	Average Breaking Strength (kg)
-178°C	38.0 47.6 39.5	41.6
- 55°C	54.8 39.9 44.2	46.3
Room Temperature	33.1 26.0 32.3	30.6
121°C	17.1 19.0 17.9	18.0
204°C	15.4 15.2 11.1	13.8

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- e) Use of the wire does not produce any damage to the reactor coolant channel
- f) The poison of the wires will remain in the reactor core under conditions of high temperatures, explosion, and impact

3. Wire Qualification Tests

The qualification effort should consist of the following tests:

- a) Tensile pull tests
- b) Flexing and handling durability tests, such as repeatedly wrapping the wire around a cylindrical mandrel.
- c) Removing a particular wire many times from the same reactor core coolant channel to ascertain the effects on both the wire and the channel surfaces.
- d) Heating a wire to high temperatures while it is inserted in a simulated fuel channel to demonstrate that the poison remains in the channel.
- e) Stress and bending endurance tests at low temperatures.
- f) Vibration tests to determine tendencies to compaction and bunching of encased materials.

Figures 7, 8 and 9 are photographs of a reactor support block hole into which one of the demonstration wires was inserted and pulled out many times. The fixture to hold the block and to guide the direction of wire pull is shown in figure 2-10. A magnification of 12 was employed to photograph the hole.

The condition of the hole before the wire pull test is shown in figure 2-7. Hole outlet conditions after 35 pulls and after 50 pulls are shown in figures 8 and 9 respectively.

Following insertion, the wire was pulled through the tube which was mounted at an angle of 30 degrees from the plane of the outlet face of the block (60 degrees from the hole axis). The rate of wire pull was approximately 20 cm per second. As can be seen from the photographs, no support block damage is detectable in a comparison of pretest conditions and after 50 pulls. The tip of the demonstration wire used is shown in figure 2-11 after 50 pulls from the hole. No change can be seen in the condition of the tip. No special modifications were made of the demonstration wire tips. The appearance of all tips was similar to that of figure 2-11.

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Figure 2-7. Fuel Element Coolant Channels Prior to Wire Pull Test

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Figure 2-8. Fuel Element Coolant Channels After 35 Wire Pulls

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Figure 2-9. Fuel Element Coolant Channels After 50 Wire Pulls

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Figure 2-10. Flexible Poison Wire Pull-Test Fixture

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Figure 2-11. Flexible Poison Wire Tip After 50 Pulls

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E. DEMONSTRATION WIRE WITHDRAWAL TESTS

1. Wire Installation

Approximately 400 demonstration wires were fabricated as shown in figures 2-1 and 2-4. The nuclear poison, B_4C , of these wires was simulated by the use of appropriately dimensioned pencil lead material. Various quantities of these wires were inserted as shown in figure 2-12 and installed in an arrangement of NERVA reactor dummy fuel clusters. A complete assembly of wires and apparatus is shown in figure 2-13. The wires were pulled from the clusters to determine the withdrawal forces.

2. Withdrawal Apparatus

The apparatus used to withdraw the wires from the dummy fuel clusters was designed and constructed to demonstrate principles and techniques that could be employed to withdraw the wires during flight of the NERVA engine.² In essence, the wires were terminated at a retractor head positioned near a simulated engine nozzle throat. A stainless steel tape, 2.54 cm in width, connected the retractor head unit to a spool on the shaft of a pneumatic motor. Upon admission of air to the motor, the spool wound the tape causing the retractor head to move toward the spool. In this manner, the wires connected to the retractor head were withdrawn from the dummy fuel clusters.

3. Wire Withdrawal Forces

Withdrawal test description techniques and results are discussed in detail in Appendix A.

Table B-4 in Appendix A shows the force results from Test 7 which was conducted with 300 wires. This test approximated a uniform distribution of the wires throughout the reactor core. The peak force recorded was 40.4 kg obtained during the breaking of static friction. This gives a maximum force value of 0.135 kg/wire. It is possible that the recorded peak force is low due to an inadequate recorder response. Considering this situation, a maximum

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Figure 2-12. Demonstration Wires Inserted in Dummy Fuel Cluster

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Figure 2-13. Demonstration Wire Withdrawal Assembly

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value of 0.154 kg/wire was estimated by using the peak force multiplied by 1.25. With respect to withdrawing 2000 wires, the extrapolated force values (on the basis of 300 wire values) would be 270 kg measured peak force, 246 kg maximum sliding friction force, and 308 kg projected peak force.

F. POISON WIRE RETENTION

1. Basis for Wire Groups

Figure 2-14 is reproduced from Reference 1 and illustrates the distribution of poison wires in the core of the reactor. This distribution approximates a uniform poison pervasion of the reactor core. There are approximately 10 wires per fuel cluster as established by the regular clusters. For convenience in assigning wires to fuel clusters, the nominal number of wires required to establish a bundle will be set at 10. Peripheral clusters will have wire bundles assigned to them which are comprised of smaller numbers of wires. An illustration of a wire bundle is presented in figure 2-4 .

2. Wire Movement Restriction

The wires must be precisely positioned in the channel of the reactor core since, during installation, the wires must not be inserted too far. The wires must be inserted to a predetermined point which provides adequate tip clearance to assure that there is no possibility of damage to the channel orifices or that the orifices do not become clogged with residue from the wire tip. The tip clearance must not become too large; otherwise the volume of the unpoisoned core wafer at the inlet to the core could become great enough to sustain criticality, independent of the remainder of the core.

Maintaining insertion and preventing random movement of the wires in and out of the fuel channels is much more complicated. The problem centers on providing a structure that will make possible accurate prediction of wire location within close tolerances of movement. Space requirements force this structure to be integrated with the bundling components.

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Figure 2-14. ACPS - Wire Distribution in Available Core Sector Coolant Channels

The bundling components must therefore provide the following capabilities:

- a) The wires must be precisely positioned in the reactor core under loading produced by flight acceleration, vibratory, and impact forces.
- b) Physical connection must be provided between the wires inserted in the core and the withdrawal actuator.
- c) Rigidity should be maintained throughout the free span distance between the reactor outlet face and the actuator connection face within the convergent portion of the nozzle.
- d) A termination should be provided which is compatible with the connection requirements at the interface between the bundle and the actuator.
- e) The poison wires should form a coordinated and organized withdrawal pattern to permit extraction and storage.

Bundling of the wires facilitates their installation into the reactor core since in confining them the tracing of wires becomes easier for the purpose of assigning them to particular coolant channels. Handling is easier since the number of free ends is reduced.

Joining of the wires to form a bundle provides a definite movement-stop and a reference for establishing insertion of the wires into the core. By integrating the wires into a bundle, sufficient rigidity is developed to maintain wire positioning by utilizing reaction forces which are transmitted to the wires from the nozzle throat wall through the actuator interface components. Weight is also minimized, since the wire bundle is self-supporting and requires no additional bracing.

The bundles extend between the reactor core outlet face and the pull actuator connection face. Since the wires are brought together into bundles, only a bundle unit need be connected to the interface with the pull actuator rather than attaching each wire individually. If it is required, the bundles may be connected together at intermediate locations between the core outlet face and the pull actuator.

One means of forming a bundle utilizing the prototype poison wire for pull test demonstrations, figures 2-4 and 2-15, is the envelopment of the group of wires by a shrinkable tubing sheath. Greater rigidity may be obtained by coating the wires with hardenable plastics or adhesives before the shrinkable tubing bundling sheath is applied. By choosing from a wide

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Figure 2-15. Typical Bundle of Poison Wires

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variety of adhesives which are satisfactory for bonding the wires together, the bundle rigidity and stiffness may be regulated over a wide range.

All or part of the bundled length of the wires may be replaced by metal element extensions. These may be partially articulated to provide controlled flexing in specific planes and directions and through a predictable angle. Termination at the actuator end of the bundle will, in all likelihood, be a simple nut or screw which is integral with or bonded to the bundled elements.

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CHAPTER III DESIGN CRITERIA FOR THE ACPS

A. GENERAL INFORMATION

The design of the poison wire system is based on the loads and environment to which it will be subjected. The following paragraphs define and explain the criteria as they are related to the design, manufacture and operational characteristics of the ACPS. These criteria were developed by the Westinghouse Astronuclear Laboratory (WANL) through coordination with the Space Nuclear Propulsion Office (SNPO) and from requirements established during the Reactor In-Flight Test (RIFT) program. Since the primary purpose of the ACPS is to maintain the reactor subcritical from the time of assembly to the time it will be operated in space, it is essential that the poison wires be positively locked into place under all credible conditions. However, it is also most important that the wires be extracted and the system ejected without complications. Credible accident conditions mentioned in the previous chapter are now discussed with regard to the entire ACPS.

During assembly, the poison wires are inserted into the fuel elements in the specified quantities and bundled according to the clusters which are then placed into the core. The quantity of wires will be sufficient to insure subcriticality of the reactor under conditions of flooding with a hydrogenous liquid and with the control drums in the most reactive (reflective) position. It is not unreasonable to expect flooding from faulty sprinkler systems or storm damage to the shelter, either in assembly, storage, or immersion in water from an accident during shipping. It is also possible that explosions on the launch pad or mission aborts could result in the reactor being dropped into a body of water.

During ground handling operations in loading for shipment, shipping, unloading, installing, and testing, the reactor will experience vibrations, shocks and possible impact due to dropping. For this reason, the design should consider provisions for securing the poison wires in position until the remainder of the ACPS is installed. This is accomplished by components which include the wire terminal retaining plate and which will be installed in the shipping container and locked into place.

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If a criticality check is conducted at the reactor assembly point and again prior to installation on the flight vehicle, the poison wires must be installed three times and removed twice in the period between assembly and launch. Because of these criticality checks, it is not advisable to install the nozzle and engine system until after the second check and the third insertion of the wires. At this time, the complete ACPS should be installed. Installation of the ACPS prior to this would necessitate removal and reattachment of the nozzle and accessory systems.

In the analysis and evaluation of the systems portion of the ACPS, the three major criteria categories are: 1) operation, 2) load and environment, and 3) credible accidents. The term "credible accidents" is used because there are probably an infinite number of accident conditions that can be postulated and to design for all of them would be impractical. The following accidents are considered credible and have been factored into the ACPS design.

B. EXPOSURE TO FIRE AND HIGH TEMPERATURES

Fire can occur during shipping due to collision, during storage from burning of the building, or during pre-launch from a Lox Hydrogen explosion. To fulfill the fire criteria, the poison wires are sheathed in a fiberglass encasement which will maintain a high level of tensile strength at extreme temperatures. This material will not burn and it will retard the neutron absorber poison in falling from the reactor. High temperature steel would be selected for use in the design of the reactor shipping wire-retaining fixture and other components of the ACPS to insure maximum protection against inadvertent wire or poison removal.

C. IMPACT OF REACTOR AND NOZZLE WITH GROUND DUE TO EXPLOSION

The ejection cylinders of the ACPS are designed to extend beyond the nozzle skirt. From a practical point of view the extension insures that the poison wires will be held in place regardless of the angle of impact of the reactor with the ground or water. The extended part will strike first in a nozzle-down attitude causing the entire ACPS to be driven toward the reactor. This is a desirable action under the circumstances.

During the launch and post-launch phases of a mission the ACPS will experience various combinations of loads and environment. These combinations are postulated on the basis of a

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three-stage vehicle, and in the sense that the conditions expressed relate specifically to the core and pressure vessel and are assumed to apply to the ACPS structure. The load magnitudes and frequencies will most likely be less than calculated depending upon the interstage structural configuration and the dampening effect of adjacent structures. The load combinations and their reactions from launch vehicle startup to the ACPS ejection are enumerated in the following paragraphs.

1. Launch Vehicle Startup

At this point, the reactor will experience engine vibrations producing a steady-state double amplitude, axial displacement of approximately 0.028 cm at frequencies up to 85 cps along with acoustic vibrations generated by 160 db at 38°C. The ACPS design should provide that the wires be held in place with a minimum capability for axial displacement. The wire extraction and ejection components are locked into place at the support braces and support platform. See figure 3-1. The protective foam in the cavity of the nozzle will absorb much of the sonic vibrations and provide a dampening effect on the ACPS structural components.

2. Post Launch

After launch, the ACPS will experience two critical load conditions. The first load occurs at first stage burnout when the accelerations are 6.0 g axial and 1.8 g lateral with the support platform in place. The second load occurs at the second stage burnout when the longitudinal acceleration is 2.8 g but without the support platform from the preceding stage. The acceleration forces increase gradually up to the maximum at first stage burnout. Axial forces are absorbed by the support platform and the lateral forces are absorbed by the system support braces. The vibratory oscillations at this time are of a minor nature.

Following the first stage separation, the load factors decrease to approximately a third of the maximum load before attaining another peak of approximately 2.8 g, prior to the second stage burnout. At this time, the second stage fuel tank deflects approximately 5 cm away from the ACPS, due to changes in second stage tank pressure, completely removing the axial reaction supplied by the support platform. The 2.8 g load will then be absorbed by the retaining fingers at the nozzle throat. Any lateral loads, due to vehicle attitude or vibration, will be absorbed by the support braces.

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Figure 3-1. ACPS Pre-Launch Condition

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3. Wire Extraction and Ejection Forces

These forces and reactions are explained in the Support Structure portion of Chapter V, System Description. A tabulation of functional data is shown in table 3-1. In addition to being capable of resisting the varied loads imposed upon them, the ACPS structural components should be designed to permit minimum displacement under all conditions. This feature is very important since the numerous release mechanisms in the system must function upon command. Excessive vibratory displacements, if not taken into account, could prevent wire extraction or system ejection.

D. ADDITIONAL DESIGN CONSIDERATIONS

The critical functional criteria, such as extreme temperature changes, vacuum conditions, corrosive effects and zero g conditions, primarily affect the electrical circuitry, the gas storage, the valve systems, the poison wires, and the pneumatic motor. All systems must be operable from $+71^{\circ}\text{C}$ to -55°C and from 795 mm Hg to 10^{-8} torr. The critical period for these systems begins at the time of wire extraction. Environmental conditions at that time (dependent upon orbital or suborbital release) are postulated to be a 0.0 to 2.0 g load at a temperature of -55°C and at pressures of ultra-vacuum. The state-of-the-art indicates that pneumatic motors and their attendant energizing systems are capable of operating reliably at the conditions stated above. The poison wires are encased in Teflon and fiberglass. Both of these materials are excellent for maintaining their strength characteristics and stability throughout the launch profile. It is readily acknowledged that there is a need for substantiating experimental data for the above conditions to ensure complete reliability of valves, regulators, lubricants and seals.

The ACPS conceptual design reflects various guidelines which are important to the overall operation of the system.

- 1) The poison wire material should have a double seal encasement that will not corrode or erode in water. This will provide assurance that the poison material remains in the core in the event of an accident.
- 2) A poison wire must have characteristics which permit its insertion and removal

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TABLE 3-1
FUNCTIONAL DATA

1) System weight including wires	189.0 kg
2) Wire weight including fittings	45.4 kg
3) Gas accumulator pressure	140 kg/cm ²
4) Pneumatic motor operating pressure	6.3 kg/cm ²
5) Piston lock pin slider spring force	16 kg
6) Estimated force for wire extraction	0.23 kg/wire
7) Nozzle bearing area at support brace	851 cm ²
8) Nozzle bearing area at throat retaining fingers	174 cm ²
9) System ejection spring force (30 springs)	16 kg/spring
10) Nozzle reaction at support brace from support platform	0.4 kg/cm ²
11) Calculated system ejection velocity	160 cm/sec
12) Maximum theoretical impact load on nozzle at support brace (2x ejection spring load)	940 kg
13) Nozzle reaction at support brace from spring ejection force (assume one-half bearing area)	2.2 kg/cm ²
14) Nozzle reaction at support brace during wire extraction	0.8 kg/cm ²
15) Maximum unit load on nozzle throat due to system acceleration at adjacent stage burnout (2.8 g)	3.5 kg/cm ²

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from the core a minimum of five times without damage to the wire or reactor components. This feature provides flexibility in the programming of criticality tests or assembly procedure.

3) The wire extraction should take place at a rate between 15 and 25 cm per second and no greater than 25.4 cm per second. The upper limit restricts the speed of extraction to assure no possibility of damage to the reactor coolant channels. A speed less than the low limit value might require a significant change in a proposed mission profile as a result of delay in the NERVA stage startup.

4) Two separate overt actions are each required to actuate the extraction of the wires and to release the inner locking cylinder. This guards against accidental wire extraction or system ejection.

5) The nozzle surface will be protected from metal to metal contact from the time of installation of the ACPS to its ejection since it is very important to protect the nozzle coolant tubes from being damaged. Dents or cracks may severely affect the heat transfer characteristics of the nozzle.

6) The nozzle reactions from the ACPS loads will always be less than the design capabilities. This again provides insurance for the prevention of damage to the nozzle coolant channels.

7) Weight of the ACPS will be kept to a minimum commensurate with the structural, environmental and operational requirements. Lighter weight requires less propellant to launch the vehicle and also less force to eject the system when required. This in turn reduces the load reactions upon the nozzle.

8) All components of the ACPS will eject from the nozzle.

9) The ACPS concept infers optimum quality control and inspection provisions throughout fabrication, assembly, and installation of the system since structural and functional reliability must be maintained to ensure successful operation.

10) The ACPS will be a complete, self-contained unit without need of auxiliary engine systems for operation.

11) The poison wires will be installed, supported, and retained in the core prior to nozzle installation in order to maintain subcriticality during shipping and handling.

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- 12) After the nozzle attachment, the ejection system can be installed and preparations made for ground handling.
- 13) The poison wire extraction and system ejection actions shall be compatible with both suborbital and orbital vehicle staging and NERVA engine startup programming.
- 14) Redundancy provisions have been incorporated for wire extraction and system ejection to add reliability.
- 15) Nozzle leak checks can be conducted with the wires in place.
- 16) Indicator signals will be provided to the ground station after each significant step in the ACPS operational sequence.
- 17) The ACPS shall be designed to ensure maximum positive retention of the poison wires during credible accident conditions.

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CHAPTER IV NEUTRONICS

This section provides information relating to reactor reactivity under flight accident conditions and the capability of the poison wires to maintain the reactor subcritical under these conditions. A parametric study has been completed to determine the effect of changing B_4C density, wire diameter, wire length, and number of wires on reactivity under a water flood condition. A critical experiment has been conducted and analyzed to determine experimentally the worth of the poison wires in a flooded reactor. A compacted reactor core has also been evaluated to determine if the poison wires are adequate to maintain the reactor subcritical in this case.

A reactor reactivity of $0.95 k_{eff}$, based on conservative calculations, is considered to provide an adequate shutdown margin when evaluated under accident conditions which give the highest reactivity value.

A. POISON WIRE REACTIVITY REQUIREMENTS

The poison wire system is designed to maintain the reactor subcritical under credible accident conditions. The accidents leading to the largest negative reactivity requirements are: 1) water flooding and 2) core compaction.

The reactivity of a water flooded reactor has been previously determined to be $1.56 k_{eff}$ by both LASL⁵ and WANL⁶. The calculations performed as part of this study showed that the reactivity of a flooded NERVA type reactor is $1.59 k_{eff}$ which is in good agreement with the other calculated values.

Potentially a NERVA reactor can impact upon land following a mission abort prior to removing poison wires. Experiments conducted by LASL⁷ as well as theoretical work by WANL²

⁵ LA-3227-MS, Effects of Adding Hydrogenous Materials to KIWI Reactors, March 1964 (CRD)

⁶ WANL-TME-713, NRX-A Core Compaction Program, March 1964 (CRD)

⁷ Private Communication, L. D. P. King, LASL, to J. M. Bridges, WANL, October 1964

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show that the NERVA type reactor under land impact forces will probably not compact sufficiently to cause a significant reactivity increase. The studies show that a reactor impact upon a solid surface will fracture the graphite fuel elements. Under impact forces sufficient to cause significant compaction, the reactor and core vessels will rupture and the fractured fuel elements will be dispersed.

The calculated reactivity of a compacted reactor, with no poison wires, is $1.12 k_{eff}$ with the beryllium reflector intact and no flooding, 2) $1.20 k_{eff}$ with the beryllium reflector intact and the regions external to the core flooded with water, and 3) $1.16 k_{eff}$ with the beryllium reflector torn loose by the impact but replaced with water.

Flooding the core with liquid hydrogen results in a reactivity of $1.55 k_{eff}$ as reported in WANL-TNR-148.⁸ Flooding the core with liquid hydrogen is a highly improbable accident and does not result in greater reactivity than the water flooded core.

B. POISON WIRE REACTIVITY CALCULATIONS

1. Calculational Methods

The fueled portion of the reactor core was divided into either one or four radial regions, consistent with the regions used for NERVA nuclear analyses at WANL. A single axial core region was used except for the calculations to determine poison wire height effect wherein the reactor core was divided into a poisoned and a non-poisoned region. The poison wires were distributed uniformly in the fueled region since previous calculations⁹ have shown that a uniform wire distribution is a more optimum arrangement than grouped or annular arrangements. Loading more wires into the center of the core, or otherwise bundling wires into groups causes "shadowing" effects between wires and reduces their net effectiveness. All basic reactor dimensions, material number densities, and void fractions were obtained from the WANL Nuclear Data Handbook.¹⁰ The poison wire dimensions and materials are given in Chapter II.

⁸ WANL-TNR-148, Safety Analysis Report - NRX Testing, April 1964

⁹ WANL-TME-546, Feasibility of a Full Core Nuclear Poison System for use During RIFT Launch Operations, September 1963

¹⁰ WANL-TME-840, Reactor Analysis Handbook, February 1965, (CRD)

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The following computer programs were used in the nuclear analyses:

- a) NSDM-II (GAM-TNS-QUERY Package)¹¹ - A program to generate multigroup fast and thermal cross sections. It includes both multiple up and down scattering, resonance absorption, and the use of one-element flux depression factors. The program was used to generate nine neutron energy group constants (4 fast, 5 thermal), consistent with the type calculations used at WANL to calculate reactivities of NRX reactors. The broad group neutron energy breakdown used in the calculations is given in table 4-1.
- b) TOPIC¹² - A one-dimensional neutron transport program for cylindrical geometry used to solve for cell neutron flux distributions in order to determine poison wire disadvantage factors.
- c) ADDICT - A one-dimensional neutron diffusion program, which incorporates both multiple up and down scatter, used for eigenvalue reactivity calculations. Since this is a one-dimensional program, care must be taken to incorporate the correct transverse neutron leakage. This was done for each eigenvalue calculation by a flip-flop iterative technique which involved alternate radial and axial calculations, converging on the correct leakages.

Nine neutron energy groups were used in the calculations in order to eliminate, to a large degree, cross section dependence on spectra variation and thus permitting the use of infinite media spectra calculations. To obtain an estimate of the error due to spectra changes, a clean, dry reactor was analyzed using both infinite media and exact spectra (previously calculated at WANL). The δk difference was found to be 0.0066. An examination of previous spectral calculations performed at WANL¹⁰ indicated that the difference should be less for water flooded reactors.

¹¹ WANL-TME-1091, Improved Nuclear Design Method for NERVA Calculations - NSDM-II, March 1965 (CRD)

¹² IDO-16898, TOPIC - A Fortran Program for Calculating Transport of Particles in Cylinders, April 1964

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TABLE 4-1
NEUTRON BROAD GROUP ENERGY LEVELS

Neutron Group	Neutron Energy		
1	10	-	0.821 mev
2	821	-	5.53 kev
3	5530	-	78.9 ev
4	78.9	-	1.855 ev
5	1.86	-	0.30 ev
6	0.30	-	0.12 ev
7	0.12	-	0.06 ev
8	0.06	-	0.02 ev
9	0.02	-	0.0 ev

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The cross section library does not presently contain bound hydrogen (for water) slowing down kernels for NSDM II calculations. The spectra weighted ratio of bound to unbound hydrogen scattering cross section in the thermal neutron energy groups was used as a disadvantage factor in the NSDM-II calculations. This scheme was used to obtain the nine group cross section constants in the regions containing no poison wires. Unfortunately, NSDM-II permits use of a disadvantage factor for only one element, and thus unbound hydrogen was used in regions containing poison wires. An upper limit on the error involved in the use of unbound hydrogen in the poison wire regions was determined by comparing the reactivity difference for a clean, water flooded reactor using bound and unbound hydrogen cross sections. The δk difference was found to be 0.0059.

A major effort in the analyses was to obtain the disadvantage factors for the poison wires containing $B_{4}^{10}C$. These factors must be introduced in the eigenvalue calculations wherein the wires are homogenized with the other reactor core materials. The factors were obtained for all nine neutron energy groups from the neutron flux distributions using one-dimensional neutron transport calculations (TOPIC Program) for cylindrical cells. In order to establish upper and lower limits and a "most probable" value of disadvantage factors for the wires, the conditions imposed were:

- a) a unit neutron source for each energy group was input at the periphery of the wire,
- b) a unit neutron source was input at the periphery of a cell containing a poison section, wire clad, and fueled region but without a fission source within the cell, and
- c) only the fission neutron source within the fuel portion of the cell was input.

Table 4-2 lists the results of these calculations for a compacted reactor core. Since use of a fission source within the cell provided a reasonably conservative value for the disadvantage factor, this type of cell calculation was used in all cases.

The disadvantage factors were also found to be sensitive to the neutron energy spectra used in obtaining NSDM-II neutron cross section constants. Table 4-3 lists the disadvantage factors as a result of assuming: 1) an infinite medium neutron energy spectrum and

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TABLE 4-2
EFFECT OF NEUTRON SOURCE ON
POISON WIRE DISADVANTAGE FACTORS

Poison Diameter - 0.147 cm
Compacted Reactor

Neutron Group	Neutron Source at Wire Boundary	Neutron Source at Cell Boundary	Fission Neutron Source in Cell
1	0.992	0.979	0.983
2	0.998	0.996	0.989
3	0.957	0.926	0.928
4	0.780	0.683	0.687
5	0.208	0.157	0.157
6	0.0872	0.0623	0.0661
7	0.0548	0.0379	0.0419
8	0.0383	0.0249	0.0292
9	0.0215	0.0107	0.0165

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TABLE 4-3
EFFECT OF NEUTRON ENERGY SPECTRUM ON
POISON WIRE DISADVANTAGE FACTORS

Poison Diameter - 0.147 cm
Flooded Reactor

Neutron Group	Infinite Medium Neutron Energy Spectrum	Homogenized Reactor Neutron Energy Spectrum
1	0.978	0.981
2	0.992	0.976
3	0.934	0.892
4	0.706	0.453
5	0.157	0.117
6	0.0653	0.0555
7	0.0413	0.0371
8	0.0390	0.0249
9	0.0162	0.0132

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2) an energy spectrum associated with a homogenized core and poison wires. The correct value should lie between these two limits. The homogenized core energy spectrum provided the more conservative disadvantage factors, and thus this type calculation was used in all cases.

The effect of poison wire diameter and B_{4C}^{10} density on disadvantage factors is shown in table 4-4. It was found for the range of cases considered the cell areas were sufficiently large that the disadvantage factors were independent of the number of wires.

Eigenvalue reactivities were calculated with a one-dimensional neutron diffusion computer program. An iterative technique between radial and axial direction calculations was used to converge on the correct transverse leakage. Generally, two iterations were sufficient to obtain nearly identical eigenvalues. A typical series of eigenvalues resulting from alternate radial-axial neutron diffusion calculations is shown in table 4-5.

Reactivity differences between cases were obtained by the relationship:

$$\beta \delta \rho = \frac{k_0(k_1 - k_2)}{k_1 k_2}$$

where $\beta \delta \rho$ is the fractional reactivity change (δk) and k_0 is the calculated eigenvalue for the critical case ($k_{\text{eff}} = 1$). The calculated eigenvalue for the just critical reactor was determined indirectly by calculating the clean, dry PAX reactor (Critical Experiment Mock-up of NERVA Reactor) with no control rods ($k = 1.017$) and comparing it to the experimentally determined k of 1.055. The δk difference between the two cases is 0.0353 by the above relationship and k_0 calculated for the just critical reactor is 0.966.

A homogeneous poison wire distribution in the fueled element was used for all calculations. As previously discussed, this provides a near optimum use of poison wires. The relative worth of poison wires as a function of radial position has been determined previously¹³ and is shown in figure 4-1.

¹³ WANL-TME-603, Selection of Material, Number and Distribution of Poison Wires for the Anti-Criticality Poison System, November 1963

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TABLE 4-4
POISON WIRE DISADVANTAGE FACTORS FOR
VARIOUS POISON DIAMETERS AND DENSITIES

Diameter (cm)	Density (percent)	Neutron Energy Group								
		1	2	3	4	5	6	7	8	9
0.137	90	0.9825	0.9772	0.8980	0.4718	0.1255	0.5958	0.03977	0.02669	0.01418
0.147	90	0.9815	0.9756	0.8915	0.4526	0.1171	0.05552	0.03707	0.02487	0.01305
0.157	90	0.9804	0.9741	0.8851	0.4347	0.1097	0.05198	0.03470	0.02329	0.01236
0.147	85	0.9821	0.9769	0.8972	0.4690	0.1238	0.05876	0.03924	0.02633	0.01382
0.147	80	0.9827	0.9782	0.9030	0.4865	0.1313	0.06241	0.04168	0.02797	0.01468

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TABLE 4-5

EIGENVALUE AND BUCKLING ITERATIONS FOR 2600 WIRES
 0.147 cm DIAMETER AND 90 PERCENT DENSITY (FULLY FLOODED)

RADIAL 1st ITERATION K= 0.8161		AXIAL 1st ITERATION K= 0.8346		RADIAL 2nd ITERATION K= 0.7928		AXIAL 2nd ITERATION K= 0.8271		RADIAL 3rd ITERATION K= .7930	
GROUP 1	$B_R^2 =$		$B^2 =$		$B_R^2 =$		$B^2 =$		
2	.003441		.001043		.003628		.001043		
3	.002560		.0008310		.002666		.008305		
4	.001634		.0004510		.001650		.0004512		
5	-.0003131		-.0002350		-.0003929		-.0002338		
6	-.005060		-.001907		-.005254		-.001902		
7	-.02593		-.004707		-.02638		-.004710		
8	-.1536		-.01755		-.1512		-.01758		
9	-.3587		-.03258		-.3459		-.03306		
9	-.9537		-.07565		-.9161		-.07815		

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Figure 4-1. Radial Worth of Poison Wires - Flooded Reactor

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C. REACTIVITY EFFECTS

1. Flooded Reactor

The effect of poison wire density, diameter, number of wires, and wire height on reactivity has been determined. Table 4-6 provides a list of cases considered.

Figure 4-2 shows reactivity (k_{eff}) as a function of B_{4C}^{10} diameter, density, and number of wires. Dashed lines indicate extrapolated values obtained by simplified calculations rather than the computer code. It can be seen that reactivity is relatively insensitive to B_{4C}^{10} over the range of 80 to 90 percent theoretical density. The maximum reactivity differential over that spread in density is less than $0.02 \Delta k$. A 10 percent change in the number of wires in the range of 2000 to 2200 wires results in about a $0.04 \Delta k$ change in reactivity, whereas changing B_{4C}^{10} diameter from 0.137 to 0.157 cm results in approximately a $0.08 \Delta k$ change in reactivity. The number of wires required to maintain a reactivity of 0.95 with a fully flooded core and full length wires is shown in figure 4-3. An allowance of 100 wires should be made to compensate for the errors in calculations discussed previously.

The effect of wire insertion height for 2600 and 1800 wires is shown in figures 4-4 and 4-5. Figure 4-6 shows the number of wires required to maintain the reactivity of a fully flooded sector at $0.95 k_{eff}$ as a function of wire height and diameter (B_{4C}^{10} density, 90 percent theoretical). In the latter figure, the dashed curves are obtained from interpolated values and they should be considered as approximations only. An examination of these figures shows that moving 2600 wires, of the sizes considered, 20 to 25 cm out of the core gives rise to a critical region above the wires. One thousand eight hundred B_{4C}^{10} wires of 0.137 cm diameter are not adequate to assure a subcritical reactor under full flood conditions, whereas 0.147 and 0.157 cm diameter wires need to be pulled 15 to 30 cm out of the core before a critical configuration is attained.

For the NRX type reactor, it would appear that 2000 wires containing 85 percent theoretical density B_{4C}^{10} of 0.147 cm diameter provides a reasonably conservative design basis to maintain a fully flooded reactor core at or below $0.95 k_{eff}$.

2. Compacted Reactor

In order to determine the adequacy of the poison wires to maintain a compacted

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TABLE 4-6

FLOODED CORE REACTIVITY CALCULATIONS

Case No.	$^{10}\text{B}_4\text{C}$ Density % Theoretical	Diameter * (cm)	Number of Wires	Wire Height (cm)
1	90	0.157	2600	132
2	90	0.147	2600	132
3	90	0.137	2600	132
4	85	0.157	2600	132
5	85	0.147	2600	132
6	85	0.137	2600	132
7	80	0.157	2600	132
8	80	0.147	2600	132
9	80	0.137	2600	132
10	90	0.157	2200	132
11	90	0.147	2200	132
12	90	0.137	2200	132
13	90	0.157	1800	132
14	90	0.147	1800	132
15	90	0.137	1800	132
16	90	0.157	1800	126
17	90	0.157	2600	120
18 & 31	90	0.157	2600 & 1800	114
19 & 32	90	0.157	2600 & 1800	108
20 & 33	90	0.157	2600 & 1800	102
21	90	0.147	2600	126
22 & 34	90	0.147	2600 & 1800	120
23 & 35	90	0.147	2600 & 1800	114
24 & 36	90	0.147	2600 & 1800	108
25 & 37	90	0.137	2600 & 1800	102
26	90	0.137	2600	126
27 & 38	90	0.137	2600 & 1800	120
28 & 39	90	0.137	2600 & 1800	114
29 & 40	90	0.137	2600 & 1800	108
30 & 41	90	0.137	2600 & 1800	102

* Diameter of Neutron Absorbing Material

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Figure 4-2. Reactivity Variation Effects of Poison Wire Diameter and Density

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Figure 4-3. Poison Wires Required for $0.95K_{eff}$ Versus Diameter and Density

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Figure 4-4. Reactivity Versus Poison Wire Height

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Figure 4-5. Reactivity Versus Poison Wire Height and Diameter

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Figure 4-6. Number of Wires Required for 0.95 K_{eff} Versus Diameter and Height

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core in a subcritical state, three conditions were assumed to be 1) the beryllium reflector is compacted but no water flooding occurs, 2) the beryllium reflector is compacted and water flooding takes place, and 3) the beryllium reflector is torn loose and is replaced with water. Wire parameters for these cases are a 0.147 cm B_4C diameter, $B_4^{10}C$ density of 90 percent, and a total of 2600 wires.

The reactivity of the compacted reactor with 1) a compacted beryllium reflector with no water flooding is $0.62 k_{eff}$, 2) a compacted beryllium reflector with water flooding is $0.72 k_{eff}$, and 3) the beryllium reflector torn loose and replaced with water is $0.62 k_{eff}$. In the latter two cases, the reactor core was also reflected axially with water.

The calculations show that designing a poison wire system to maintain a water flooded reactor subcritical will provide ample shutdown margin for a compacted core.

3. Experimental and Analytical Poison Wire Worth

A series of tests were performed in the PAX critical facility to experimentally determine poison wire worth; see Appendix B. The worth of the poison wires was also determined analytically by essentially the same procedures as outlined in the previous chapters. The calculations gave conservative values of poison wire worth as is shown in table 4-7. This table presents the average poison wire worth, in cents, obtained experimentally and analytically. One dollar (100 cents) of poison wire worth is equivalent to $0.0071 \Delta k/k$ in the PAX critical reactor. The approximate total reactivity worth of the poison wires can be obtained by multiplying the worth of the individual wire by the number of wires in the reactor and dividing by the relative radial worth of the wires in the particular location where wire worth was determined.

The relative radial worth of the wires in the PAX-C experiment as compared to the average worth over the entire core is slightly less than 1.8; see figure 4-1. However, the important fact to be obtained from the PAX experiments is the degree of conservatism in the calculated wire worth versus experimentally determined values. The calculated values of poison wire worth were expected to be conservative since disadvantage factors were determined with a neutron energy spectrum associated with a homogenized core and poison wires. An iterative procedure, as discussed previously, between cell disadvantage factor calculations and cross-sectional calculations should result in a greater accuracy of analytical values for

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TABLE 4-7
 POISON WIRE WORTH
 PAX EXPERIMENTAL VS. ANALYTICAL VALUES

Case Number	<u>$^{10}\text{B}_4\text{C}$ Wires Per Element</u>		<u>CH_2 Rods Per Element</u>		<u>Core Inventory</u>		<u>^{10}B Worth, μ</u>	
	0-Cluster	A-Row	0-Cluster	A-Row	Total $^{10}\text{B}_4\text{C}$	Total CH_2	PAX Experimental Value	Analytical Value
1	1 - 0	0	0	0	6 - 0	0	-5.94	-4.1
2	1/2 - 0	0	0	0	6 - 3	0	-5.8	-3.9
3	1-2/3	0	18	0	6 - 4	108	-10.9	-7.4
4	1-1/3 - 1	0	17-2/3		8 - 6	106	-10.1	-6.9
4	1-1/2 - 1-4/9	1-1/2	17-1/2	17-1/2	63 - 61	735	-9.25	---
5	1-1/3 - 1	1-1/4	17-1/2	17-2/3	50 - 48	742	-12.6	-9.2
6	1-1/3 - 1	1-1/3	17-2/3	17-2/3	56 - 54	742	-11.7	-8.5
7	1-2/3	1-1/3	17-2/3	17-2/3	54 - 52	742	-12.6	-9.3
8	2/3 - 1/3	1-1/3	17-2/3	17-2/3	52 - 50	742	-13.4	---
9	1/3 - 0	1-1/3	17-2/3	17-2/3	50 - 48	742	-13.9	---

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poison wire worth. Agreement between experimentally and analytically determined values of wire worth is reasonably good. The analytical values are 25 to 35 percent below the experimental values. As shown in Appendix B, the experimental error in wire worth determination is approximately 10 percent. Thus, the difference between experimentally and analytically determined poison wire worths could be as low as 15 to 25 percent.

A more exact determination of poison wire worth is not warranted at this state of the ACPS development. It is evident that the calculations are sufficiently conservative so that a high degree of confidence can be placed on 2000 wires containing 85 percent theoretical density (0.147 cm diameter). This number of wires is adequate to provide at least a 5.0 percent Δk shutdown margin for a fully flooded NERVA type reactor. Future estimates on poison wire worth may show that a reduction in the number of poison wires is feasible.

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CHAPTER V SYSTEM DESCRIPTION

A. ACPS COMPONENT SECTION

The ACPS is basically a mechanical spring actuated system, with the exception of the pneumatic motor which is used for initiating wire extraction. The principle of operation utilizes relative movement of an inner and outer cylinder and the mass momentum generated by instantaneous release of pre-compressed springs. Proper operation is highly dependent upon generating the required acceleration and velocity at each spring release to actuate succeeding mechanisms or eject the system as required. A self contained winding tape actuator derives its power and control from components completely independent of the NERVA engine components which are designed primarily for other purposes. This independence permits greater freedom in selecting suitable and efficient components.

The ACPS can be readily divided into nine distinct sections, illustrated in figure 1-1, and are listed as follows:

- 1) Poison wires and support
- 2) Wire retention system
- 3) Piston
- 4) Inner locking cylinder
- 5) Outer ejection cylinder
- 6) Locking mechanisms and springs
- 7) Poison wire extraction system
- 8) Control system
- 9) Support structure

The following paragraphs describe each section of the conceptual ACPS. A complete explanation of the operational sequence is contained in a separate section of this document.

1. Poison Wires

Poison wires are long, slender, flexible rods intended for insertion into selected reactor core coolant channels. The wires contain a neutron absorbing material, boron carbide,

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enriched with the effective isotope of boron of atomic weight 10. A sufficient number of poison wires distributed throughout the core volume assure that the reactor cannot attain criticality. Poison wire criteria, construction and utilization are described in detail in Chapter II of this report; a representative poison wire is illustrated in figure 2-1 and 2-2.

2. Wire Retention System

During reactor ground handling, storage, testing and flight operation, it is imperative that the poison wires be maintained in the core without slippage. If the wires are allowed to penetrate the fuel element coolant channels beyond the prescribed length, there is a possibility of damaging the flow restriction orifices. If the wires are partially withdrawn from the channels, the subcriticality margin is reduced.

The retention plate is basically a circular plate with wire attachment fittings spaced to accommodate the wire bundles. For the flight configuration, this plate (head) is an integral part of the piston structure. (See figure 5-1.) Since it is mandatory that the poison wires be installed in the core from the time of reactor assembly and prior to nozzle attachment, a dummy retention plate is provided, with rigid supports, to maintain wire immobility during handling and shipping. Both plates will be made of 301 stainless steel to meet the fire exposure criteria as described in Chapter III, Section B of this report.

3. Piston

The piston, as illustrated in figure 5-2, is a composite structure, circular in shape, with the wire retention plate on top and a support plate on the bottom. It is secured inside the inner locking tube by means of the spring loaded locking pins. Teflon "O" rings attached to upper and lower plates provide the sliding surface and prevent piston cocking within the cylinder. The spring mechanism, the pin release lever and the pre-pressurized redundant system for activating the pin release are internally mounted in the piston. To fulfill fire exposure criteria, 301 stainless steel was chosen as the most suitable material.

4. Inner Locking Cylinder

The inner cylinder is a machined circular tube of stainless steel with variable thickness and is approximately 2.1 meters long. (See figure 1-1.) It serves two primary purposes in

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Figure 5-1. Plan View of Retaining Plate and Retaining Fingers

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① WIRE RETAINER PLATE	⑦ WIRE EXTRACTION TAPE
② PRE-PRESSURIZED REDUNDANT SYSTEM	⑧ INNER LOCKING TUBE
③ SLIDER SHAFT	⑨ PADDING
④ PISTON LOCKING PIN	⑩ RETAINING FINGERS
⑤ PRELOADED SPRING	⑪ WIRE BUNDLE ATTACHMENT
⑥ SLIDER LOCK PINS	

Figure 5-2. Detail Cross Section A-A of Piston

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the overall operation of the ACPS. First it provides a locking mechanism for the retainer fingers and secondly, when actuated, it provides the force for unlatching the ejection tube lever. Locking latches are placed around the periphery of both the inner and outer cylinder at their lower extremities. The latches prevent relative movement between the two cylinders and also lock the pre-compressed inner cylinder actuating spring. The only way the inner cylinder can actuate, after it has been locked into place, is to release the latches. After this is accomplished, the actuator spring drives the inner cylinder downstream from the nozzle throat, relative to the outer cylinder. After a travel of approximately 3.8 cm, bumpers machined onto the inner cylinder strike the retention levers, unlocking the whole system.

5. Outer Ejection Cylinder

The outer cylinder fits around the inner cylinder with a gap of approximately 0.25 cm between them. It is essentially a circular stainless steel machined tube with cutouts and thickness variations where required. See figure 1-1. It serves three important functions:

- 1) It provides support for the throat retaining fingers, gas accumulator, pneumatic motor and inner cylinder locking latches.
- 2) It anchors the piston locking pins.
- 3) It drives the support brace, the protective foam and the complete ACPS out of the nozzle when actuated.

Actuation is initiated by the ejection impulse from the inner cylinder impact of the retention lever and release of the throat retaining fingers. After the retention lever is released, the system ejection springs are released and movement of the outer cylinder is relative to all other components of the system. The mass momentum generated by the outer cylinder impacts the support braces and ejects the entire system.

The entire ACPS is prevented from moving out of the nozzle under flight vehicle acceleration by the throat retaining fingers. The loading is transmitted to the nozzle throat wall surface through the pressure exerted by the retaining fingers and padding. These items, 9 and 10, are illustrated in figure 5-2.

The reactor nozzle assembly had been pressure tested during the current NRX ground test series to pressures which exceed the magnitude exerted by the retaining fingers and padding. To pressure test the nozzle assembly, an expandable plug is employed to seal the throat area of the nozzle. In order to develop forces which hold the plug in place under internal

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assembly pressure, a flexible rubber-like material on the outer plug surface is compressed, causing the flexible material to conform to the surface irregularities and to the annular volume between the plug mandrel and the nozzle wall. Aerojet-General Corporation drawings 293700 and 293701 show the plug that is employed to seal the nozzle throat.

6. Locking Mechanisms and Springs

The ACPS operates as a self energized mechanical release system highly dependent upon reliable spring locking mechanisms. The design requirements include provisions for devices in which the locks are positive in order to prevent accidental release, and, at the same time, be responsive to release signals without complications.

There are three primary spring and lock systems designed into the ACPS. See figure 1-1. These, in the order of sequential system actuation, are the piston lock slider spring, the inner locking tube ejection spring, and the outer tube system ejection spring. The piston lock slider spring is pre-loaded to approximately nine g's, taking into consideration the mass of the piston structure and terminal fittings. This operation is performed in order to prevent unlocking due to launch acceleration forces. Its prime function is to maintain the piston locked in the desired position which in turn prevents movement of the wire terminal retainer plate. The actuation of this lock is very essential if the poison wires are to be extracted. Therefore, a pressurized redundant system capable of overcoming the spring is provided to prevent the pins from returning to a lock position if the redundant system is used. In the design evaluation the locking pins are notched so that a relatively low pressure produced by release of propellant through the NERVA engine can shear them if all other systems fail.

The inner locking tube ejection springs are also pre-loaded and locked into place by a series of latches. The springs are designed to eject the inner locking tube with sufficient initial velocity to unlatch the system ejection lever and at the same time be capable of locking the throat retaining fingers in place under all conditions of force and vibration. It is very important that the actuation of these springs can be controlled closely in order to prevent premature accidental release of the latches. This system differs from the piston lock system in that release of the pins initiates a chain reaction culminating in the ejection of the entire

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system. To preclude any credible accident, the latch mechanisms must be armed by a separate ground signal before the spring release mechanism is operable. This requires two separate overt actions to unlock the latches, one to engage and arm the mechanism and one to release the latches. Provisions are made for two methods of release, one electrically via a solenoid and one by a pneumatic cylinder. The release of these springs thrusts the inner locking tube downstream from the nozzle throat, unlocking the throat retaining fingers by its movement away from the area and releasing the system ejection lever by impacting it. Approximately 30 springs of 4.5 kg capacity each will be required for this action. This part of the ejection sequence is considered to be the most critical. Extraordinary caution will be exercised in this area during design and assembly to ensure a positive and reliable operation.

The system ejection springs are pre-loaded and are by far the largest and most heavily loaded springs in the system. The primary functions of these springs are to dislodge the support braces and eject the complete system out of the nozzle. Since it is most important to dislodge the support braces, the spring forces are designed for twice the static requirements. This does not take into account the impact factor which may be as much as three times the static force. Approximately 30 springs, spaced equally around the outer periphery, with an average force of 16 kg per spring, will be utilized. These springs are contained in a housing and locked into place with four cam-latch spring loaded ejection levers. If more than four are required to insure a uniform spring release or to reduce the unit lever load, the system is adaptable to additional levers. The operation of this system is dependent upon a successful actuation of the inner locking tube system.

7. Poison Wire Extraction System

The extraction system is composed of a pneumatic motor, an energizing gas storage accumulator, an arming clutch mechanism, a winding spool, and the pull tape. The system will be mounted on a plate welded to the lower portion of the outer ejection tube. The pneumatic motor will be of a special design utilizing the lightest weight materials and sealed from the elements.

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The conceptual design shows that the accumulator will be of the aircraft type, using a stainless steel body and a siliconized rubber bladder pressurized to 140 kg/cm^2 for either nitrogen or helium. Two separate and independent regulator systems are mounted to the accumulator; one actuates the wire extraction motor and the other is connected to the redundancy system for releasing the inner locking springs.

The arming mechanism which engages the motor shaft will be of a clutch type actuated by an electric signal. The pull tape will be made from a nickel cobalt alloy with a high yield and ultimate strength. Tests indicate yield strengths up to $19,700 \text{ kg/cm}^2$ and ultimate strengths to $25,900 \text{ kg/cm}^2$ for this material. A tape approximately 0.025 cm thick and 5 cm wide will be adequate for use in extracting the wires. Elgiloy or Haver tapes exhibit strength and unusual ductility in the operating range of the ACPS temperature and possess characteristics which will fulfill the requirements for poison wire extraction. The spool will be in the range of 5 to 7.5 cm in diameter and will be machined from an aluminum forged block. A pillow block will be supplied if necessary to support the motor shaft. See figure 1-1.

The pneumatic motor spool-winding tape principle was proven during tests conducted to establish withdrawal force conditions with respect to the demonstration wire. Figure 2-13 shows the entire assembly and figure 5-3 provides a better view of the motor and tape assembly.

8. Control System

The control system is described as any piece of equipment that signals, actuates or regulates the function of the ACPS components. Figure 5-4 is a schematic of the control system as presently designed. The steps are numbered in sequence of operation, and dotted lines indicate the ultimate routes of the functions which will be required if the redundant system is utilized.

The ACPS control not only includes that portion of the system mounted on the NERVA rocket, but also a ground control station. Communications between the rocket and the ground station are accomplished by means of a two-way radio link or transceiver. The transceiver on the rocket will receive the control signals in coded form from the ground station, decode them, and present them in a form necessary to operate the various ACPS control

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Figure 5-3. Assembly of Pneumatic Motor and Withdrawal Tape

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Figure 5-4. Block Diagram of the Control System

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functions. Indication signals will be returned to the ground station in a similar fashion. This transceiver, which may be a part of a large communication system for other NERVA engine control functions, will be capable of rejecting all spurious signals. The ACPS control functions will be initiated at the ground station by contact closures and all "operation complete" indications will be verified by lamp.

The ACPS control system aboard the rocket will be composed of low voltage dc circuitry, with all "operation complete" indications generated by contact closures actuated by signals from the transceiver. There are no servo or feedback loops. This was done to increase the reliability and to simplify the circuitry by minimizing the number of components. This type of system relinquishes as much of the control function as possible to the ground station and its operators, a feature which provides maximum flexibility.

9. Support Structure

ACPS support structures are the components that support or react the system loads due to launch and wire extraction and are independent of the system functional requirements. There are two major support structures in ACPS, 1) the support braces and 2) the system support platform. The design of both structures was interrelated due to a mutual load apportionment. The support braces are a series of stainless steel tubes with welded curved plates (to conform with the nozzle curvature) covered with a siliconized rubber pad molded to fit the contour of the nozzle flow tubes. The brace structure is locked into the outer ejection tube and is adjustable in the axial direction. This permits a position variation in relation to the support platform in order to control the allocation of load reactions. Additional brace adjustment is provided by a ball connection to the pads. The support platform will have a lateral guide tube built in for the sole purpose of preventing horizontal pivoting and movement of the system due to lateral acceleration and vibrations. The surface of the platform will be covered with a hard durometer siliconized rubber pad which will allow the system to translate axially about 0.25 to 0.6 cm during maximum acceleration of the flight vehicle. The schematics in figures 5-5 to 5-8 indicate the installation loads and reactions to be expected at the critical loading points on the support structure. In conjunction with the illustrations, table 2-2 lists functional data pertinent to the system.

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- ① RETAINING FINGERS
- ② INNER TUBE
- ③ OUTER TUBE
- ④ EXTRACTION TAPE
- ⑤ FLEXIBLE PAD
- ⑥ EJECTION LEVER
- ⑦ SUPPORT BRACE
- ⑧ OUTER EJECTION SPRING
- ⑨ FLEXIBLE PLASTIC FOAM
- ⑩ INNER EJECTION SPRING
- ⑪ ACCUMULATOR
- ⑫ GUIDE TUBE
- ⑬ SUPPORT PLATFORM
- ⑭ TOP OF PRECEDING STAGE
- ⑮ FLEXIBLE PAD
- ⑯ PNEUMATIC MOTOR
- ⑰ INNER TUBE RELEASE MECHANISM
- ⑱ PISTON
- ⑲ FLEXIBLE PAD
- ⑳ POISON WIRE BUNDLES

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CONDITIONS:

A. PRE-LAUNCH-1.0 g LOAD	C. RETAINING FINGERS
FREE OF THROAT PAD
B. ACPS WEDGED INTO NOZZLE &
SUPPORT PLATFORM	D. SUPPORT BRACES & PLATFORM PADS
REACT WEDGE LOADS

Figure 5-5. ACPS Pre-Launch Condition

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- ① RETAINING FINGERS
- ② SUPPORT BRACES
- ③ SUPPORT PLATFORM PAD
- ④ GUIDE TUBE

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CONDITIONS:

- A. MAX. ACCELERATION FORCE OF 6.0 g JUST PRIOR TO 1ST STAGE BURNOUT
- B. SUPPORT PLATFORM PADS DEFLECTED TO REACT PORTION OF AXIAL LOAD
- C. RETAINING FINGERS REACT PORTION OF AXIAL LOAD
- D. SUPPORT BRACE INITIAL AXIAL LOADS RELIEVED - ZERO REACTION
- E. LATERAL LOADS OF 1.8 g REACTED BY SUPPORT BRACES AND GUIDE TUBE

Figure 5-6. ACPS - Maximum Acceleration Condition

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- ① RETAINING FINGERS
- ② SUPPORT BRACES
- ③ SUPPORT PLATFORM
- ④ GUIDE TUBE
- ⑤ SECOND STAGE

CONDITIONS:

- A. JUST PRIOR TO 2ND STAGE BURNOUT
- B. 2ND STAGE TANK WITH SUPPORT PLATFORM
DEFLECTS 5 CM. AWAY FROM ACPS
- C. RETAINING FINGERS REACT 2.8 g LOAD
- D. SUPPORT BRACE REACTS LATERAL ACCELERATIONS
- E. ACPS COMPLETELY FREE FROM GUIDE TUBE

Figure 5-7. ACPS - At Second Stage Burnout

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- ① POISON WIRES
- ② SUPPORT BRACES

CONDITIONS:
A. 2ND STAGE SEPARATED
B. ZERO "G" LOADS
C. POISON WIRES BEING EXTRACTED
D. EXTRACTION LOADS REACTED PRIMARILY
BY SUPPORT BRACES

Figure 5-8. ACPS - Wire Extraction Conditions

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At the final installation of the system on the launch vehicle, the support braces will be resting on a platform located on the second stage propellant tank. In order to stabilize the ACPS under dynamic operating conditions, the braces will receive part of their support from the second stage. Such a concept has the following advantages:

- 1) Increase in system stabilizing before and after launch.
- 2) Dampening of vibrational effects on the ACPS and nozzle.
- 3) Reduction of the reaction loads of the ACPS on the nozzle during maximum acceleration of the rocket.
- 4) Inherent compensation for temperatures and pressure changes.
- 5) Positive maintenance of the alignment of the ACPS.
- 6) Compensation for inter-stage structural contractions.

Immediately prior to the preceding stage burnout, it is postulated that the fuel tank upon which the system platform support is attached will deflect 5.0 cm away from the ACPS. Also, an instantaneous load factor of 2.8 is expected on the NERVA (S-N) stage. Without the platform support, this load will be absorbed by the retaining fingers on the nozzle throat, figure 5-7. The support brace pads will remain in contact with the nozzle wall with no appreciable load (greater than 1.0 g) on them. The platform guide tube is so designed that the ACPS will be completely free of lateral restraint after the 5.0 cm movement of the platform. The 2.8 g load occurs simultaneously with the 5.0 cm movement but is a momentary occurrence lasting only a fraction of a second.

Following separation of the preceding stage, the nuclear stage will be programmed for operation. At this time, the poison wires will be withdrawn from the reactor core.

As a conservative estimate, 308 kg is presumed as the force required to break static friction for extraction of the poison wires. This value was derived from ground withdrawal tests. Furthermore, this value is conservative because the nuclear stage will, in all likelihood, be in a condition near "zero-g". Consequently, frictional force influences should be lower than those of the horizontal ground pull tests because no directed weight-force causes the wires to align against the reactor core coolant channel walls.

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The withdrawal forces will be reacted through the support brace pads bearing against the nozzle wall, figure 5-8. Maximum unit reaction loads on the nozzle wall due to wire extraction are approximately 0.8 kg/cm^2 . Maximum unit loads are excited on the nozzle wall at the brace during ACPS ejection. Unlatching of the outer ejection lever releases the system ejection springs (a total spring load of approximately 469 kg) driving the support braces against the nozzle wall. To take into account the effect of an instantaneous spring release, the nozzle reaction loads are considered double the spring load. Only one half the brace pad area was considered in calculating the unit load. This, in effect, provides a factor of four times the nominal spring load on the nozzle wall or approximately 2.2 kg/cm^2 .

To insure against possible damage to the nozzle coolant channels, a pliable padding will be bonded onto all ACPS surfaces that contact the nozzle. In addition, polyurethane foam buns wrapped in polyethylene or Teflon sheets will be installed between the nozzle and the ACPS support components.

B. REDUNDANT SYSTEMS

Due to the ACPS requirements for a positive retention system and an equally positive extraction and ejection system, alternate methods for these operations would be provided. A summary of redundancy provisions are:

- 1) A pre-pressurized system to release the piston lock pins in the event the pneumatic motor arming mechanism or the pneumatic motor becomes inoperative.
- 2) Notched piston lock pins which will shear at a low engine flow if the primary system fails to operate. This can be considered a backup system for wire extraction.
- 3) A pneumatic cylinder for extracting the inner locking tube pins. In normal operation an electrically operated solenoid will extract the pins.

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Figure 6-2. Pre-Launch In Ejection Sequence

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CONDITIONS:

A. SECOND STAGE SEPARATED	C. WIRES EXTRACTED AND STORED
B. SYSTEM LOCKED IN PLACE	D. ZERO "G"

Figure 6-3. Wires Stored in ACPS Ejection Sequence

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- ① INNER LOCKING TUBE SPRINGS
- ② RETAINING FINGERS
- ③ EJECTION LEVERS

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CONDITIONS:

- A. INNER LOCKING TUBE SPRINGS RELEASED
- B. RETAINING FINGERS RELEASED
- C. OUTER EJECTION LEVER IMPACTED

Figure 6-4. Release Initiated in ACPS Ejection Sequence

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CONDITIONS:

- A. EJECTION SPRINGS RELEASED
- B. SUPPORT BRACE FREE
- C. COMPLETE ACPS LEAVING NOZZLE
- D. EJECTION SEQUENCE COMPLETE

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Figure 6-5. Ejection Complete in ACPS Ejection Sequence

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CHAPTER VII RELIABILITY OF THE ANTI-CRITICALITY POISON WIRE SYSTEM

A. RELIABILITY

Due to the nature of the ACPS, its usage, and the environment in which it must operate, the reliability goals established must equal or exceed those established for the NERVA engine subsystem. In a complex design of this type, there are areas in which further development and testing are required. A preliminary reliability design review indicated that emphasis should be placed on a further study of the following sections:

- 1) The electrical circuitry and control system.
- 2) A quality control program for the manufacturing process.
- 3) Provisions for inspection during installation.
- 4) The development of a material for retaining finger and support system pads which must be capable of exposure to extreme environmental conditions.
- 5) Dynamic testing of poison wire support structures.
- 6) Environmental tests for actuating components.

A thorough reliability analysis complete with numerical values can only be obtained from a detailed design. The conceptual stage in which the ACPS now exists presents many obvious limitations. However, with respect to further effort required, direction and insight can be gained from a qualitative reliability review. Tables 7-1 and 7-2 provide this qualitative evaluation.

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TABLE 7-1

ACPS QUALITATIVE RELIABILITY EVALUATION
COMPONENTS SECTION

ITEM	WEIGHT (LBS.)	MATERIAL	ANALYSIS VALIDITY	DESIGN AND SYSTEM COMPLEXITY	DEVELOPMENT EFFORT	SAFEGUARDS COMPATIBILITY
1. Complete System	189.0			Proven principles and devices	Mechanical synchronization and timing problems	Minimum influence
2. Poison Wires	45.4	Non-metallic	Good	Basic fabrication established	Retention in reactor and nozzle	Primary component
3. Wire support Piston	4.7	S.S.	Good	Close tolerance machining to minimize friction	Minimum	Mandatory for anchoring poison wires
4. Outer Ejection Tube	26.2	S.S.	Good	Close tolerance machining required	Structural and mechanical tests	Required to eject system independently
5. Inner Locking tube	14.4	S.S.	Good	Same as above	Same as above	Locks system retainer fingers
6. Throat Locking Fingers	5.5	S.S.	Good	Contour surface to match nozzle tubes will be difficult	Minimum	Retains system and wires in place until ejection
7. Flexible Padding	1.2	Siliconized Rubber	Fair	Molding problems and temperature effects	Extensive environmental testing to determine flexibility	Protects nozzle coolant tubes
8. System Levers and Locks	0.7	S.S.	Good		Minimum	
9. Ejection Springs, Housing and Associated Hardware	18.9	Piano wire and S.S.	Good	Installation and retention problems	Uniform load release mechanism tests	Provides force to eject system
10. System Brace and Support Structure	13.8	Aluminum	Excellent			Include interface with nozzle wall
11. Pull Tape, Pulley and Associated Hardware	0.9	Elgiloy tape, aluminum pulley	Excellent	Attachment problems	Minimum	Attached to piston for extracting poison wires
12. Accumulator and Support Structure	19.8	S.S. and Aluminum	Good	Actuation and control problems	Dynamic and environmental experiments	Provides pressure to actuate air motor
13. Air Motor and Support Structure	13.6	Special design motor and aluminum supports	Good	Similar systems operative in space required close cooperation with vendor	Dynamic and environmental integrity tests	Actuates the pull tape for pulling poison wires.
14. Piston Redundant System	2.4	S.S.	Good	Temp. and dynamic conditions can trigger system	Environmental and dynamic tests	Provides alternate wire extraction method
15. Arming cylinder and miscellaneous clutch and mechanisms	7.1	S.S. Aluminum	Good	Systems actuation and integration	Environmental and dynamic tests	Provides locking and releasing mechanisms
16. Protective foam	14.4	Polyurethane			Flexibility and compression tests	Protects nozzle structure

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TABLE 7-1 (Continued)

REMARKS

1. Mechanical lock and release provide high reliability - latest wire pull test data indicates a need for 50% of preliminary estimated loads.
2. Termination and structure of wire-bundling in convergent portion of nozzle requires definition.
3. Provisions for minimum friction using Teflon sliding surfaces makes this highly reliable.
4. Tube locks and ejects system when required.
5. Provides the actuating force to unlock outer ejection tube.
6. Most suitable area at nozzle throat for system retention.
7. Problems may arise in ejection sequence where pads could interfere and cause deceleration of system.
8. Locks and releases system for ejection in space.
9. Uniform release is a must to prevent hang up during release.
10. Maintains axial and lateral stability of system.
11. High strength Elgiloy reduces weight.
12. Carried to make system completely independent of reactor systems.
13. Proven principles will allow for motor design at reduced weight.
14. Safety feature if accumulator system air motor system fails.
15. Chronological arming and release of actuation systems must be coordinated to obtain optimum ejection speeds.

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TABLE 7-2

ACPS QUALITATIVE RELIABILITY EVALUATION
OPERATION SECTION

EFFECTS OF SEPARATION	UNIFORMITY OF OPERATION	CONSTRUCTION	COMPLEXITY
<p>Mechanical release utilizing spring forces is a good positive method of separation.</p>	<p>1) Wire extraction procedure very positive and smooth</p> <p>2) Ejection sequence depends highly upon successful mechanism operation when required.</p>	<p>1) Close tolerance components are required to maintain rigid support.</p> <p>2) Close tolerances required for ejection sequence to be successfully completed.</p>	<p>1) Major consideration is to design the mechanism that can be assembled into a workable system under the required conditions.</p> <p>2) The forces, flexibility, weight, timing, and actuating mechanisms must be all coordinated to a precise degree.</p>
VIBRATION EFFECTS	ADJUSTMENTS	OTHER INERTIAL FORCES	HAZARDS
<p>1) System vibration can bind levers and locks.</p> <p>2) Misalignment of system can prevent ejection.</p> <p>3) Piston lock pins can prevent wire extraction.</p>	<p>1) Alignment fixtures must be used during installation.</p> <p>2) Component design should allow for adjustment.</p>	<p>Not Significant.</p>	<p>1) Capable of preventing reactor criticality under all credible accident conditions.</p>

TABLE 7-2 (Continued)

FAILURE MODES	INTERACTIONS	TEMPERATURE EFFECTS	PRESSURE EFFECTS
<ol style="list-style-type: none"> 1) Tape failure unlikely-- high margin of safety. 2) Malfunction of sensing or actuating control mechanism-- faulty design fabrication, installation or calibration. 3) Faulty installation of system components difficult; accessibility and visibility poor in nozzle throat. Inspection is difficult. 4) Flexible pad freezing when contacted by Liquid Hydrogen-- development and test program required. 5) System ejection failure due to binding of lock pins, pressure controls on accumulator or air motor, insufficient velocity generated by tube mass and release lever binding. Requires careful design, manufacturing and installation. 6) Accidental initiation of ejection sequence due to vibratory or acceleration forces on actuating mechanism. Requires careful design and experimental testing. 7) Component structural failures-- proper analysis and choice of material. 	<ol style="list-style-type: none"> 1) Electronic telemetering equipment must be integrated with the overall sequential operation. Extensive development and testing required. 	<ol style="list-style-type: none"> 1) Low temperature effects on structural components can cause brittleness and failure. 2) Lubrication problems on moving mechanism at low temperature. 3) Design must accomodate contraction of materials due to low temperature. 	<ol style="list-style-type: none"> 1) Effects on accumulator controls and velocity at which gas is released must be considered. 2) Effect of pressure on air motor operation. This can be controlled by design.

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APPENDIX A

The pull test mechanism of figure A-1 was constructed to provide a means for applying and determining wire withdrawal forces. Following the insertion of flexible wire bundles into fuel clusters, as shown in both figures A-1 and A-2, air from the cylindrical steel "bottle" was permitted to flow through the hand-operated valve to drive the pneumatic motor. A flexible steel tape winding up on a spool fastened to the pneumatic motor shaft caused the retractor head to move through the guide tube toward the winding spool. Since the wire bundles were connected to the retractor head, the flexible wires were withdrawn from the fuel clusters.

A transducer load cell located between the flexible steel tape and the retractor head provided a signal proportional to the withdrawal force. Upon amplification, this signal produced an ordinate or Y-axis force deflection of the pen trace on the X-Y recorder. A distance transducing potentiometer which was connected by means of a wire to a point on the steel tape near the retractor head, provided a signal proportional to the withdrawal distance. This was employed to deflect the pen in the abscissa or X-axis direction.

A Program Sheet, figure A-2, provided a record of wire bundle locations for each withdrawal test. Cluster locations of this figure are presented as the view an observer would see looking into the nozzle in a direction upstream of the propellant discharge. Cluster numbers 1 through 43 were arbitrarily assigned for reference purposes. Table A-1 lists the location of wires for the eight tests that were conducted.

The X-Y recorder trace for Test 7 is shown in figure A-1. This trace is a good representation of the patterns of force behavior which were common to all tests. During a wire withdrawal, it was noted that the sequence of the various types of behavior could be segregated into distinct portions (zones) of the wire withdrawal distance. The various patterns of behavior

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Figure A-1. Typical Wire Withdrawal Recorder Tract - Test No. 7

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ONLY CLUSTERS DESIGNATED
ARE TO BE USED.

TEST NO. _____

DATE _____

NO. OF TESTS REQUIRED _____
TIME PERIOD FOR TEST _____
MATERIAL BEING TESTED _____

NO. OF CLUSTERS _____
NO. OF WIRES PER CLUSTER _____
TOTAL NO. OF WIRES _____

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Figure A-2. Poison Wire Pull Test Program

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TABLE A-1
INSTALLATION OF FLEXIBLE WIRES FOR WITHDRAWAL TESTS

TEST NUMBER	TOTAL WIRES WITHDRAWN	NUMBER OF CLUSTERS	NUMERICAL DESIGNATION OF CLUSTERS UTILIZED *	CLUSTER DIAMETER cm	WIRES INSERTED IN EACH CLUSTER
1	120	12	1 - 12	82.5	10
2	120	12	13 - 24	61.0	10
3	120	12	25 - 36	40.7	10
4	70	6	37 - 42	20.3	10
		1	43	Center	10
5	360	12	1 - 12	82.5	10
		12	13 - 24	61.0	10
		12	25 - 36	40.7	10
6	360	8	2,3,5,6,8,9, 11,12	82.5	10
		4	1,4,7,10	82.5	20
		12	13 - 24	61.0	10
		8	25,27-29,31, 33-35	40.7	10
7	300	12	1 - 12	82.5	10
		9	13,15-17,19, 21-24	61.0	10
		6	25,27,29,31, 33,35	40.7	10
		3	37,39,41	20.3	10
8	200	8	1,3-5,7,9-11	82.5	10
		6	13,15,17,19, 21,23	61.0	10
		4	25,28,31,34	40.7	10
		2	38,41	20.3	10

* Cluster numbers correspond to those shown in Figure A-2

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are delineated on the trace of figure A-1.

Zone 1 is the wire withdrawal distance in which the applied force overcomes wire resistance due to static friction. The static friction occurs through a distance of approximately 5 cm. The wire and the bundle are not loaded by the pulling force simultaneously; thus, wires near the center of the reactor core and directly in line with the extraction mechanism start exit movement immediately as removal forces are applied. Wires near the outer periphery of the core are somewhat delayed in extraction due to the angle at which the force is applied and to bending in the bundle section of the wires. This zone is graphically illustrated in all test plots by the high initial peak loading and by a rapid drop to sliding friction conditions.

Zone 2 is typically illustrated on test number 7 shown in figure A-1. It is characterized by the relatively small erratic fluctuation in the sliding frictional forces shown on the recording plot. This zone occurs immediately following the initial peak load and continues to an extraction distance of 55 cm. This fluctuation is caused by the irregular cross-sectional configuration of the bundle portion of the wires rubbing the retaining ring at the simulated nozzle throat. Zone 2 terminates as soon as the flexible wires reach the initial portion of the extraction plot. The bundling arrangement for these wires was designed to give a general geometrical configuration for the pull test. It is possible to eliminate this erratic force characteristic in the final bundling design. The force required in this zone is dependent upon the rigidity of the bundling. The bundling in turn would be determined by test analysis of the force required to maintain the wires in the reactor during launch of the vehicle.

Zone 3 of the plot occurs when the only frictional forces present are those of the wires rubbing the retaining ring during their extraction. This zone extends from the end of zone 2 to approximately 105 cm of pull head movement. It is characterized by the smoothest portion of the force plot and shows that the frictional force connected with the wire extraction is a linear function of the length of wire remaining in the reactor core.

With the establishment of the inverse relationship between the length of poison wires in the core and the sliding frictional forces required for extraction, a straight line extrapolation was drawn back to the origin of the plot in figure A-1. This line should closely approximate

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the maximum sliding frictional forces involved in the extraction of the wires. For test No. 7, this force was approximately 37 kg. The peak recorded force was 31 kg or about 5 kg required to overcome the static frictional forces. This is a 13.5 percent increase over the sliding frictional forces. This graphical procedure established at lower limits can be used to determine the maximum resistance for other arrangements of wires. The apparent value of maximum sliding friction resistance occurring at the initiation of withdrawal would always be less than the maximum force required to brake static friction. Although the latter type of peak force actually occurred near the initiation of withdrawal in zone 1, it was delayed since movement does not begin simultaneously for all the wires.

Zone 4 extends from the end of zone 3 to the completion of the wire extraction. An increase in the bending moment occurs as the wires near the exit of the reactor core due to the angle at which the outer wires are extracted. The wires used for the pull tests were of a uniform length and caused the wires of the outer radius to exit first. This uneven exit sequence was the reason for the force variations evidenced over some distance of the extraction plot of zone 4.

Indications similar in nature to those of zones 1 and 4 have been reported in Reference 2. In this reference, the information pertained to forces produced in pulling stainless steel wires from an arrangement of fuel clusters.

Figure C-1 of Reference 2 showed a typical trace obtained upon pull testing 555 stainless steel wires. The connected dashed lines superimposed on figure A-1 are a simplified representation of figure C-1 which has been proportioned from 555 to 300 wires. These dashed lines connect prominences of the solid line trace in Reference 2 which have been multiplied by 300/555 to proportion the values to 300 wires.

These proportioned values can be compared directly with the trace of figure A-1 since the number of wires represented is the same. The comparison especially illustrates the dramatic reduction of forces in zone 4 resulting from the use of the flexible poison wire.

In comparison to the behavior in zones 1, 2, and 4, the pull force pattern for zone 3 of each test trace was apparently produced by a minimum number of different influences acting upon the wires. The resistance and behavior exhibited in zone 3 was attributed to the sliding

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friction between the wires and fuel element coolant channel and between the peripheral wires and the circular lip at the end of the guide tube, figure A-3.

Table A-2 lists the values obtained for each withdrawal test which indicated a significance with respect to test record pen-trace zones 1, 2, 3, and 4.

Test 7 provided data for a withdrawal with the largest number of wires approximating a uniform wire distribution throughout the cluster arrangement cross section. Since this distribution is analogous to that presumed for the reactor, it was desirable to use test 7 as the basis for determining withdrawal force requirements of the ACPs.

To establish the degree of uncertainty of test 7 results, various combinations of results from the other tests were compared with the appropriate value of test 7. Obtaining consistency on the basis of the reasons previously stated, the specific type of value extracted from the different tests is the derived maximum force due to sliding friction, table A-2. The combination of test result values are adjusted to a 300 wire basis to facilitate comparison with the test 7 value.

Results of some of the tests are related to a particular radius of withdrawal and obtained on the basis of a different number of wires than that inserted at the particular radius for withdrawal in test 7. To sum a value of this nature into the total force to be compared, it must be multiplied by the ratio of the number of test 7 wires at the particular radius to the number of wires withdrawn at the time the value under revision was obtained. This manipulation is indicated in table A-3.

Table A-3 provided three comparisons with the desired test 7 value, lines 1, 4, and 9. Line 1 shows extremely close agreement between the test 8 value and the modified test 7 value. This indicates that the measured withdrawal force per wire is not sensitive to the total number of wires removed since the type of distribution of wires in the cluster arrangement cross sections is the same for any two tests compared.

Results of combinations entering values of lines 4 and 9 are respectively 4.1 and 8.1 percent different from the test 7 value. This agreement is quite reasonable considering that the results of combinations of lines 4 and 9 include an undetermined resistance produced by friction in bending the wire over the guide tube leading edge as shown in figure A-3. This type of

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Figure A-3. Guide Tube Inlet

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TABLE A-2

SIGNIFICANT WITHDRAWAL TEST FORCE VALUES

TEST NUMBER	NUMBER OF WIRES PULLED	CLUSTER DIAMETER OF WIRE INSERTION cm	ZONE 1 STATIC FRICTION PEAK FORCE kg	ZONE 3 INITIAL FORCE kg	ZONE 3 FINAL FORCE kg	ZONE 4 MAXIMUM FORCE kg	DERIVED MAXIMUM SLIDING FRICTION FORCE kg	REMARKS
1	120	82.5	20.7	11.4	5.2	5.8	18.3	
2	120	61.0	18.4	10.7	6.0	6.3	17.3	
3	120	40.7	12.9	7.1	2.7	2.9	12.0	
4	70	20.3 and Center	5.4	2.7	1.2	1.5	5.8	
5	360	82.5 61.0 40.7	46.8	28.7	13.2	13.2	50.1	120 wires each cluster diameter
6	360	82.5 61.0 40.7	47.6	29.6	15.0	15.7	47.7	Wires per cluster diameter varies with diameter
7	300	82.5 61.0 40.7 20.3	40.4	23.3	11.1	11.4	36.8	Wires per cluster diameter varies with diameter
8	200	82.5 61.0 40.7 20.3	26.6	15.4	7.4	7.4	24.4	Same distribution as Test 7

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TABLE A-3
CORRELATION OF TEST RESULTS

Line	Test Providing Derived Maximum Sliding Friction Force	(A) Derived Maximum Sliding Friction Force, kg	* Radius, R_{ww} , of Wire Withdrawal, cm	(B) Wires at R_{ww} for (A)	(C) Wires at R_{ww} for Test 7	(D) Contribution toward comparison Value $= \frac{(A) \times (C)}{(B)}$, kg	(E) Test 7 Value of (A) to Compare with (D) Summation kg	(F) Difference, (D) Summation Less (E)	Percent Difference $\frac{(F) \times 100}{(E)}$
1	8	24.4	Distribution same as Test 7	200 for 4 radii	300 for 4 radii	36.6 summation	36.8	-0.2	-0.54
2	6	47.7	Distribution same as Test 7	360 for outer 3 radii	270 for outer 3 radii	35.8	--	--	--
3	4	5.8	10.2 and center cluster	70	30	2.5	--	--	--
4	6 & 4	--	--	--	--	38.3 summation	36.8	1.5	4.1
5	1	18.3	41.2	120	120	18.3	--	--	--
6	2	17.3	30.5	120	90	13.0	--	--	--
7	3	12.0	20.4	120	60	6.0	--	--	--
8	4	5.8	10.2 and center cluster	70	30	2.5	--	--	--
9	1,2,3,4	--	--	--	--	39.8 summation	36.8	3.0	8.1

* See Figure A-2 for pictorial representation and Tables A-1 and A-2 for wire location and distribution.

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resistance existed for test 7 also, but this undetermined resistance varies nonlinearly from combination to combination of results.

That is, the sum of resistance values due to guide tube inlet friction of any of the combinations, line 4 or 9, would not equal the same value for test 7 even if all had been determined. The summing of parts does not equal the total in this situation since the number of wires in contact with the inlet edge of the guide tube remains nearly constant and varies in percentage between large and small numbers of wires withdrawn. Also there is a physical limitation on the number of wires that can seat side-by-side over the inlet edge. The guide tube inlet edge bending resistance probably accounts for most of the force measured in zone 4 of figure A-1.

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APPENDIX B

PAX-C REACTOR CORE, ACPS FLEXIBLE POISON WIRE MEASUREMENTS

A. INTRODUCTION

During the performance of the critical experiments conducted on the PAX-C, a series of measurements were performed to determine the reactivity worths of flexible poison wires in simulated flooded core conditions. The measurements employed flexible poison wires whose composition was boron carbide enriched in the B^{10} isotope to about 87 percent. The wires were fabricated as part of the program to develop an ACPS for the NERVA program.

B. SUMMARY AND CONCLUSIONS

From the measurements that were obtained with the $B_4^{10}C$ wires in various arrays and under various degrees of simulated flooding, it appears that the wires are very capable of preventing an accidental criticality due to core flooding. This can be inferred from figure B-1 which shows that with an effective 89.7 percent water flooding in the 000 and A-row clusters, the net reactivity change of the flooded-poisoned region is negative if more than 53 $B_4^{10}C$ wires are inserted into this region. It was found that the dry worth of the $B_4^{10}C$ wires in the 000 cluster was about -5.8 cents per wire which is about 4.3 times as much as the standard B_4C poison wire. In a flooded condition (89.4 percent water) the $B_4^{10}C$ worth in the 000 cluster is between -11.7 and -13.9 cents depending on the number of poison wires in the core.

From the measurements it was also noted that the PAX-C incremental drum worth was reduced from about 7.5 cents per degree at its peak to about 6.9 cents per degree when the 000 and A-row clusters were flooded and poisoned. This is a reduction in the incremental worth of about eight percent.

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Figure B-1. Effect on Core Reactivity as a Function of Density - PAX-C

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C. EXPERIMENTAL METHODS AND DETAILS

In this series of measurements, the reactivity effect on the PAX-C core was determined with various flexible $B_{4}^{10}C$ poison wire arrays and for various degrees of simulated core flooding with water. The poison wires used in the measurements were enriched in the B^{10} isotope to approximately 87 percent, and the core flooding was mocked-up using polyethylene rods whose chemical composition was CH_{2m} . A description of the flexible poison wires and the polyethylene rods is given in table B-1. Only the central region of the core was utilized in these measurements.

The actual measurement techniques employed during the experiment were similar to those used in previous PAX-C reactivity determinations. That is, the reactivity effect produced by the insertion or removal of a known amount of poison and/or polyethylene was measured using the standard period technique. In using this technique, the reactivity change is determined by measuring the reactor period before and after the change and then determining the reactivity change by converting the two period measurements to reactivity values and subtracting.

D. RESULTS AND ANALYSIS

The major objective of this series of experiments was to determine the effectiveness of boron carbide poison wire enriched in the B^{10} isotope under various degrees of core flooding by water. Since it was not feasible to mock-up the flooding and poisoning conditions over the entire PAX-C core, a series of experiments were designed wherein flooding conditions were mocked-up in the center section of the PAX-C core, and the effects on the core reactivity studied. In conducting the experiments in this manner, the experimental data obtained can be used as a check of the analytical techniques employed to calculate the degree of subcriticality under various flooding and poisoning conditions.

The set of experiments designed to determine the effectiveness of the flexible $B_{4}^{10}C$ poison wires is given in table B-2. The measurements that were obtained are given in table B-3 and cross referenced by "case number" with the original proposed measurements. Table B-3 lists the changes made to the core for each measurement and the reactivity effect produced by that change as well as the cumulative reactivity effect produced during each successive measurement. In order to more clearly visualize the configuration in the core during the measurements

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TABLE B-1

DESCRIPTION OF EXPERIMENTAL MATERIALS

1. Flexible $B_{10}C$ Poison Wires

a. Poison wire cross section and materials:

Given below is a cross section of the flexible poison wire identifying the materials of construction and the various cross-sectional dimensions.

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b. Other physical and chemical properties of the flexible poison wires:

- 1) Average $B_{10}C$ density 1.87 gms/cc
- 2) Boron content 77%
- 3) B_{10} enrichment 87%
- 4) B_{10} form - Sintered rod
Average O. D. of B_4C rod prior to sintering - 0.1427 cm
- 5) Overall average length of wire 135.84 cm
- 6) Average weight of assembled wire 9.32 gms (based on the measured weight of 20 wires)
- 7) Average weight of $B_{10}C$ in wire 4.06 gms

2. Polyethylene Rods

Given below are the major physical properties of the polyethylene rods:

Average density of rods	0.96 gms/cc
OD of rods	0.218 cm
Length of rods	132.1 cm
Chemical composition	CH_2

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TABLE B-2

$B_{4}^{10}C$ POISON WIRE WORTH
MEASUREMENTS ON PAX-C

Case Number	<u>$B_{4}^{10}C$ Wires/Element</u>		<u>CH_2 Rods/Element</u>		<u>Totals</u>	
	000	A Row	000	A Row	$B_{4}^{10}C$	CH_2
1	1	0	18	0	6	108
2	1-1/3	0	17-2/3	0	8	106
3	1-1/2	0	17-1/2	0	9	105
6	1-1/2	1-1/2	17-1/2	17-1/2	63	735
7	0	1-1/2	17-1/2	17-1/2	54	735
8	0	1-1/2	0	17-1/2	54	630
9	1-1/3	1-1/3	17-2/3	17-2/3	56	742
10	0	1-1/3	17-2/3	17-2/3	48	742
11	0	1-1/3	0	17-2/3	48	636

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TABLE B-3

B_{4C}^{10} MEASUREMENTS IN PAX-C

B_{4C}^{10} and CH_2 Changes to Core	Case No.	B_{4C}^{10} Wires Per Element		CH_2 Rods Per Element		Total Core Inventory		Core Reactivity Changes - β		Unit Worths β		Degree of Flooding
		000	A-Row	000	A-Row	B_{4C}^{10}	CH_2	This Step	Total	B_{4C}^{10}	CH_2	Percent
Basepoint	Base	0	0	0	0	0	0	0	0	---	---	---
Add 6 B_{4C}^{10} to 000		1	0	0	0	6	0	-35.6 $\pm$ 1.1	-35.6 $\pm$ 1.1	-5.9 $\pm$ 0.2	---	0
Remove 3 B_{4C}^{10} from 000		1/2	0	0	0	3	0	17.3 $\pm$ 0.3	-18.3 $\pm$ 1.2	-5.8 $\pm$ 0.1	---	0
Add 3 B_{4C}^{10} and CH_2 to 000		1	0	9	0	6	54	13.3 $\pm$ 0.3	- 5.0 $\pm$ 0.8	---	---	44.6
Add 27 CH_2 to 000		1	0	13-1/2	0	6	81	+18.5 $\pm$ 0.4	+13.5 $\pm$ 0.9	---	0.68 $\pm$ 0.02	67.0
Add 27 CH_2 to 000	1	1	0	18	0	6	108	+19.7 $\pm$ 0.4	33.2 $\pm$ 1.4	---	0.73 $\pm$ 0.01	89.7
Remove 2 B_{4C}^{10} from 000		2/3	0	18	0	4	108	21.9 $\pm$ 0.4	55.1 $\pm$ 2.0	-11.0 $\pm$ 0.2	---	89.7
Add 5 B_{4C}^{10} to 000 Remove 3 CH_2 from 000	3	1-1/2	0	17-1/2	0	9	105	-55.0 $\pm$ 1.6	0.1 $\pm$ 0.8	---	---	89.7
Remove 1 B_{4C}^{10} from 2 000 Add 1 CH_2 to 000	2	1-1/3	0	17-2/3	0	8	106	10.8 $\pm$ 0.2	10.9 $\pm$ 1.1	---	---	89.7
Remove 2 B_{4C}^{10} from 1 000 Add 2 CH_2 to 000		1	0	18	0	6	108	23.0 $\pm$ 0.5	33.9 $\pm$ 1.5	---	---	89.7
Add 18 B_{4C}^{10} and 210 CH_2 to A row Add 3 B_{4C}^{10} to 000 Remove 3 CH_2 from 000		1-1/2	1/2	17-1/2	5-5/6	27	315	-38.1 $\pm$ 1.1	-4.2 $\pm$ 0.9	---	---	---
Add 36 B_{4C}^{10} and 420 CH_2 to A row	6	1-1/2	1-1/2	17-1/2	17-1/2	63	735	-104.2 $\pm$ 3.0	-108.4 $\pm$ 3.9	---	---	89.7
Remove 2 B_{4C}^{10} from A row		1-1/2	1-4/9	17-1/2	17-1/2	61	735	18.5 $\pm$ 0.4	-89.9 $\pm$ 3.3	-9.2 $\pm$ 0.2	---	89.7
Remove 3 B_{4C}^{10} from A row		1-1/2	1-1/3	17-1/2	17-1/2	58	735	28.9 $\pm$ 0.6	-61.0 $\pm$ 2.6	-9.6 $\pm$ 0.2	---	89.7
Remove 1 B_{4C}^{10} from 9 000 Remove 1 B_{4C}^{10} from A row Add 1 CH_2 to 000 Add 7 CH_2 to A row		1-1/3	1-1/3	17-2/3	17-2/3	56	742	24.5 $\pm$ 0.5	-36.5 $\pm$ 2.0	---	---	89.7
Remove 3 B_{4C}^{10} from A row		1-1/3	1-1/4	17-2/3	17-2/3	53	742	32.1 $\pm$ 0.6	-4.4 $\pm$ 1.1	-10.7 $\pm$ 0.2	---	89.7
Remove 3 B_{4C}^{10} from A row		1-1/3	1-1/6	17-2/3	17-2/3	50	742	33.4 $\pm$ 0.7	29.0 $\pm$ 1.8	-11.1 $\pm$ 0.2	---	89.7
Remove 2 B_{4C}^{10} from 000		1	1-1/6	17-2/3	17-2/3	48	742	25.2 $\pm$ 0.5	54.2 $\pm$ 2.3	-12.6 $\pm$ 0.3	---	89.7
Add 6 CH_2 to A row		1	1-1/6	17-2/3	17-5/6	48	748	3.7 $\pm$ 0.1	57.9 $\pm$ 2.4	---	0.62 $\pm$ 0.01	89.7

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TABLE B-3 (Continued)

B_4C and CH_2 Changes to Core	Case No.	B_4C Wires Per Element		CH_2 Rods Per Element		Total Core Inventory		Core Reactivity Changes - β		Unit Worths β		Degree of Flooding
		000	A-Row	000	A-Row	B_4C	CH_2	This Step	Total	B_4C	CH_2	Percent
Add 6 B_4C to A row Remove 6 CH_2 from A row Add 2 B_4C to 000		1-1/3	1-1/3	17-2/3	17-2/3	56	742	-94.5 $\pm$ 2.8	-36.6 $\pm$ 2.1	---	---	89.7
Remove 2 B_4C from 000		1	1-1/3	17-2/3	17-2/3	54	742	23.4 $\pm$ 0.5	-13.2 $\pm$ 1.4	-11.7 $\pm$ 0.2	---	89.7
Remove 2 B_4C from 000		2/3	1-1/3	17-2/3	17-2/3	52	742	25.3 $\pm$ 0.5	12.1 $\pm$ 1.4	-12.7 $\pm$ 0.2	---	89.7
Remove 2 B_4C from 000	10	0	1-1/3	17-2/3	17-2/3	48	742	27.8 $\pm$ 0.6	66.7 $\pm$ 2.7	-13.9 $\pm$ 0.3	---	89.7
Remove 106 CH_2 from 000	11	0	1-1/3	0	17-2/3	48	636	-72.0 $\pm$ 2.2	-5.3 $\pm$ 1.3		0.68 $\pm$ 0.02	---
Add 106 CH_2 to 000 Remove 6 CH_2 from A row Add 6 B_4C to A row	7	0	1-1/2	17-2/3	17-1/2	54	736	2.2 $\pm$ 0.1	3.1 $\pm$ 1.2	---	---	---
Remove 106 CH_2 from 000	8	0	1-1/2	0	17-1/2	54	630	-66.4 $\pm$ 2.0	-69.5 $\pm$ 2.9	---	0.62 $\pm$ 0.02	---
Remove 12 B_4C and 222 CH_2 from A row		0	1-1/6	0	11-1/3	42	408	3.0 $\pm$ 0.1	-66.5 $\pm$ 2.8	---	---	---
Remove 24 B_4C and 408 CH_2 from A row		0	1/2	0	0	18	0	-30.0 $\pm$ 0.6	-96.5 $\pm$ 3.4	---	---	0
Remove 5 B_4C from A row		0	13/36	0	0	13	0	26.6 $\pm$ 0.5	-69.9 $\pm$ 2.8	-5.3 $\pm$ 0.1	---	0
Remove 5 B_4C from A row		0	2/9	0	0	8	0	27.2 $\pm$ 0.5	-42.7 $\pm$ 2.2	-5.4 $\pm$ 0.1	---	0
Remove 5 B_4C from A row		0	1/12	0	0	3	0	28.9 $\pm$ 0.6	-13.8 $\pm$ 1.5	-5.7 $\pm$ 0.1	---	0
Remove 3 B_4C from A row		0	0	0	0	0	0	17.9 $\pm$ 0.4	5.9 $\pm$ 1.2	-5.9 $\pm$ 0.1	---	0

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of major interest, a number of figures which are cross-referenced by case number to table B-2 and which show the poison and polyethylene positions for typical cases are included in figures B-2 through B-7. Also given in table B-3 are the percentages of effective flooding that existed in the central core section for the measurements of major interest. These percentages are based on the fraction of polyethylene that was in the test section for each measurement. The data from which these flooding percentages were obtained are given in table B-4. Depending on the flooding and poison array used, the flooding percentage varied from 89.5 to 90 percent which gives an average flooding condition of 89.7 percent. This average flooding percentage has been used in all cases since the accuracy of the actual percent flooding is probably ± 1.0 percent. From the measurements that were obtained with the central 000 cluster and the A-row clusters at the maximum flooding condition (89.7 percent flooded), the effect of various arrays of flexible $B_{4}^{10}C$ poison wires was determined and is shown in figure B-1.

In addition to the data obtained under fully flooded conditions, several other graphical presentations of the data obtained in the experiment are shown in figures B-8, 9 and 10. Figure B-8 indicates the reactivity effect produced in the central cluster as the degree of flooding is varied with one $B_{4}^{10}C$ wire per element in the 000 cluster. Also shown are the reactivity effects that could be expected to exist with various other poison arrays as the degree of flooding is varied. These latter cases assure that the shape of the curves obtained with the other poison arrays are the same as that obtained with one poison wire per element.

Figure B-9 indicates the reactivity effects produced when the number of poison wires in the 000 central cluster is varied under full flooding conditions in the 000 and A-row. Also shown is the data in figure B-8 with full flooding in the 000 cluster and no flooding in the A-row. In addition to the complete set of data obtained for a given poison inventory in the A-row (1-1/3 wires per element), a number of points are plotted showing the effect on reactivity with zero wires in 000 and differing amounts of poison in the A-row.

Figure B-10 shows some of the poison wire worths as a function of the number of wires in the core for both flooded and dry conditions. From this data it can be seen that the dry and flooded worths of the poison wires vary to a great extent, depending on the number of wires

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- POISON WIRES
- ⊕ POLYETHYLENE RODS
- EMPTY

610730-6-4

Figure B-2. PAX Test Flexible Poison Wires - Case 1

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● POISON WIRES
⊕ POLYETHYLENE RODS
○ EMPTY

610730-16B

Figure B-3. PAX Test Flexible Poison Wires - Case 2

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- POISON WIRES
- + POLYETHYLENE RODS
- EMPTY

610730-15B

Figure B-4. PAX Test Flexible Poison Wires - Case 3

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Figure B-5. PAX Test Flexible Poison Wires - Case 6

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Figure B-6. PAX Test Flexible Poison Wires - Case 7

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- POISON WIRE
- ⊕ POLYETHYLENE RODS
- EMPTY

610730-10B

Figure B-7. PAX Test Flexible Poison Wires - Case 8

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Figure B-8. Poison Wire Effectiveness as a Function of the Degree of Flooding

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Figure B-9. Core Reactivity Under Various Poisoning and Flooding Conditions

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Figure B-10. Poison Wire Worth as a Function of Density - PAX-C Core

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TABLE B-4

PAX-C CENTRAL REGION DEGREE OF FLOODING DATA

The flooding percentages given below are based on the basic modular unit of one cluster in the PAX-C core.

Volume of cluster (contained)	$2.929 \times 10^3 \text{ cm}^3$
Volume of cluster void	$0.788 \times 10^3 \text{ cm}^3$
Volume of $B_{10}^{10}C$ wires per cluster	$0.027 \times 10^3 \text{ cm}^3$
1 wire per element	
Net volume of cluster void	0.761×10^3
1 wire per element	
Volume of polyethylene rods per cluster	
1) 18 rods per element (108)	0.533×10^3
2) 13-1/3 rods per element (81)	0.400×10^3
3) 9 rods per element (54)	0.266×10^3
Percent void occupied by polyethylene	
1) 18 rods per element (108)	70.0%
2) 13-1/3 rods per element (81)	52.5%
3) 9 rods per element (54)	35.0%
Percent flooding by H ₂ O	
1) 18 rods per element (108)	90.0%
2) 13-1/3 rods per element (81)	67.0%
3) 9 rods per element (54)	44.6%
(The H content in H ₂ O is 9/7 times the H content in polyethylene.)	
Average flooding percentage for the 18, 17-2/3, and 17-1/2 polyethylene rods per element case	89.7%

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in the core. This is due to a neutron energy spectrum change and possibly a mutual shadowing effect between wires.

During the measurements, a very noticeable effect arose in the reduction in the incremental drum worths of the PAX-C drums. This effect was taken into account in calculating the reactivity effect produced by a given core change. These effects, which were caused by the addition of the polyethylene rods and the flexible poison wires in the 000 and A-row clusters, have been plotted in figure B-11 along with the previously measured incremental drum worths obtained during the initial reactivity shimming of the PAX-C core described in Section III. As can be noted from the curve, the reduction of the incremental drum worths is about 4 to 8 percent, depending on the degree of flooding and the poison inventory. Of particular interest are the incremental worths obtained with only the flexible poison wires in the core. From these data points, it can be seen that the incremental worths are lower by about 4 percent than those obtained with the standard poison wires in the core. This indicates that the redistribution of flux in the reactor with the flexible wires is different than with the standard wires present.

E. EXPERIMENTAL UNCERTAINTIES

The major uncertainties encountered during the measurements fall into three categories:

- 1) Those associated with the reproducibility of critical configurations and variations in the measurement of successive periods during any one measurement,
- 2) Those associated with the uncertainty in the incremental drum worths, $\frac{\Delta \rho}{\Delta \theta}$, and
- 3) Those associated with the uncertainty involved in converting a measured period to a reactivity using the "inhour" relationship $\delta \rho$.

Of the three uncertainties listed above, the first was determined for each measurement by checking the variation in the reactor period and applying a fixed uncertainty due to core variations and drum angle variations. In most cases, it was found that the magnitude of this error was about 2 percent in reactivity. The second type error involving the unknown in the incremental drum worths was an assigned error of about 3 percent. The error associated with the conversion of a period to a reactivity, using the "inhour" relationship, was taken as being 2.5 percent of the reactivity shift from the base reactivity. The following method was

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Figure B-11. PAX-C Drum Worths as a Function of the Degree of Flooding

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employed in applying the various uncertainties to the measurements:

If the reactivity values obtained for each of the measurements are $\rho_1, \rho_2, \rho_3, \dots, \rho_n$, then the uncertainty involved in each individual measurement is $\Delta\rho_1, \Delta\rho_2, \Delta\rho_3, \dots, \Delta\rho_n$, and each $\Delta\rho_i$ is based on either the uncertainty in the period measuring system or the uncertainty in the incremental drum worths depending on which of these two systems was employed in the particular measurement. The total reactivity change and its associated uncertainty for any number of successive measurements from 1 to n is obtained as follows:

$$\rho_T = \sum_{i=1}^n \rho_i \pm \left(\sqrt{\sum_{i=1}^n (\Delta\rho_i)^2} + \delta\rho \right)$$

The $\delta\rho$, which is based on the "inhour" uncertainty, is applied to the total change, ρ_T , i.e.,
 $\delta\rho = 0.025 \times \rho_T$.

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APPENDIX C

REFERENCES

- ¹ WANL-TME-603, Selection of Material, Number and Distribution of Poison Wires for Anti-Criticality Poison Wire System, November 1963 (CRD)
- ² WANL-TNR-155, Status Report on the Anti-Criticality Poison Wire System, March 1964 (CRD)
- ³ WANL-TME-1172, Status Report on the Flexible Poison Wire Development, May 1965
- ⁴ G. V. Samsonov, Handbooks of High-Temperature Materials, Volume 2-Properties Index, Plenum Press, New York, 1964
- ⁵ LA-3227-MS, Effects of Adding Hydrogenous Materials to KIWI Reactors, March 1964 (CRD)
- ⁶ WANL-TME-713, NRX-A Core Compaction Program, March 1964 (CRD)
- ⁷ Private Communication, L. D. P. King, LASL, to J. M. Bridges, WANL, October 1964
- ⁸ WANL-TNR-148, Safety Analysis Report - NRX Testing, April 1964
- ⁹ WANL-TME-546, Feasibility of a Full Core Nuclear Poison System for use During RIFT Launch Operations, September 1963
- ¹⁰ WANL-TME-840, Reactor Analysis Handbook, February 1965, (CRD)
- ¹¹ WANL-TME-1091, Improved Nuclear Design Method for NERVA Calculations - NSDM-II, March 1965 (CRD)
- ¹² IDO-16898, TOPIC - A Fortran Program for Calculating Transport of Particles in Cylinders, April 1964
- ¹³ WANL-TME-603, Selection of Material, Number and Distribution of Poison Wires for the Anti-Criticality Poison System, November 1963

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