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**SELECTION OF MATERIAL,
NUMBER & DISTRIBUTION
OF POISON WIRES FOR THE
ANTICRITICALITY
POISON SYSTEM**

(Title Unclassified)

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Figure 1 - ACPS Design Concept

SELECTION OF MATERIAL, NUMBER AND DISTRIBUTION OF POISON WIRES FOR THE FLIGHT ANTICRITICALITY SYSTEM

INTRODUCTION

A flight anticriticality poison system, ACPS, is being developed as a special safety measure to prevent accidental criticality of the NERVA reactor. The system as presently envisioned consists of sufficient poison wires (or poison filled tubes) in the reactor core to prevent criticality during both the preflight period and in the flight period prior to startup. It will also be used during periods of credibly maximum danger produced by any conceivable accident or hazard situation. These wires would be inserted into the reactor core coolant channels from the nozzle end. A mechanism of novel design will be used to extract the wires at a predetermined point in flight and prior to second and third stage separation. The wires must be sufficiently clear of the reactor so that it can attain criticality before the stages separate. The design concept for the system is shown in figure 1.

Tests have been conducted to determine the feasibility of this concept. They indicate that plastic coated poison wires can be used and extracted from the core in about ten seconds without damage to either the wires or the reactor. Test data has also been obtained on the mechanical forces required to extract the wires.

A September 1963 Westinghouse Astronuclear Laboratory report¹ describes the poison system development effort to that date. It also outlined the basic method of approach.

1. Westinghouse Astronuclear Laboratory. WANL-TME-546. Feasibility of a Full Core Nuclear Poison System for Use During Lift Launch Operations. September 1963. 35 p.

Manuscript released by the author on 15 November 1963 for publication as a WANL Technical Memo External

Figure 2 - Worth Relative to .020 in. Thick Cadmium vs. Surface Density

The present report is concerned with the establishment of the following fundamental parameters in connection with the poison system.

1. The definition of the nuclear poison material to be used for criticality control.
2. The number of poison wires required to maintain $0.95 K_{eff}$ under a credible maximum hazard condition.
3. The distribution of wires in the coolant channel of the reactor core.

SECTION 2

SUMMARY

Because of the limited space available for extracting poison wires through the throat of the nozzle the number of wires must be kept to a minimum. Boron B_{10} has been tentatively selected for this application since it is one of the best poison materials. It has a very high thermal and epithermal neutron absorbing cross section. Boron B_{10} can be readily packed into a stainless steel tube. Its high melting temperature and nonsoluble characteristics also make it a desirable material for this particular application. At a future date the possibility of utilizing other materials or combinations of materials will be investigated.

A number of possible wire distribution arrangements were analyzed. Even distribution throughout the core, even distribution to specific radii from the center of the core, center concentrations and zone concentrations were all evaluated. The optimum convenient distribution from a nuclear standpoint is an evenly spaced matrix of wires throughout the core. This is not quite the optimum arrangement from the standpoint of the pull forces involved. The pull forces decrease about 11% if the poisoned volume cylindrical bundle radius is decreased from the entire core value to the value corresponding to minimum pull force. However, this would require the use of 300

LEADING PARTICULARS

$$K_{\text{eff}} = 0.95$$

WIRE LENGTH: 52 INCHES (ACTIVE)

OVERALL LENGTH : 80 INCHES

B_{10} WT. PER WIRE : 3.4 gm. (ACTIVE)

NUMBER WIRE REQUIRED : 2620

Figure 3 - Poison Wires for NERVA Anticriticality Poison System

additional wires. The lesser number of wires in a complete core distribution was selected as the best choice between minimization of wires and minimization of pull force.

Once the distribution pattern and poison material were selected the number of wires required was determined by utilizing an appropriately modified computer code, namely a 4 group, one dimension, diffusion code "AIM-5". A 4 group, one dimension, transport code "DSN" with the S4 approximation was used to determine flux depression factors in the wires. These calculations indicated that the use of 92% B_{10} with 85% compaction in 0.050 inch ID tubes inserted the full length of the core would require 2380 wires. This number of wires will give a $0.95 K_{eff}$ with the reactor immersed in water and all control drums rotated to 180° or the maximum reactivity position. Since this was an approximate theoretical number with no test data available a 10% contingency factor was introduced. This increased the number of wires required to 2620.

SECTION 3

BASIC REQUIREMENTS FOR SELECTION OF POISON WIRE AND MATERIALS

The selection of poison wires and materials is determined by the requirements and functions of the operational system. The following basic outline criteria were used in establishing the number, distribution and materials for the poison wires.

1. The wires must provide a $0.95 K_{eff}$ with the reactor immersed in water and with the control drums in the maximum reactivity position.
2. The wires must be operable under environmental conditions as described in "Summary of NERVA Reactor Environment".²
3. The wires must be able to withstand long term immersion in salt water.

2. Westinghouse Astronuclear Laboratory. WANL-TME-476. NERVA Reactor Environment. March 1963. 35 p.

4. The weight of the ACPS system must be kept to a minimum compatible with good design and reliability.
5. The overall reliability of the ACPS system must be maintained. The probability of system failure must be commensurate with overall NERVA system reliability requirements.
6. The probability of each component failure must be of such value as to meet the overall ACPS system requirement.
7. The maximum time for the removal of poison wires after the receipt of the designated signal must not exceed 10 seconds.
8. Poison wires that have been removed with a nozzle in place must not be reinserted in the core until they have been realigned and properly inspected to provide sufficient evidence of specified integrity.
9. The poison wires must be evenly coated with Teflon or equivalent material so as to prevent damage to the internal channels in the reactor core or the Columbium coating on the exit end of the fuel clusters. This protection must be adequate not only during insertion and removal but also during the environmental conditions encountered during shipment and launch.
10. The material to be used for the nuclear poison must be primarily selected on the basis of minimizing the number of poison wires required. Factors such as the metallurgical characteristics, solubility, producibility and cost must be taken into consideration.
11. Poison wires must be placed only in fuel element coolant flow channels axially in line with cluster support block holes which are 0.098 inch in diameter at the outlet end.
12. Following the removal of the poison wires, there must be no obstruction in the coolant channels.
13. The wires must be designed to minimize the forces required for their extraction.

SECTION 4

SELECTION OF POISON MATERIAL

Two poison materials evaluation studies have been conducted at the Westinghouse Astronuclear Laboratory to date. The first program was for the application of poison wires in the shipment of a reactor wherein such materials as boral, cadmium, and boron carbide were studied. Wires with B_4C were selected for the aforementioned use. They consisted of a 0.048 inch ID tubes of stainless steel with a polyethylene coating which contained 3.10 grams of B_4C for each wire. It took 5400 wires to provide a K_{eff} of 0.090. For additional safety and simplified placement, 6648 wires are used for shipment of the reactor.

The second study³ gave the results of calculations on the use of B_{10} for poison control. This report shows that it would require about 2.5 times as many wires if B_4C were used instead of B_{10} .

Since the wires for an inflight system must be extracted through the throat of the nozzle, it is necessary that a minimum number of wires be used. Approximately 4000 wires are the maximum that can be attached to a pull system and removed through the nozzle throat. Minimizing the number of wires will also reduce the damage potential and raise the system reliability.

The General Electric Company has published a number of reports on related work on poison material under AEC Contract AT-(04-3)-189.⁴ Figure 2 shows a graph

3. Westinghouse Astronuclear Laboratory WANL-TME-546. Feasibility of a Full Core Nuclear Poison System for Use During RIFT Launch Operations. September 1963. 15 p.

4. General Electric Reports GEAP 3201-1, 3202-2, 3345 AEC Contract AT-(04-3)-189

Figure 4 - Variation of K_{eff} With Poison Wire Concentration Per Fuel Element
Uniformly Dispersed Throughout the Completely Immersed Core

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reproduced from one of these reports on the relative worth of various materials versus the surface density. These values were determined in a water moderated critical facility using 1.6% enriched uranium. Since the worst case for a NERVA reactor is a flooded condition, the cited values of relative worth should have general validity. The B_{10} was not originally shown on the graph but values were readily introduced by using 20% of the surface density equivalent relative worth values of natural boron. This plot established B_{10} as one of the best poisons available from a nuclear standpoint.

This material has other advantages as a neutron poison, i.e., a high melting point of 2300°C , insolubility in water and a crystal form readily suitable for use in a tube. The main disadvantages are the scarcity of the material and the cost which is approximately \$1360 per pound.

Tests indicate that a packing factor of 85% can be obtained with 92% Boron B_{10} . This is based upon the use of material graded between 100 and 325 mesh with not more than 0.2% of larger or 0.2% of smaller particle size. This material of presumed 2.40 grams per cm^3 actual density is contained in a table with an assumed packed density of 2.04 grams per cm^3 .

Figure 3 shows the cross section of the poison element (wires). These wires consist of 0.050 inch ID stainless steel and can be filled with Boron B_{10} . The stainless steel has a 0.0075 inch wall and is coated with a 0.010 inch Teflon covering. This gives an insertion OD of 0.085 inches.

SECTION 5

DETERMINATION OF NUMBER AND DISTRIBUTION OF POISON WIRES

The nuclear analysis of the in-flight poison system was completed in May 1963 and documented.⁵ This analysis dealt solely with a 0.05 inch diameter pure B_{10} poison wires and was based on providing a 5% shutdown capability for the completely immersed

Figure 5 - Uniformly Poisoned Bundle Radius Required Versus Total Number of Wires Employed for 5% Shutdown

Figure 6 - Product of Thermal Flux and Thermal Adjunct Flux Radially in the Completely Immersed NRX-A Core for Various Poison Wire Distributions

NRX-A core. A 100% isotopic B_{10} purity and 100% theoretical density were assumed in the calculations. However recent information indicates a 92% isotopic purity and 85% theoretical density are more realistic. Some of the original results have been scaled for these effects and both the original and scaled results are shown on Figures 4 and 5. The scaling factor was obtained by assuming the reactivity is directly derivable from the total amount of poison. This is conservative since less dense poison wires would have less flux depression and therefore a larger depression factor. The depression factor is defined as the ratio of average flux to average cell flux.

Various poison wire distributions were investigated in the original analysis primarily from the standpoint of isolating core regions which would in themselves be sub-critical. It was found that isolation could not be effectively accomplished due to fast neutron coupling of these core regions. The results inferred and it was finally recommended that a uniform distribution would require the least number of poison wires (approximately 1850). To further substantiate this claim, thermal flux and adjoint flux radial distributions were calculated for various poison distributions. The product of the flux and its adjoint at the point represents the relative reactivity worth of neutrons at the point. It is not necessary to consider epithermal distributions since fission is predominately due to thermal neutrons for the poison systems considered. Figure 6 shows the results of these calculations. The unpoisoned cases indicate an important divergence in neutron worth radially which seems to recommend a redistribution of wires with a larger concentration of wires in the central portion of the core.

In response to these results non-uniform distributions of wires were examined in an effort to obtain an approximately constant flux-adjoint product radially. The core was divided into three radial regions: 0-14 cm, 14-28 cm, and the remainder.

5. Westinghouse Astronuclear Laboratory. WANL-TME-546. Feasibility of a Full Core Nuclear Poison System for Use During RIFT Launch Operations. 30 September 1963. 15 p.

Figure 7 ACPS - Variation of Withdrawal Peak Force

It was found that 1.4, 1.2, and 1.0 wire concentrations per fuel element in each of these regions respectively would have a maximum flux-adjoint variation of less than 30% as shown in Figure 3 and a K_{eff} of 0.953. The peaking at the outer periphery is misleading and should be neglected since the actual fuel loading in the outer 2 cm of the core is about a factor of 2 less than the loading used in these calculations. The difference between this arrangement and an even distribution is in the order of 1% which is less than the accuracy of the calculations.

The uniform poison wire distribution is still recommended as the optimum poison system from the standpoint of least number of wires required even though the corresponding flux-adjoint radial distribution is not uniform. The flux-adjoint variation is not an applicable indication of relative poison worth due to its rapid variation with poison redistribution.

The effect of the poison volume size and number of wires on the pull forces required is illustrated in Figure 7. This graph shows that with uniform distribution of wire to a specified radius of the core, there is an optimum point for radial distribution of the wires. On this graph 2650 wires are required in a 37 cm bundle radius for a minimum pull force of 1915 pounds. A minimum number of 2380 wires would be needed for an even distribution throughout the core requiring a pull force of 2210 pounds. Thus, at the expense of 270 wires additional to the minimum, a reduction of about 13.3% in the maximum pull force can be obtained.

Due to the relatively high cost of wires and the reliability factors, it is desirable to minimize the number of wires rather than reduce the pull load.

After setting the material, geometry, and distribution of the wires, the required number was determined on the computer to obtain 0.95 K_{eff} with the reactor submerged in water and all control drums rotated to the maximum output position. The computed number of wires required was 2380. Since this requirement was calculated on a purely

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Figure 8 - ACPS - Wire Distribution in Available Core Sector Coolant Channels

theoretical basis without reference to empirical test data, a 10% safety factor was added. This would bring the total number of wires to 2620.

Figure 8 shows a 120° sector of the exit end of the reactor core. The actual placement of the wires is indicated in a 60° sector. The other five sectors would have an identical number and arrangement of poison wires.