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Westinghouse Astronuclear Laboratory

STATUS REPORT ON FLEXIBLE POISON WIRE DEVELOPMENT

MASTER

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TME-1172

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INTRODUCTION

This report presents the developmental status of the Anti Criticality Poison Wire System (ACPS) designed to prevent accidental criticality of the NERVA reactor. Wires of neutron absorbent material are inserted into the core coolant channels in order to provide shutdown of the reactor. A safety system of this type must be effective under all normal environmental conditions and such credible accident situations as fire, explosion and water immersion. The control drums alone do not provide sufficient poison to prevent criticality if the reactor should become immersed in water.

Conceptual design efforts and tests are being conducted at WANL to develop a neutron poison wire system with an extraction mechanism. The proposed procedure is to insert high neutron cross section capture material into a number of the coolant channels of the reactor core. A neutron poison material is encapsulated in one or more outer casings thus constituting a "poison wire".

For shipping purposes, the present poison wires use a boron carbide core encased in a stainless steel sheath with an outer jacket of polyethylene. These wires are not flexible and must be inserted or removed in close alignment with the coolant channel. Utilization of this method prevents installation of the wires in the peripheral areas of the core when the nozzle is attached. The wires are approximately 0.082 inch in diameter with a 54 inch active length. A total of 6648 wires are currently being used to provide an adequate shutdown safety margin.

The practical upper limits of the number of wires that can be removed through the nozzle throat of a flight system is approximately 3000. Regardless of the neutron poison material used, a significantly high percentage of the wires must be located in areas not directly in line with the nozzle throat opening. The wires must therefore be fairly flexible in order to facilitate their removal from the nozzle.

The physical limitations described above will determine the basic requirements for a flight type poison wire system; briefly, these are:

- 1) The length and diameter of the poison wires are limited by the dimensions of the core coolant channels.
- 2) The total cross-sectional area of the poison wires must be within the size limitations of the nozzle throat.
- 3) The wires must be flexible in order to converge in the throat of the nozzle during removal.
- 4) The wires must be capable of insertion and removal without damage to themselves, the reactor or the nozzle.

Design analysis and test programs have been successfully conducted which have demonstrated the feasibility of the above test requirements.

SECTION 1

FLEXIBLE WIRE REQUIREMENTS

The design criteria for the flight type poison wires were based on the functional requirements stated in the Introduction. These criteria should be considered tentative since the information in certain areas of operation and under accident conditions have not been completely defined for the NERVA I engine. For purposes of this study, it is assumed that the poison wires will be used in a NERVA engine as the third stage of a Saturn V vehicle. Each design criterion has been derived from the most current information and will indicate a source reference. If any of the design criteria become particularly restrictive to the orderly development of the program, the justification for the requirement will be reviewed. As more complete information becomes available, it will be incorporated. These criteria have been separated into two categories; the requirements under normal operating conditions and under the maximum credible accident conditions. The criteria refer only to the poison wire component of the ACPS.

1-1 NORMAL OPERATING CONDITIONS

A Environmental Requirements

- 1) Poison wires must be able to withstand pressure conditions from 79.5 mm Hg to 10^{-8} Torr¹.
- 2) The wires must be able to function at a high temperature of 160°F¹.
- 3) The wires must be functional at a low temperature of -100°F. Since this is an arbitrary value, no temperature profiles have been set. Previous space flight information indicates that the temperature range can be controlled by the paint color and pattern on the outside of the nozzle.
- 4) The wires must be functionally operative in humidity conditions from 0 to 100 percent¹.
- 5) The wires must have a useful storage life of at least two years under ambient conditions and remain operationally functional. NOTE: While this is an arbitrarily selected time requirement, it seems reasonable for this purpose.

¹ WANL-TME-576, Contract Year 1963, Administrative Summary Presentation, October 22, 23, 1963; November 1963; (CRD)

6) There are no radiation environment requirements for the poison wires since the sole function of the wires is to prevent accidental criticality of the reactor.

B Materials Requirements

1) All poison wire materials will have the minimum weight consistent with other requirements as determined by a flight system.

2) All materials in their final assembled form must be capable of functioning with a 2.0 inch bend radius without damage. Any bundled group of wires must have a useful bend radius of not less than 6.0 inches. Pull and bend tests indicate that these are reasonable, functional values.

3) The wire outer cover which will come in contact with the reactor will be a smooth, soft plastic material which will prevent any damage under normal operating conditions.

4) The neutron absorbing material should be selected on the basis of its ability to maintain a balance between adequate shutdown and weight economy required for a flight system.

5) The assembled wires must not have an elongation greater than 0.5 percent between 70°F and their maximum operating temperature. This requirement is a function of the length of the wires and the length of the coolant channels in which they are inserted.

6) The minimum tensile strength of the wires will be 20 pounds. The maximum anticipated pull load on a wire is approximately 1.0 pound; thus providing a safety factor of 20.

7) The wire material will be dual encased in order to isolate the neutron poison from the reactor.

C. System Functional Requirements

1) The wires must be able to withstand extraction from the reactor at a rate of 6 to 10 inches per second without damage to the reactor, the nozzle, or the wires themselves. A maximum wire extraction time of 10 seconds is a functional requirement.

2) The wires must be flexible enough to facilitate extraction from the reactor through the nozzle throat. This is the only readily available route for removal of the wires.

3) The wires must be so designed that they will remain in the reactor under the acceleration conditions of the vehicle².

4) It is not necessary to consider the reinsertion of the poison wires in the reactor. The removal of the wires has been defined as a one time, one way, non-reversible process.

D. Mechanical Feature Requirements

1) The diameter of the active wire section inserted into the reactor will not exceed 0.084 inch at ambient temperatures or more than 0.086 inch at the maximum operating temperatures. The size of the coolant channels in the reactor and the ease of extracting the wires dictate these dimensions.

2) The practical limit of the number of poison wires which can be extracted through the nozzle is approximately 3,000.

3) A material having a low coefficient of friction should be used on the outer covering of the wires in order to reduce the extraction force required.

4) The wires will be designed so as to prevent an insertion depth greater than 51.0 inches. Inserting the wires any further could damage the coolant channel orifices.

5) The tips of the wires inserted in the coolant channels should be so designed as to minimize the peak loading conditions due to bending moments. The maximum load occurs as the tips are pulled out of the support blocks. Tapering or the use of a soft coating will minimize any tendency to chip the support block or the block coating material.

6) The poison wires should be capable of reuse and extraction through the nozzle a minimum of five times. This figure is in addition to any performance test or check-out of the wires. This requirement provides a functional safety factor for the wires and also includes provision for their reuse as shipping wires.

2 WANL-TME-476, NERVA Reactor Environment; August 1963; (CRD)

E. Neutronic Requirements

1) The wires will provide at least a $0.95K_{\text{eff}}$ shutdown of the reactor with the control drums in their most reactive (reflective) position and with the reactor submerged in water. The $0.95K_{\text{eff}}$ number has been selected as a reasonable value commensurate with unknown variables and the limitations of the computational techniques. As system assurance develops and empirical data on the "worth" of wires become available the K_{eff} number may be raised as conditions justify.

1-2 MAXIMUM CREDIBLE ACCIDENT CONDITIONS

The ACPS is required to prevent accidental criticality of the reactor during any handling or shipment of the reactor when the nozzle is attached, during launch pad operations, during launch of the vehicle and during the early flight stages of the vehicle. Credible accident conditions place special requirements on the wires.

A. Fire Accident Requirements

1) AEC regulations, AEC-489, Chapter 0529 "Safety Standards for the Preparation of Radioactive and Fissile Material for Transportation" refers to NFPA-251 which define the maximum credible fire during shipment of special nuclear materials as exposure of the vessel to a heat profile that produces temperatures up to 1700°F in a one hour period. Temperature profiles for this condition have not been calculated for the NERVA reactor. Preliminary laboratory tests utilizing a support block and a bunsen burner indicate stabilization temperatures in the center of a cluster at approximately 1200°F . Until further information is available, the arbitrary definition that the poison wires must maintain their position under a 1 g load at 1500°F will be used as a basis for design criteria.

2) Information on Lox-Hydrogen and launch pad fire are currently under investigation.

B. Explosion Accident Requirement

1) Launch pad explosions and Lox-Hydrogen explosions are currently being investigated.

C. Impact and Compaction Accident Requirements

1) LASL KIWI impact testing indicates that no compaction of the core is likely to occur unless there is sufficient velocity at impact (with a concrete surface) to rupture the pressure vessel^{3, 4}. Further study is necessary to determine the cleavage profile of the reactor under such conditions.

2) The poison wires will be designed to stay in the reactor as long as the pressure vessel is intact regardless of the impact force.

3) The wires will be designed to break and remain in the coolant channels of the fuel elements if the elements are broken apart by shear rupture along their horizontal axis.

4) Analytical studies of the reactor compaction and the effects on poison wires are scheduled for this contract year.

D. Water Immersion and Hydrogenous Material Accident Requirements

1) Water immersion requirements for a reactor are discussed in Section 1, E (1).

2) Compaction and water immersion of the reactor is scheduled for analytical study this contract year.

3) The ACPS will be designed to prevent the ejection of the poison wires by retarding the accidental flow of hydrogen from the propellant tank.

4) The neutron poison and other materials used in the wires will be selected for the quality of being insoluble in sea water and the capability of withstanding corrosion or erosion when submerged for a period of one year.

3 WANL-TME-713, Core Compaction Program; March 15, 1964; (CRD)

4 LAMS- 2998, Radiation Transmission Measurements On Two KIWI Model Impact Tests; January 3, 1964; (CRD)

SECTION 2

SELECTION AND EVALUATION OF POISON WIRE MATERIALS

The selection of the neutron absorbing material for the poison wire core has undergone considerable investigation. In particular, the requirement that the wires be flexible under all operating conditions involved many factors. The principal items evaluated were:

- 1) Neutronic characteristics of the poison wire materials including the number and distribution of wires required for adequate protection of the reactor.
- 2) Factors affecting the functional capability of the poison wire materials. Such aspects as tensile strength, flexural characteristics, material form, stability under extreme environments, etc., were considered.
- 3) Poison wire manufacturing techniques, processes, and costs. Prototype poison wires were produced in some cases.

A study was conducted by the reactor analysis group on the use of alternate poison wires for shipping purposes. The presently used boron carbide (B_4C) wires encased in stainless steel are not flexible and are expensive to manufacture. It is desirable to have the shipping wires flexible and to reduce the number required. Since these objectives are the same as the flight wire requirements, this study is also pertinent to flight program analysis.*

In addition to B_4C the following materials were considered: Boron ten (B^{10}) in stainless steel, hafnium (Hf), gadolinium (Gd) and an alloy of silver (Ag), indium (In), and cadmium (Cd). All of these materials required more than 3900 wires. Since we have a limit of approximately 3000 wires for the flight system, these materials were not considered acceptable for this application. With the elimination of other possible poisons, our efforts have been directed toward the development of wires using a suitable form of B^{10} .

*See Appendix A

2-1 BORON EVALUATION

Early studies clearly indicated that from a strictly neutronic standpoint the (B^{10}) isotope would be the most effective neutron absorber that could be used in the poison wires for the NERVA reactor. As a consequence of this consideration, most of our efforts were directed toward finding the most suitable form of this material that could be used in the wires.

Naturally occurring boron contains only 18.8 percent of the B^{10} isotope. It requires 6648 of the non-flexible shipping wires to provide adequate safety for the reactor. These wires use boron in the form of B_4C as the poison material.

Isotopically separated B^{10} is available from the Government in two forms. One form is amorphous B^{10} , which can be obtained with up to 92 percent by weight w/o enrichment, and crystalline B^{10} , some of which is available to 94 w/o enrichment of B^{10} . The problem was to select the best and most economical form in which this material could be used.

Selection of B^{10} Containing Poison Material

Boron in its natural chemical state oxidizes very rapidly at temperatures above $700^{\circ}F$. The resulting compound of boron oxide is soluble in water. Since part of the criteria was the possible exposure of the poison wires to high temperatures due to fire with the probable subsequent immersion in water, the consideration of the use of pure boron material was eliminated.

A review of other boron compounds which could possibly be used was initiated. Boron carbide (B_4C), boron silicide (B_6Si), and aluminum boride ($B_{12}Al$), all showed promising characteristics. See table 2-1 for a comparison of boron compounds. All of these compounds have a very high temperature stability. They are not soluble in water and are potentially usable forms as far as criteria is concerned. As shown in table 2-1, $B_{12}Al$ contains a higher percentage of boron by weight and atoms per cubic centimeter than the other listed compounds. $B_{12}Al$ has been produced in very limited quantities and the manufacturing process is expensive. Additionally, it is extremely difficult to obtain high purity material. The best available purity of commercial $B_{12}Al$ is about 83 percent. As contrasted with this experience on $B_{12}Al$, relatively large quantities of B_4C and enriched boron carbide ($B_4^{10}C$) have been produced with purities better than 98 percent. The conversion techniques and characteristics are well known.

TABLE 2-1
BORON COMPOUND COMPARISON

Natural Boron (18.8% Boron 10) Ingredient

Compound	Molecular Weight	Specific Weight gm/cc	Specific Boron Weight gm/cc	Boron Percentage by Weight	Specific Weight Boron 10, gm/cc	Boron Atoms/cc $\times 10^{-23}$	Boron 10 Atoms/cc $\times 10^{-23}$	Relative Boron 10
(N/18.8)*B	10.82	2.34	2.34	100	0.44	1.30	0.26	0.22
(N/18.8) B ₄ C	55.3	2.52	1.97	78.3	0.37	1.10	0.22	0.18
(N/18.8) B ₆ Si	93.0	2.47	1.72	69.8	0.32	0.96	0.19	0.16
(N/18.8) B ₁₂ Al	156.8	2.58	2.14	82.8	0.40	1.19	0.24	0.20
(N/18.8) B N	24.8	2.20	0.96	43.6	0.18	0.54	0.11	0.09
(E/92)**B	10.10	2.18	2.18	100	2.01	1.30	1.20	1.00
(E/92) B ₄ C	52.4	2.39	1.84	77.0	1.69	1.10	1.02	0.85
(E/92) B ₆ Si	88.7	2.34	1.59	68.0	1.46	0.96	0.88	0.73
(E/92) B ₁₂ Al	148.2	2.44	2.00	82.0	1.84	1.19	1.10	0.92
(E/92) B N	24.1	2.14	0.90	42.0	0.83	0.54	0.50	0.42

*Natural boron percentage

**Enriched boron percentage

In addition, B_4C is readily available for development investigation at a cost of from \$12 per pound to \$45 per pound depending upon the purity requirement and the form in which it is purchased. A considerable amount of information and experience has already been gained on the high density extrusion and compaction processes of B_4C . The other compounds considered contained a much lower percentage of boron than does the B_4C . Taking all of these factors into consideration, B^{10}_4C has been selected as the most practical material to use as a neutron absorber in the poison wires.

2-2 BORON CARBIDE DEVELOPMENT

B_4C is manufactured in the form of a black powder ranging over a wide variety of particle sizes. It can be readily obtained in grades or blends of from 100 to 1 micron sizes. In its natural particle or crystalline form it is very hard and abrasive. B_4C is chemically stable and begins to melt at $2280^{\circ}C$. It is insoluble in water, non-corrosive and does not react with any common organic solvents. All of these characteristics are ideal for the poison wire application under consideration.

The WANL specifications for the chemical composition of B_4C powder is as follows:

<u>Element</u>	<u>Range or Limit, Per Cent*</u>
Boron (total)	76.0 - 80.0
Boron ¹⁰ **	17.50 - 18.85
Boron (total) plus Carbon	98.0 - 99.5
Iron	0.50 max.
Silicon	0.50 max.
Aluminum	0.20 max.
B_2O_3	1.50 max.
Water	0.20 max.
Other Impurities, each	0.10 max.
Other Impurities, total	0.50 max.

*As stated in PDS 30036-B.

**As determined by isotopic analysis.

From the beginning of WANL studies on the use of B_4C for flexible poison wires, it has been recognized that the main problem would be to get as much of this material into a core area of a poison wire as reasonably possible and still maintain the flexibility. Thus the actual packing factor or apparent density of the finished material was an important consideration.

The theoretical density of this material is 2.52 grams per cubic centimeter. The apparent density of the B_4C will vary greatly depending upon what form it is in. The following table 2-2 shows the percentage of the theoretical density obtained by this material in different forms. The impurities that usually run from one to two percent by weight are neglected.

TABLE 2-2
DENSIFICATION OF B_4C POWDERS

<u>Form of B_4C</u>	<u>% of Theoretical Density</u>
1. B_4C powders as received	58 to 64
2. B_4C powders vibrated	65 to 68
3. Extrusion compaction of B_4C in S.S. sheaths (laboratory process)	86 max.
4. Extrusion compaction of B_4C in S.S. sheaths (production of shipping wires)	80 min. 85 max.
5. B_4C with added ethylene glycol to make a viscous material	40 to 45
6. Norton Company, B_4C laboratory sample of 0.062 inch diameter rods (extrusion and sintering)	89 to 91
7. Norton Company, B_4C pilot production of 0.062 inch diameter rods (extrusion and sintering)	81 to 89
8. Norton Company, B_4C pilot production of 0.058 inch diameter rods (extrusion and sintering)	Not sinterable
9. Norton Company, B_4C Hot press production of cylindrical shakes	99.5

Determination of Density Requirements for $B_{4}^{10}C$

Neutronic calculations indicated that 92 percent density boron would be the most effective available neutron absorber. The self shielding affect of the higher density materials does not substantially reduce the effectiveness as a neutron poison in the particular geometry being contemplated. Additional calculations on this subject are currently being conducted. Available data clearly indicate that any increase in B^{10} concentration obtainable in boron carbide enriched with boron ten isotope ($B_{4}^{10}C$) will reduce the number of poison wires required. Preliminary calculations show a requirement of approximately 2600 to 2900 wires for a 90 to 80 percent of theoretical density of $B_{4}^{10}C$. The current extraction system design limits the number of wires that can be used to approximately 3000. These considerations establish the practical range of $B_{4}^{10}C$ densification as being between 80 and 90 percent.

Boron Carbide Development by the Norton Company

The Norton Company supplied the $B_{4}C$ powders that were used in a mechanically compacted form for the current shipping poison wires. In connection with this effort, the Norton Company produced a small laboratory quantity of extruded and sintered $B_{4}C$ rods about 3 inches long and $0.062 \pm .001$ inch in diameter. These rods were 90 ± 1.5 percent of theoretical density. Chemical analysis showed these samples to be 98 percent pure $B_{4}C$.

Figure 2-1 shows a 50 power photograph of the cross sections of these $B_{4}C$ rods. The dark spots are voids or depressions. The $B_{4}C$ crystals are very regular and compact.

On the basis of these samples, the Norton Company was awarded a lump sum contract to produce a pilot production run of $B_{4}C$ rods. The purchase order was for a minimum of 1.5 pounds each of 0.058 ± 0.002 inch and 0.062 ± 0.002 inch diameter rods with a minimum of 85 percent apparent density of $B_{4}C$.

After many repeated extrusion and sintering runs, very few of the rods met either the dimensional or density requirements. In addition, there was extreme difficulty in sintering smaller diameter rods. During the sintering heat treatment, the smaller rods would either melt and flow or react with the graphite trays.

The Norton Company used a $B_{4}C$ powder size for which 75 percent was below 30 microns

WANL TEST RUN NUMBER 7

10 TO 45 MICRON B_4C

BINDERS METHYL CELLULOSE -3 W/O
GUM GHATTI 1 W/O

SINTERING TEMPERATURE 2200°C

APPARENT DENSITY 61.5%

WANL TEST RUN NUMBER 13

10 TO 45 MICRON B_4C

BINDER - METHYL CELLULOSE 1.0 W/O

SINTERING TEMPERATURE 2260°C

APPARENT DENSITY 65%

NORTON CO., LABORATORY SAMPLE

10 TO 30 MICRON B_4C

BINDERS METHYL CELLULOSE 23.6 W/O
TEXACO NUMBER 4 GREASE 2.6 W/O

SINTERING TEMPERATURE 2270°C

APPARENT DENSITY 90%

Figure 2-1 Boron Carbide Rods - Photomicrograph 50X

and 40 percent was 10 microns. All of the material consisted of the following mixture for extrusive sintering:

75 w/o B_4C
23.6 w/o methyl cellulose
2.6 w/o Texaco No. 4 grease

The original laboratory samples were sintered by a process which would be extremely expensive; i.e., the extruded rods were brought to $2270^{\circ}C \pm 5^{\circ}C$ in nitrogen, and were held at this temperature for a specified time and then cooled. This heating schedule was not used in the pilot production runs. Later rods were heat treated in a stoking furnace, heated by an eight inch diameter carbon resistance element. The furnace was preheated to a temperature of 2250° to $2275^{\circ}C$ with carbon boats loaded throughout the length of the furnace. The stoking mechanism was engaged to stabilize the furnace at the aforementioned temperature. The extruded B_4C rods were placed in the furnace and stoked through the heating zone which was 14 inches in length. During this heat treatment, the temperature of the B_4C rods exceeded $2280^{\circ}C$ at various instances. Since the B_4C eutectic melting occurs at $2280^{\circ}C$, the B_4C rods reacted with the graphite trays used to hold the rods during the heat treatment. It was concluded that the temperature range in the stoking furnace and the temperature gradient throughout the transfer boats exceeded the sintering zone necessary for a reasonable production process.

Laboratory tests verified the results of this operation by utilizing the same B_4C particle blend and rod shape. The following reactions occur depending on the exposure temperature.

$< 2250^{\circ}C$ no sintering of the B_4C rods.
 2260° to $2270^{\circ}C$ even sintering of the rods.
 $> 2280^{\circ}C$ eutectic melting of the rods.

After a review of the efforts and processing techniques conducted by the Norton Company, the pilot production contract was canceled.

Boron Carbide Sintering Development at WANL

As a result of the difficulties with the B_4C sintering program at the Norton Company, investigations were initiated in the WANL Materials Department to study this area. A review

of the literature and consultations with representatives of other divisions within Westinghouse who had experience with B_4C or related materials sintering brought about the following conclusions:

- 1) A near pure B_4C causes the effective sintering range to be extremely narrow.
- 2) The pure material requires a gradual temperature increase and precise control that results in an expensive manufacturing process.
- 3) A controlled variation in the particle size produces the most acceptable sintering results.
- 4) The most acceptable sintering results are produced by use of the smaller B_4C particles.
- 5) The addition of certain metallic materials and compounds lowers the required sintering temperature.
- 6) Various cover gases or vacuum will improve the sintering process.

Experimental Test Program Outline

An experimental test program was outlined at WANL in an effort to produce 0.056 to 0.058 inch diameter B_4C rods with a theoretical density of 80 to 90 percent. The proposed approach was:

- 1) To evaluate and determine the best inorganic materials which could be used as an extrusion and sintering aid.
- 2) To determine the effects of B_4C particle size and distribution on sintering.
- 3) To determine the effects of B_4C material impurities on sintering.
- 4) To study the improvement of sintering methods by furnace and equipment control.
- 5) To study the possibilities of modifying a known process for the extrusion and sintering of B_4C into rods using only organic additives.
- 6) To study the possible improvements of the sintering process by the addition of metallic sintering aids.
- 7) To evaluate other methods of obtaining high density B_4C rods.

B_4C Development Tests at WANL

Developmental tests on B_4C materials by the WANL Materials Department were conducted as follows:

1) In order to produce the B_4C rods from a powder some method must be used to form the basic shape. Efforts of this nature have been primarily directed toward a high pressure extrusion process. To accomplish this, a liquid or fluid extrusion aid must be added to the powders to form a paste which can be forced through a die. The selection of the extrusion aid or binder affects a number of factors such as the ability to extrude the material, the ability of the green material to cohere, and the sintering characteristics. Extrusion batches were prepared using various organic binders. The binders used were: Carbowax 6000, gum ghatti, Carbopal 934, Carbopal 938, and methyl cellulose. Of these, the methyl cellulose provided the best plasticity for extrusion and also produced the best green strengths. The use of 1 w/o methyl cellulose with 28 w/o distilled water also produced the best sintered material developed to date.

2) The earlier experiments were conducted with Norbide 325F B_4C powder (Norton Company). The particle size distribution is shown in table 2-3. Variations in the heat treating sintering aids and binders seemed to have very little effect on the final rods. Batch No. 13, tables 2-3 and 2-4, is typical of the test results obtained. Figure 2-2 is a cross section photographic enlargement of a rod from these tests. The large void sections and the lack of crystalline formation can be clearly seen. Identical material was further reduced in size in a tungsten carbide mill using the procedure described in table 2-5 for Batch No. 19 and 20. This reduced the average particle size from 20 to 30 microns to 10 microns. Sintering by the same process previously used increased the apparent density of B_4C from 65 to 82 percent. The theoretical increase in density for the presence of 1.5 w/o of tungsten was subtracted from the overall weight to arrive at the 82 percent number.

These encouraging results justified the purchase of 10 pounds of B_4C from the Carborundum Company with a particle size ranging from 1 to 10 microns, figure 2-3. This material was produced by a steel ball milling and acid leaching process. A preliminary sintering test on a 250 gm. batch reveals a variation in apparent density, but all samples were in excess of 80 percent of the theoretical density for B_4C . Tests are being continued on this material.

3) The most significant impurities in commercially available B_4C are iron (Fe), silicon (Si), aluminum (Al), and boron oxide (B_2O_3). Total impurities on received materials have not exceeded a quantity of 1.5 w/o. The specification PDS-30036-B allows a maximum of 2.0 w/o. The silicon will convert to SiO_2 in preference to any carbon reaction. This material is in a stable molten

TABLE 2-3
SIEVE ANALYSIS

As received		
Sieve size (microns)	Percent Retained	Cumulative Percent
60	0.8	0.8
45	6.2	7.0
30	41.3	48.3
20	36.2	84.5
10	11.6	96.1
5	0.6	96.7
Ball milled - 24 hrs.		
60	0.0	0.0
45	0.5	0.5
30	0.2	0.7
20	4.7	5.4
10	86.7	92.1
5	5.0	97.0
DENSITY		
Batch Identity	Powder Preparation	Average Density % B ₄ C
B ₄ C - 13	Powder as received	65
B ₄ C - 19	Powder milled	82
B ₄ C - 20	Powder milled 2 w/o TiO ₂ added	88

TABLE 2-4
CHEMICAL ANALYSIS
(ppm)

Element	B ₄ C - 13	B ₄ C - 19	B ₄ C - 20
Ag	<10	<10	<10
Al	110	<100	<100
Ba	<10	<10	<10
Be	<1	<1	<1
Bi	<100	<100	<100
Ca	15	4	8
Cd	<1000	<1000	<1000
Co	<100	4000	4600
Cr	<80	300	310
Cu	<10	<10	<10
Fe	500	6400	6800
K	<400	<400	<400
Li	<40	<40	<40
Mg	2.9	3.1	3.3
Mn	<40	<40	<40
Mo	58	170	180
Na	<100	<100	<100
Nb	<100	320	310
Ni	<100	250	320
Pb	<400	<400	<400
Sb	<400	<400	<400
Si	120	450	560
Sn	<400	<400	<400
Sr	<30	<30	<30
Th	<1000	<1000	<1000
Ti	680	450	9800
V	1050	370	780
W	<200	15000	15000
Zn	<2000	<2000	<2000
Zr	3300	830	860
Ta	<1000	<1000	<1000
C%	22.42	18.21	18.53
B%	77.00	78.94	77.52
Impurities %	0.58	2.85	3.95

Figure 2-2 Characteristics of Prototype Poison Wire

Figure 2-3. High Boron-Boron Carbide Particle Size Analysis

TABLE 2-5

PROCEDURE FOR NATURAL B_4C POISON WIRES

1. Equipment

- 1.1 U. S. Stoneware Jar rolling mill.
- 1.2 One-half gallon WC lined mill with WC balls.
- 1.3 Hot plate.
- 1.4 Hamilton Beach mixer, Model K with stainless steel bowl.
- 1.5 Universal No. 3 hand food chopper.
- 1.6 Loomis 37 1/2 ton extrusion press.
- 1.7 Graphite extrusion trays with 0.070 inch wide x 0.070 inch deep slots.
- 1.8 Blue M circulating air oven.
- 1.9 Consolidated Vacuum Corporation vertical vacuum furnace.

2. Materials

2.1	Norbide 325F B_4C powder	(Norton Company)
2.2	Ethylene glycol	(Fisher Scientific)
2.3	Methyl cellulose	(Fisher Scientific)
2.4	Titanium dioxide	(Fisher Scientific)
2.5	Distilled water	

3. Process

- 3.1 Weigh Norbide 325F B_4C powder to nearest 0.1 gram.
- 3.2 Add 2 w/o Ti O_2 (weighed to nearest 0.01 gram) to the B_4C powder.

TABLE 2-5 (Continued)

- 3.3 Charge $B_4C + TiO_2$ into WC lined mill that is one-half filled with WC balls.
- 3.4 Add ethylene glycol to the mill to produce a fluid.
- 3.5 Mill for 24 hours on U. S. Stoneware Jar rolling mill.
- 3.6 Pour milled fluid into a shallow tray.
- 3.7 Evaporate slowly to dryness on hot plate.
- 3.8 Complete drying in Blue M oven at $100^{\circ}C$ for four hours.
- 3.9 Weigh dry blend to nearest 0.1 gram into stainless steel mixing bowl.
- 3.10 Add 1 w/o methyl cellulose to the dry blend.
- 3.11 Mix dry for 15 minutes.
- 3.12 Add 28 w/o distilled water (add slowly while mixing).
- 3.13 Mix wet for 15 minutes.
- 3.14 Grind once through universal food chopper.
- 3.15 Charge into Loomis 37 1/2 ton press extrusion cylinder.
- 3.16 Extrude through 0.065 inch diameter die.
- 3.17 Place in graphite extrusion trays.
- 3.18 Dry in air for 12 hours.
- 3.19 Dry in Blue M oven for 4 hours at $100^{\circ}C$.
- 3.20 Sinter in CVC furnace at $2225^{\circ}C$ for 6 hours in 2/3 atmosphere helium.

state at the sintering temperatures. Al and Fe are materials commonly used for sintering aids in carbon metallic compounds. The addition of 1 w/o of Al and Fe was not found to have any significant effect on the sintering characteristics of the Norton 325F, B_4C powder. Further studies on these materials may be conducted at a later date in an effort to improve the sintering characteristics.

B_2O_3 is some what soluble in water and for this reason it is desirable to minimize the amount of this impurity for neutronic control. B_4C is readily available with less than 1.5 w/o of B_2O_3 , however, special leaching will reduce this figure to the range of .2 to .4 w/o. Tests conducted up to this date on B_4C with 1.3 w/o to less than 0.2 w/o of B_2O_3 and using 325F powder indicate no adverse affects on sintering.

4) The sintering process used at this present time is described in table 2-5. Studies are currently underway to analyze the degree of sintering at different temperatures starting at $1900^{\circ}C$. Tests are also being conducted with vertical holders instead of horizontal sintering trays in order to improve the temperatures and straightness control.

5) A number of elemental metals and metallic compounds have been used to improve the sintering characteristics of carbonaceous compounds. The effects of additives have been found particularly effective on hard to sinter materials.⁵ The most pronounced effect of such additive materials is to reduce the temperatures at which uniform sintering normally occurs. Since near pure B_4C sinters best 10° to $20^{\circ}F$ below the eutectic melting point, the ability to use much lower temperatures could be of considerable value in the relief of furnace control requirements and could substantially reduce cost.

The addition of metallic impurities would not adversely affect the neutronic poison value of the wires per se. Since the purpose of the wires is to prevent accidental criticality of the reactor, neutrons will not be available for activation of the materials. The primary concern is to maximize the total number of B^{10} atoms per unit length of the wire. Additives can increase the weight and take up space in the wires, therefore, a judicious trade off between these factors must be considered. The usual range of additive required for satisfactory sintering is between 1 w/o to 2 w/o.

5 J. Bell, Uranium Dioxide Properties and Nuclear Applications, Naval Reactors Division AEC, Section 7.3.

Literature surveys indicate that aluminum (Al), iron (Fe), cobalt (Co), nickel (Ni), Boron (B), titanium oxide (TiO_2), and cerium oxide (CeO_2) have been used in connection with B_4C sintering or with similar materials. Small samples of 2 w/o Al, Fe, and TiO_2 were added to the Norton 325F B_4C material before sintering and it was found that the additives had no significant effect on the final density of the material.

In Batch No. 20, table 2-3 and 2-4, 2 w/o of TiO_2 was added. The apparent density was increased to 88 percent compared with 82 percent for the same B_4C material without the additives.

Further studies will be conducted in the use of sintering aid additives. The affect of sintering aids which lower the eutectic melting point significantly are of particular interest.

SECTION 3

NEUTRON POISON ENCASEMENT

The ultimate purpose of a poison wire necessitates an encasement material which is flexible and of a minimum thickness. Materials used in this process must be capable of withstanding all the temperature and mechanical extremes to which the poison wires will be subjected. The specific functions of the encasement materials are to:

- 1) Isolate the B_4C core material from the reactor.
- 2) Transmit and absorb the tensile and translational forces during the extraction of the poison wires.
- 3) Maintain the geometrical configurations of the poison wires.
- 4) Permit a curved path of extraction without damage to the wire or reactor components.
- 5) Maintain poison wire integrity and resist deteriorations in the presence of extreme environmental and emergency conditions.

A review of these functions makes it clear that this problem requires the use of more than one material.

3-1 ENCASEMENT REQUIREMENTS

A. Force Filled Plastic Tube

Boron carbide powder, Norton 325 F mesh, was mixed with various organic binders and epoxies and forced into a plastic tube. This concept was discarded when a boron carbide density greater than 40 percent could not be obtained.

B. B_4C Rods Encased in Fiberglass and Metallic Braid

Boron carbide rods with a density of 80 to 90 percent were successfully produced making it possible to concentrate efforts on the development of encasement sleeves. Fortunately, similar shielding is already in use for wire and hose requiring high strength, high temperature and abrasion resistance. The common electrical or E-type fiberglass encasement combines

tensile strength and temperature characteristics capable of sustaining a load up to 1200°F. Special fiberglass, S-type is capable of sustaining loads at a temperature of 1800°F. The S-type fiberglass is relatively new and is not currently available in a wide range of sizes. However, a small number of samples were acquired for tensile and temperature testing. All prototype work on poison wire encasement has been conducted with E-type fiberglass.

A comparison of E and S braids utilizing a fiber of 0.003 inch diameter is illustrated in figure 3-1. Fiberglass braids lose their strength at elevated temperatures. This is due primarily to the effect of heat on fillers which are organic materials added in manufacturing to maintain fiber position and to act as a lubricant to prevent abrasive action between fibers. The tensile strength of E and S type sleeving braids before and after exposure to elevated temperatures is indicated in table 3-1. Braids 1 through 4 have identical weave patterns and test results indicated suitable dimensions for poison wire encasement. Braids 2 and 4 were normalized by passing them through a controlled furnace. Normalizing burns out the starch filler and reduces the tendency of the braid to unravel. The braid is finally immersed in vegetable or silicone oil to re-establish the lubricant.

2) Metallic braids of copper and stainless steel are available in a wide selection of strand configurations. Copper braids will sustain a 50-pound load up to a temperature of approximately 1800°F. Stainless steel braid will sustain a comparable load to 2200°F. These temperature values are based on handbook stress versus temperature data at low loads.

C. B₄C Rods Encased in Teflon

Teflon was selected as the most satisfactory material for B₄C encasement after an investigation of the material and consultation with DuPont. The following characteristics indicate the basis for this selection.

1) Vacuum stability: Teflon has been used extensively in space vehicles. Samples of Teflon FEP are reported to lose less than 0.1 percent of their weight in 100 hours of exposure at pressures of 10⁻⁷ mm Hg.

Figure 3-1 Comparison Between Strengths of E and S Types of Fiberglass

TABLE 3-1

FIBERGLASS SLEEVING TENSILE BREAKING STRENGTH

Braided Sleeving Designation	Type of Glass in Yarn	Treatment Subsequent to Braiding	Average Breaking Strength (Two Specimens), Lb.		
			Unheated	Heated One Hour @ 800°F	Heated One Hour @ 1000°F
1	E	None	58.8	31.2	14.6
Variation			49.4 - 68.2	28.4 - 34.0	12.5 - 16.8
2	E	Normalized and Treated	31.0	27.0	16.3
Variation			26.1 - 36.0	23.3 - 30.6	8.6 - 24.0
3	S	None	95.9	40.0	19.2
Variation			91.8 - 100.0	34.1 - 46.0	18.1 - 20.3
4	S	Normalized and Treated	33.8	29.4	16.0
Variation			28.0 - 39.5	28.6 - 30.3	11.0 - 21.1
5	E	None	69.2	27.4	19.5
Variation			61.8 - 76.6	23.0 - 31.8	16.7 - 22.3

2) Temperature stability: Teflon TFE is stable from less than -300° up to 600°F . Teflon has no liquid state at normal or low pressures but is subject to a sublimation which occurs at a negligible rate up to 100°F above the higher temperature limits indicated.

3) High tensile strength: Teflon has a tensile strength of 300 psi.

4) Low coefficient of friction: Teflon TFE has a lower coefficient of friction than any of the other materials considered for B_4C encasement. This characteristic is very significant, since it affects the extraction force and also the force applied to the reactor coolant channels.

The DuPont technical representatives recommended the application of Teflon to the braid by the use of a Teflon emulsion and sintering process. This process was previously developed for the addition of Teflon to fiberglass cloth and for the encasement of electrical wires using fiberglass sheaths. The process involves dipping the B_4C rods, encased in a fiberglass or metallic braid, into a water-Teflon emulsion and heating the wire until the Teflon sinters. At this point, the Teflon becomes a homogeneous material encasing the braid fibers and partially displacing voids. At least three separate coatings and sintering cycles were required to accumulate sufficient fiber depth and to displace the voids between the wires or fiberglass strands.

Samples of B_4C rods treated by this technique were fabricated at WANL. The test rods were 0.057 to 0.059 inch in diameter sheathed with metallic or fiberglass braid and encased in Teflon. The completed poison wire measured 0.082 to 0.084 inch in diameter. Testing of wires encased in fiberglass and Teflon produced the following information.

- 1) The breaking strength was 40 to 60 pounds.
- 2) The bend radius was less than 1.0 inch before wire damage occurred.
- 3) The force required to extract the wires from the coolant channels at a 45 degree angle was 4 to 6 ounces.
- 4) No damaging effects were apparent on the cluster block coating or the wire integrity when extracted from a coolant channel up to 50 times.

Testing of wires encased with metallic braid and Teflon produced the following information:

- 1) Testing with the copper braid produced results similar to those of fiberglass.
- 2) Testing with the stainless steel braid produced results similar to those of fiberglass with the exception of the breaking strength which was about 30 percent lower.

From a physical and functional standpoint, test results indicated that suitable poison wires could be manufactured by using the braid-Teflon-emulsion process. The metallic braid wires were significantly heavier than the fiberglass and thus were less desirable.

An irregularity on the surface of the Teflon was caused by uneven filling of the voids in the braid. Another problem was that this type of wire could not be produced by existing manufacturing techniques. Present wire encasement machinery used to apply Teflon coatings are based upon the use of long continuous wire lengths of sufficient strength to retain original configuration under the pressure of roller and pulley operations. The B_4C rods tend to separate and voids are produced unless a tension is applied to the encasement and a compression applied to the rods during fabrication. Manufacturing these wires by hand is possible; however, the process is time consuming and expensive.

An approach which utilized shrinkable Teflon tubing was reconsidered. This concept had been previously rejected due to a limited source of tubing with a wall thickness less than 0.010 to 0.012 inch. Fiberglass and metallic tubing were equally as thick and limited the B_4C rod to a 0.050 inch diameter in order to maintain the poison wire outside diameter at 0.084 inch. These conditions were not compatible with the neutron evaluations and the B_4C apparent density of 90 percent. Another possibility developed as a result of an investigation with various companies to determine the minimum wall thickness which could be obtained for Teflon shrinkable tubing and fiberglass sleeving. Through these efforts, a wall thickness of 0.007 to 0.008 inch became available for Teflon tubing; this was later reduced to a minimum of 0.0045 to 0.0050 inch.

The first attempts to use the shrinkable tubing consisted of placing the fiberglass braid over the B_4C rod, dipping and sintering one coat of Teflon TFE on the fiberglass and finally shrinking the Teflon FEP tubing in place as an outer layer. A satisfactory poison rod was produced by this method; however, the process was still cumbersome and failed to eliminate small voids between the lengths of B_4C rod. A translucent polyvinylidene fluoride (PVDF) shrinkable tubing was developed with a 0.0025 to 0.0030 inch wall thickness. This tubing was shrunk directly onto the B_4C rods making it possible to visually detect voids and conveniently weigh the B_4C material. These features are particularly advantageous from a quality control and neutronic standpoint since a positive assurance can be obtained for the amount and location of the B_4C poison.

The present laboratory technique in the development of prototype poison wires consists of the following operations:

- 1) The polyvinylidene fluoride (PVDF) tubing is shrunk onto the B_4C rods.
- 2) The thin wall fiberglass sleeving is slipped over the PVDF layer and tension is applied.
- 3) The thin wall Teflon tubing is slipped over the fiberglass and shrunk.

This method utilizes a 0.058 to 0.059 inch diameter B_4C and produces a completed poison wire with an 0.084 to 0.086 inch outside diameter, see figure 2-2. The expected weight distribution in the core section of a B_4C poison wire is illustrated in table 3-2. Preliminary testing of poison wires made by this method produced the following results:

- 1) A breaking strength of 30 to 35 pounds.
- 2) A bend radius of less than 1.0 inch.
- 3) A 4 to 6 ounce force was necessary to extract the poison wire from a coolant channel at a 45 degree angle.
- 4) No damage effects were apparent on cluster block coating or poison wire integrity when pulled out of a coolant channel hole fifty times.

TABLE 3-2
 WEIGHT DISTRIBUTION IN CORE OF B_4C POISON WIRE

	Weight per Inch (gram)	Proportion of total weight (percent)
Core material, 98.5 W/o (B-10) $_4C$, 87.5 percent filled	0.0909	40.9
PVDF core sheath	0.0166	7.5
Fiberglass sleeve	0.0609	27.4
Teflon outer sheath	0.0537	24.2
Total	0.2221	100.0

3-2 POISON WIRE TIP REQUIREMENTS

The poison wire tip attains the deepest insertion into the reactor core and requires a special design. This section is approximately one-half inch in length and its function is to:

- 1) Prevent loss of poison material through the end of the encasement.
- 2) Smooth and round off the end of the encasement to eliminate contact of sharp edges with the coolant channel wall.
- 3) Provide a transition length to reduce gouging action and high localized forces on the coolant channel exit surfaces as the wire leaves the channel.

Objectives (1) and (2) are obtained by molding a material with appropriate adhesive characteristics into the desired configuration. Objective (3) is realized by the proper selection and combination of materials required to control the resistance which the poison wire tip presents to a specific type of bending couple. This type of couple appears if the wire is pulled out of the channel in a direction that is not parallel to the axis of the channel. A tip 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 a minimal possibility of the tip penetrating and chipping the coating of the coolant channel wall.

SECTION 4

POISON WIRE INDUSTRIAL MANUFACTURING PROCESS

Plans are underway to construct a quantity of 1000 simulated poison wires to a prototype design for utilization in poison wire and withdrawal system evaluation tests. The prototype rod design is a rational approach which satisfies poison wire criteria and permits manufacture by simple methods. Flexibility is provided for future modification of the design and production techniques.

The first step in manufacturing the prototype poison wire is the insertion of cylindrical core pieces of 0.056 to 0.058 inch diameter into a thin walled plastic tube. The core pieces are butted end-to-end inside the plastic tube to form a single element of the desired length. Construction of the poison wire becomes less complex since only a single unit must be manipulated. To minimize wall buildup the thin plastic tube will have a maximum thickness of 0.003 inch.

The core unit is slipped into a braided fiberglass sleeve to complete the next step of the poison wire construction. The wall build-up contributed by the fiberglass sleeve will be no greater than 0.005 inch.

The next step in the process is the insertion of the fiberglass enclosed core unit into a Teflon sheath. Application of heat to shrink the Teflon tube tightly onto the fiberglass completes the encasement of the poison wire. After shrinkage, the Teflon sheath will contribute approximately 0.006 inch to the wall build-up.

In the event there are a large number of wires involved, the procedure identified above may be mechanized. For example, the insertion of the core pieces into the core sheath tubing can probably be accomplished by the use of a vibratory feeder in conjunction with appropriate holding fixtures. The vibratory feeder would compensate for the spooling curl of the tubing and funnel the sticks, fed one-at-a-time, into the tubing entrance.

Wire units encased in unshrunk tubing will be moved past heating elements to obtain shrinkage of the tubing. In order to obtain shrunk tubing surfaces of a uniform texture, the combinations of exposure time and temperature will be precisely controlled by varying the settings of an auto-transformer providing current to the heating elements and by varying the speed of the motor driving the conveyor.

At this point in production, B_4C core will consist of rods three-to-six inches in length, butted end-to-end in the core sheath. To obtain the required flexibility characteristics, the core rods are broken into pieces 1/8-inch or less in length. Severing of the core sheath is reason for rejection since the purpose of the sheath is to maintain the fractured core pieces in a single unit during subsequent encapsulating operations.

A method used to produce fracturing involves passing the sheathed core unit through a mill equipped with a rubber roll which compresses against a driven steel roll during rotation. The rubber deforms to accommodate the intrusion of the wire. 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 wire which has passed the nominal line of maximum compression between the two rolls. This extension of the sheathed core unit is bent in cantilever fashion against the curved surface of the steel roll until fracture occurs.

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

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

Figure 4-1 represents a typical bundle of wires to be utilized in wire and actuator feasibility trials. These feasibility trials will be one of the major activities undertaken for the duration of this contract year.

Figure 4-1 Poison Wire Bundle and Single Poison Wire

APPENDIX A

STUDY OF ALTERNATE SHIPPING POISON WIRES

By D. J. Diamond

The problem in this study was to evaluate several nuclear poisons for use in the shipping wire system. The conclusion reached was that the present B_4C poison wires could be safely replaced by any one of four alternate types of 0.065 inch diameter wires. The compositions used for these wires were: 2 w/o boron (enriched to 92 percent B^{10}) in stainless steel encasement, Hf, Gd, and Ag-In-Cd (80 w/o Ag, 15 w/o Cd). Tables A-1 and A-2 summarize the results of the study. For each of the substitutes, the number of wires required to provide shutdown in case of a flooding accident ranges from three to five wires per fuel element, or approximately the present number. It is therefore recommended that the present number of poison wires (6648) be used in cost comparisons of the candidate poisons.

The current shipping poison system consists of 0.067 inch outside diameter stainless steel tubes containing B_4C and coated with 0.0055 inch of polyethylene to reduce abrasion of the channel liners. The poison region is 0.048 inch in diameter. This system was designed to ensure shutdown in a reactor completely flooded with water. Since the manufacturing of these wires has proven to be an expensive process, a study has been initiated to develop an economical alternative. A wire diameter of 0.065 inch was used in this study. It was assumed that all wires utilized the current polyethylene coating. Two approaches were employed; an analytical method and a semi-empirical method.

A. ANALYTICAL METHOD

For wire loadings of 5000 and 8000 wires, cross sections were generated using the MUFT and TNS codes for each poison using a range of assumed self-shielding factors. Thermal and epithermal self-shielding factors were calculated from the cross sections using the first-flight transport approximation. The poison number density for which the predicted and calculated flux-average self-shielding factors converge was taken as the correct reduced density. The final cross sections were generated using this number density and then used in a four-group DSN code to obtain the multiplication factor.

TABLE A-1
 NUMBER OF WIRES NECESSARY FOR $K_{\text{eff}} = 0.90$ IN THE FLOODED CORE

<u>Material</u>	<u>DSN Calculation</u>	<u>Inferred From GEAP 3201</u>		<u>Inferred from NERVA Expts.</u>
		<u>Thermal Spectrum</u>	<u>Epithermal Spectrum</u>	
B_4C	5500	5500	5500	5500
B^{10} in SS	4250	5814	5660	6300
Hf	3600	7442	5500	
Gd	3950	5621	5660	
Ag-In-Cd	4650	6248	5253	

TABLE A-2
 NUMBER OF WIRES NECESSARY FOR EQUIVALENCE TO 6648 B_4C WIRES

<u>Material</u>	<u>DSN Calculation</u>	<u>Inferred From GEAP 3201</u>		<u>Inferred From Expt' l. Data</u>
		<u>Thermal Spectrum</u>	<u>Epithermal Spectrum</u>	
B_4C	6648	6648	6648	6648
B^{10} in SS	5400	7027	6841	7650
Hf	4500	8995	6648	
Gd	5000	6794	6841	
Ag-In-Cd	6000	7552	6615	

The problems in this study considered the core as a single region. An effectively infinite water region was placed outside the reflector regions. To be on the conservative side, the control vanes were omitted.

The results of these runs are shown in figure A-1 with the results for B_4C wires.¹ This graph was used to obtain some of the numbers tabulated in tables A-1 and A-2. As can be seen from the curves, each set of substitute wires would provide a shutdown greater than that achieved with the present system. Several points should be noted regarding these calculations. Since Gd is not in the MUFT library, the epithermal contribution it makes was completely ignored. Although Gd is primarily a thermal absorber, the omission of its resonance absorption will cause the calculation for Gd to be conservative.

In the Ag-In-Cd calculation, the effect of indium was not taken into account due to its absence from the TNS and MUFT tapes. Since indium is an excellent poison, this also tends to make the results for Ag-In-Cd conservative. This is borne out in tables A-1 and A-2 where comparisons with hafnium indicate the worth of the Ag-In-Cd alloy to be greater in both thermal and epithermal spectra in a water moderated reactor.

The epithermal self-shielding factor used in all three fast groups was that obtained for the third group alone. Since there will be negligible self-shielding in groups one and two, the use of this factor for all groups leads to slightly conservative results. Although the geometric self-shielding was accounted for in all wires, no energy self-shielding was assumed in the generation of the fast cross sections. This would tend to diminish the effect of the wires. The only material this would be important for, however, is Hf which acts as a strong resonance absorber in the calculations.

B. SEMI-EMPIRICAL METHOD

To obtain additional information on the effect of different types of wires in a flooded reactor, it is advantageous to utilize known worth measurements. The worth of a wire is proportional to the number of absorptions that take place within it or $f_0 (\sum_a R) \sum_a V\phi$, where

¹ WANL-TNR-128, Status Report on Reactor Analysis of NRX-A2, September, 1963

Figure A-1. K_{eff} a Factor Versus Poison Wires in Flooded Core

Figure A-2. Worth of B_4C Wires

f_o is the overall self-shielding factor; Σ_a , R , and V are the macroscopic absorption cross section, radius, and volume of the wire; and ϕ is the flux at the position of the wire with no wire present. The ratio of the worths of two different types of wires at the same point within a core (if the absorbing material is the same in both wires) then becomes:

$$\frac{W_1}{W_2} = \frac{f_o (N_1 R_1) N_1 R_1^2}{f_o (N_2 R_2) N_2 R_2^2}$$

where N is the atom density of the absorber. If the product NR is kept the same in two wires, then the worth of one wire can be obtained from the worth of the other using:

$$W_1 = \frac{R_1}{R_2} W_2$$

Applying the above procedure, data available on the present B_4C wires can be used to obtain the worth of a boron impregnated stainless steel wire. The worth of a B_4C wire in the central region of the core obtained from measurements made in PAX is 1.1¢. If the boron to be used in the stainless steel wire is enriched to 92 percent B^{10} , then the wire would have to be 3.15 w/o boron in order to give a self-shielding equivalent to the B_4C wire. The worth of this wire is then $\left(\frac{0.065}{0.048}\right) 7.1¢$ or 1.49¢ in the central region. This point is plotted in figure A-2. Also shown on this curve is another point obtained from an experimental worth measurement of a B_4C wire in a KIWI reactor.²

For a particular wire, the ratio of the worth of a B_4C wire (1.1¢) to the wire's worth yields the number of these wires needed to give a worth equivalent to the B_4C wire. This number will then be independent of where the wires are to be compared. For a wire containing 2 w/o boron 1.15 wires are needed to give a worth equivalent to the B_4C wire. Therefore, 6210 poison wires would be necessary to give an effective multiplication shutdown (K_{eff}) = 0.90 in a flooded core and 7650 would be necessary to replace 6648 B_4C wires.

Utilizing the B_4C curve shown on figure A-1 a new curve for the boron-stainless steel wires, incorporating the above results, was drawn. This curve illustrates results that differ from those obtained using a DSN calculation by approximately 2000 wires in the range of interest, however, this conclusion is conservative. It can be shown that the curve in figure A-2 should in reality have a decreasing slope and, therefore, the worth values obtained from the straight line are low.

The actual number of boron-stainless steel wires needed to have $K_{eff} = 0.90$ in case of flooding will probably lie between the two estimates shown in figure A-2, 4300 to 6300 wires. The number required to replace 6648 B_4C wires is approximately in the range of 5400-7700 wires. Therefore, if the present system employing four wires per element or a total of 6648 wires is retained boron-stainless steel wires should provide suitable poisoning.

From figure A-1, Hf, Gd, and Ag-In-Cd all require from 3600 to 4600 wires to achieve a $K_{eff} = 0.90$ or from 4500 to 6000 wires to equal the present B_4C worth. As with the stainless steel wires in order to insure an adequate margin of safety with these wires, the present system involving the use of 6648 wires could be retained. Then all of the substitute wires are adequate substitutes for the present wires with no increase in the number of wires required.

To further demonstrate the worths of these materials, additional experimental data was utilized. The relative worths of different slabs in one reactor will give an indication of the relative worths of the corresponding wires in another reactor providing the spectra are similar and the self-shielding of corresponding slabs and wires is kept the same. Surface densities of slabs of material corresponding to wires with the same poison were calculated. Since the self-shielding must be the same in both types of samples, the surface density calculated (poison density times thickness) is equal to the product of poison density and radius for the wire. The relative worths of these slabs in both a bare and cadmium-covered configuration in a water moderated reactor is given in table A-3.

TABLE A-3
 RELATIVE WORTHS OF MATERIAL IN WATER MODERATED REACTOR

<u>Wire</u>	<u>Comparable Slab Surface Density gm/cm</u>	Relative Worth ³	
		<u>Bare</u>	<u>Epi-Cadmium</u>
B ₄ C	0.0862 (B)	0.92	1.05
B ¹⁰ - SS	0.0638 (B)	0.87	1.02
Hf	1.08	0.68	1.05
Ag-In-Cd	0.827	0.81	1.10
Gd	0.738 (Gd ₂ O ₃)	0.90	1.02

3 GEAP-3201 and GEAP-3201-2, Relative Effectiveness of Reactor Control Materials,
 December 1963.

The number of wires, N , of a particular poison needed to give a worth equivalent to $N' \text{ B}_4\text{C}$ wires may be written: $N = \frac{W'}{W} N'$ where W is the worth per wire. Using the data in table A-3, the results given in tables A-1 and A-2 can, therefore, be generated. Data are shown for both the thermal and epithermal range. Although a flooded reactor would be thermal, if sufficient poison is present, the mean fission energy would be in the epithermal region.