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# Report to the Atomic Energy Commission Concerning the Deformation of the Ford Nuclear Reactor Shim-Safety Rods

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# DEFORMATION OF THE FORD NUCLEAR REACTOR SHIM-SAFETY RODS

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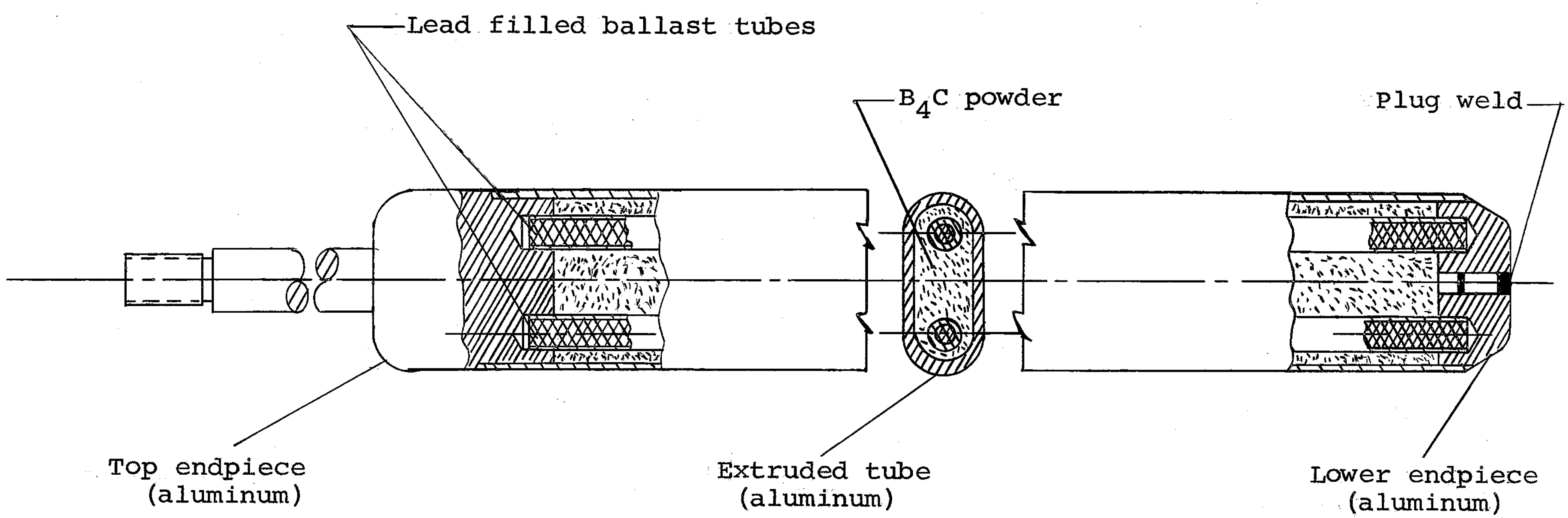
# DEFORMATION OF THE FNR SHIM-SAFETY RODS

## I. INTRODUCTION

The Ford Nuclear Reactor (FNR), located in the Phoenix Memorial Laboratory on the North Campus of The University of Michigan, is a one megawatt pool type reactor fueled with MTR type fuel elements. Control of the reactor is accomplished by the use of three shim-safety rods and one control rod. These rods move vertically inside special fuel elements in which guide tubes have been inserted in place of the center fuel plates. The shim-safety rods for the FNR, as their name implies, serve the dual function of shim control and safety protection. These rods, worth approximately 3 per cent negative reactivity each, drop into the reactor under the influence of gravity when potentially dangerous conditions exist in the reactor. This results from an interruption of the currents to electromagnets which normally couple the rods to their respective drive mechanisms. A shim-safety rod is constructed from an extruded aluminum tube welded to appropriate endpieces and filled with boron carbide powder (see Sketch I page 2). The powder is loaded through an aperture at the bottom end of the rod. This hole is plugged and welded after the rod is filled.

The FNR was put into operation in September of 1957 and, after initial calibrations, was raised to a power level of 100 kilowatts in February of 1958. Full power operation at one megawatt began in September 1958.

In August of 1960 a potentially hazardous condition arose when one of the shim-safety rods jammed in its special fuel element during a routine start-up of the reactor. There were no operational




SKETCH I - FNR SHIM-SAFETY ROD

consequences in that the condition was immediately detected and no further attempt was made to start the reactor. All three shim-safety rods were removed and examined. The jammed rod appeared to be deformed. To keep the reactor in operation, three new shim-safety rods were procured, installed and calibrated. The new rods were identical to the original set except for the addition of cadmium liners. The original shim-safety rods are designated as 1-A, 1-B and 1-C, and the new rods as 2-A, 2-B and 2-C. The original set of rods had been in the reactor for 2200 megawatt hours before the jamming incident occurred.

In view of the potentially serious consequences of jammed shim-safety rods, the new rods were removed from the reactor after 320 megawatt hours for an accurate dimensional check. All three rods showed evidence of swelling, and rod 2-C was off-gassing through the bottom plug weld. One of the original rods (1-C) which was in good condition, was substituted for rod 2-C. The shim-safety rods presently installed in the FNR are 2-A, 2-B and 1-C, all of which undergo daily rod-drop tests and are removed from the reactor on a regular schedule and measured dimensionally.

The following sections of this report describe the jamming incident and rod deformations in greater detail, discuss our initial exploratory investigations, and suggest a program of investigation which might establish conclusively the cause of these difficulties. A final report will be distributed after the completion of the program of investigation suggested herein.

## II. DESCRIPTION OF SHIM-SAFETY ROD INCIDENTS

### A. Incident Involving Rods 1-A, 1-B and 1-C

During reactor start-up on August 11, 1960, the magnet-contact light for shim-safety rod 1-A indicated loss of contact when the rods had been raised about ten inches from their lower limits. This indicated that rod 1-A had become disengaged from the electromagnet which had been pulling the rod out of the reactor core. Withdrawal of the rods was immediately stopped. The staff observer at pool side reported that rod 1-A was still in the raised position even though magnet current was automatically cut off when the magnet-contact light on the operating console indicated the loss of the rod. The special fuel element for rod 1-A was not dislodged from its position in the reactor core.

At this point the currents to the other two electromagnets were manually cut off. The pool side observer reported that rods 1-B and 1-C dropped normally into the core, but rod 1-A remained suspended. The electromagnets were lowered and 1-A magnet-contact light indicated contact as soon as the electromagnet struck the suspended rod. The rod was then successfully driven to its lower limit of travel by its electromagnet and drive mechanism.

The reactor was further secured and fuel was removed from the lattice along with the special control element containing safety rod 1-A. The rod-element assembly was moved to a holder in the center of the reactor pool. A grappling tool pulled the rod about ten inches out of the control element before the rod jammed again. Inspection showed noticeable swelling of the rod.

A special tool was built to remove the rod from the element. Plate No. 1, page 5, is a photograph of this removal device.

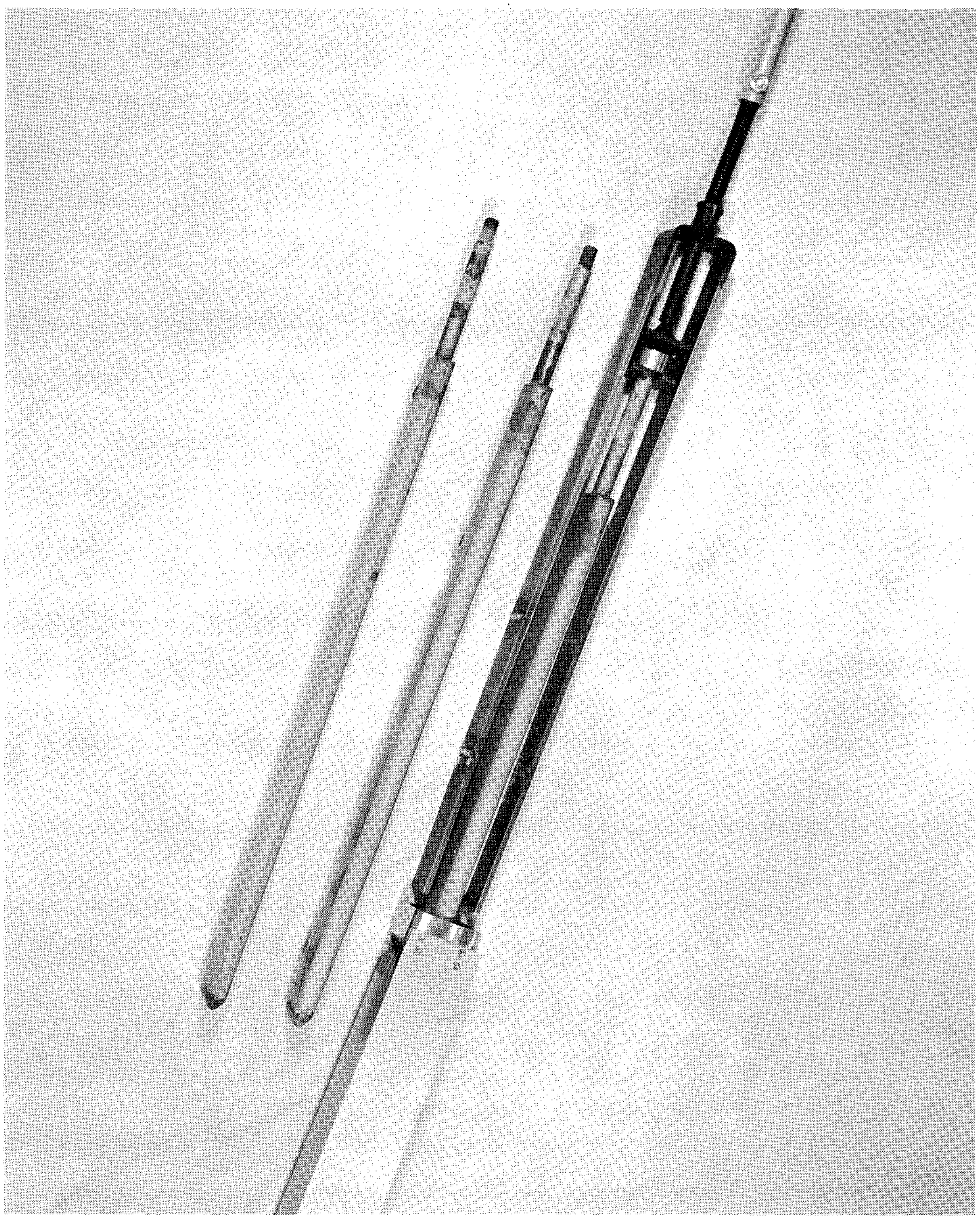


PLATE I - REMOVAL DEVICE

This device attached to the special fuel element was used to remove shim-safety rod 1-A. Rods 1-B and 1-C are also shown.

During the extraction procedure the fuel element was kept submerged in four feet of water for radiation shielding purposes. There was no serious galling of the rod during the removal procedure, nor was there any off-gassing from the rod. There was no evidence of corrosion or damage to the external surface of the rod. Also, there was no apparent damage to the special fuel element.

The three shim-safety rods had been in the reactor since the beginning of operation in September 1957. The reactor had operated at power levels up to one megawatt for a total of 2200 megawatt-hours. There were no indications prior to the incident that safety rod 1-A was sticking within the guide tube of the special fuel element. The rods on the FNR were inspected on several occasions since 1957 by removing them from the reactor and visually inspecting them under about six feet of water. Also, during that time, frequent rod-magnet release time measurements were made. Further, prior to every start-up rod drop tests are performed. None of these indicated potential jamming.

B. Incident Involving Rods 2-A, 2-B and 2-C

After the above incident a new special fuel element was installed in the lattice and three new replacement shim-safety rods 2-A, 2-B and 2-C were installed and calibrated. On November 25, 1960, these rods were removed from the reactor for observation and dimensional checks. Micrometer measurements showed that all three rods had increased in thickness after only 320 hours at one megawatt. Furthermore, rod 2-C was off-gassing at the bottom plug weld. A water-filled Erlenmeyer flask was held over the submerged rod to collect a sample of the gas for analysis.

The cadmium liners in the new set of rods hindered operations because of the induced radioactivity which gave a 6 roentgens per hour reading at the center of the rods. The bottom ends of the rods read greater than 25 roentgens per hour. In contrast, rods 1-A, 1-B and 1-C, without cadmium liners, read one-third of a roentgen per hour at the lower end.

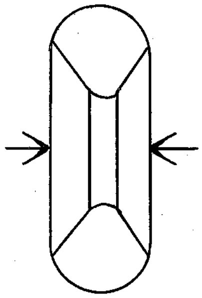
## III. INVESTIGATIONS

### A. Dimensional Inspection

After removal from the reactor a complete dimensional inspection was made of rods 1-A, 1-B and 1-C. The thickness and width dimensions are shown in Tables I and II respectively (see pages 8 and 9). The dimensions of the replacement rods 2-A, 2-B and 2-C before installation in the reactor are also shown in these tables. Although no records of the initial dimensions are available for rods 1-A, 1-B and 1-C, a reasonable indication of the degree of swelling which took place can be obtained by an intercomparison of rod dimensions. However, initial and final thickness measurements taken at the middle of the rod are available for rods 2-A, 2-B and 2-C which had been in the reactor for 320 megawatt hours. These measurements are as follows:

| Measurement | Shim-Safety Rod | | |
|---|---|---|---|
| | 2-A | 2-B | 2-C |
| Initial | 0.922 in. | 0.890 in. | 0.913 in. |
| Final | 0.928 | 0.921 | 0.925 |
| Change | 0.006 | 0.031 | 0.012 |

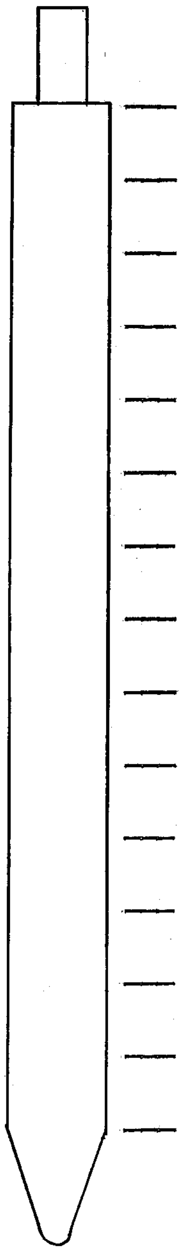
The inside dimensions of the guide tube of the special fuel elements are presented in the last column of Table I.



Thickness

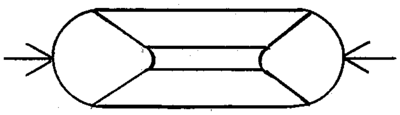
TABLE I - SHIM-SAFETY ROD THICKNESS DIMENSIONS

Note: The corresponding internal dimensions of the guide tube inside special fuel element 1-A are given in the last column.

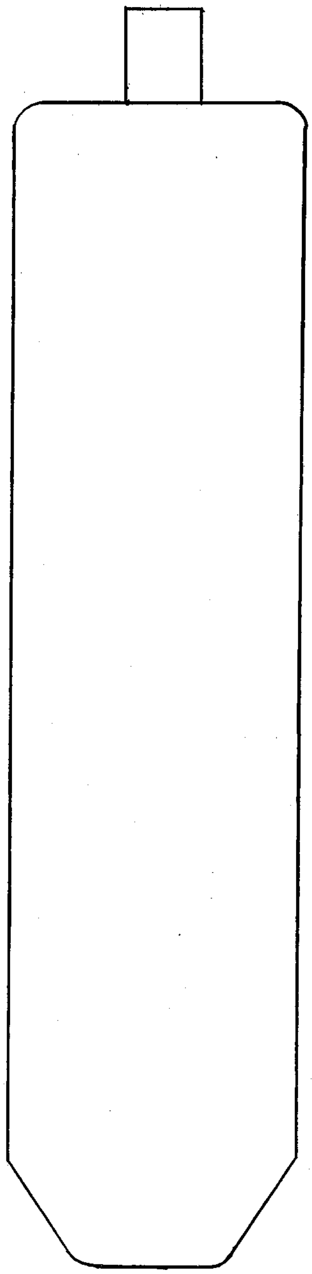


| 1-A | 1-B | 1-C | 2-A | 2-B | 2-C | GUIDE TUBE |
|---|---|---|---|---|---|---|
| 0.882 | 0.880 | 0.865 | 0.875 | 0.877 | 0.875 | 1.100 |
| 0.925 | 0.920 | 0.904 | 0.901 | 0.883 | 0.889 | 1.100 |
| 1.078 | 0.915 | 0.905 | 0.910 | 0.883 | 0.909 | 1.100 |
| 1.107 | 0.916 | 0.905 | 0.915 | 0.889 | 0.914 | 1.100 |
| 1.103 | 0.912 | 0.906 | 0.920 | 0.892 | 0.915 | 1.100 |
| 1.097 | 0.915 | 0.908 | 0.922 | 0.891 | 0.914 | 1.100 |
| 1.093 | 0.913 | 0.909 | 0.922 | 0.890 | 0.913 | 1.100 |
| 1.091 | 0.913 | 0.909 | 0.922 | 0.890 | 0.913 | 1.100 |
| 1.087 | 0.914 | 0.909 | 0.922 | 0.892 | 0.913 | 1.105 |
| 1.088 | 0.919 | 0.909 | 0.923 | 0.892 | 0.914 | 1.105 |
| 1.106 | 0.920 | 0.908 | 0.921 | 0.892 | 0.915 | 1.105 |
| 1.090 | 0.915 | 0.909 | 0.922 | 0.884 | 0.915 | 1.105 |
| 1.057 | 0.917 | 0.909 | 0.917 | 0.882 | 0.910 | 1.105 |
| 1.009 | 0.886 | 0.867 | 0.897 | 0.872 | 0.888 | 1.105 |
| 0.875 | 0.888 | 0.890 | 0.886 | ----- | 0.870 | 1.105 |

TABLE II - SHIM-SAFETY ROD WIDTH DIMENSIONS



Width



| 1-A | 1-B | 1-C | 2-A | 2-B | 2-C |
|---|---|---|---|---|---|
| 2.242 | 2.242 | 2.245 | 2.251 | 2.245 | 2.248 |
| 2.239 | 2.249 | 2.246 | 2.258 | 2.245 | 2.239 |
| 2.175 | 2.244 | 2.249 | 2.255 | 2.232 | 2.227 |
| 2.187 | 2.250 | 2.247 | 2.255 | 2.225 | 2.225 |
| 2.187 | 2.247 | 2.250 | 2.252 | 2.225 | 2.225 |
| 2.184 | 2.250 | 2.250 | 2.251 | 2.225 | 2.225 |
| 2.187 | 2.249 | 2.250 | 2.250 | 2.225 | 2.226 |
| 2.191 | 2.248 | 2.251 | 2.250 | 2.225 | 2.226 |
| 2.184 | 2.248 | 2.253 | 2.248 | 2.225 | 2.226 |
| 2.183 | 2.247 | 2.253 | 2.251 | 2.225 | 2.227 |
| 2.185 | 2.247 | 2.255 | 2.252 | 2.225 | 2.226 |
| 2.200 | 2.245 | 2.255 | 2.252 | 2.225 | 2.226 |
| 2.227 | 2.251 | 2.247 | 2.255 | 2.230 | 2.231 |
| 2.246 | 2.250 | 2.250 | 2.257 | 2.245 | 2.245 |
| ----- | ----- | 2.232 | 2.250 | ----- | ----- |

B. Radiographic and Dye Penetrant Studies

Complete radiographs were taken to determine the conditions inside the rods. The most significant finding from these radiographs was the presence of a void above the $B_4C$ powder in the rods. This is shown in Plate II on page 11. Dye penetrant tests indicated pitting on the surface of the rods but no cracks were revealed.

C. Techniques for Collection of Gas and $B_4C$ Powder Samples

The apparatus shown in Sketch II, page 12, was set up to measure any existing pressure and to collect any gas contained in the rod. The apparatus consisted of a self-sealing puncturing device with a pressure-vacuum gauge and an evacuated reservoir for collecting gas samples from the rod. Two rods, 1-A and 1-B, were punctured at the top where the voids were located. After the gas samples were removed, both rods were subjected to internal pressures of 40 psig while immersed in water.

The rods were then opened by cutting out a section on one side of each rod. The section that was removed is shown in Sketch III on page 13. Care was taken to avoid getting aluminum shavings in the $B_4C$ powder. Samples of the powder were removed from different positions along the length of the rod.

D. Analysis of Contents of Shim Rods

<u>Gas Analysis</u>

When pressure measurements were made on the two shim-safety rods, 1-B had a pressure of 20 psig while rod 1-A, the deformed rod, was at atmospheric pressure. The gas samples from 1-A, 1-B and 2-C were analyzed using a mass spectrometer.

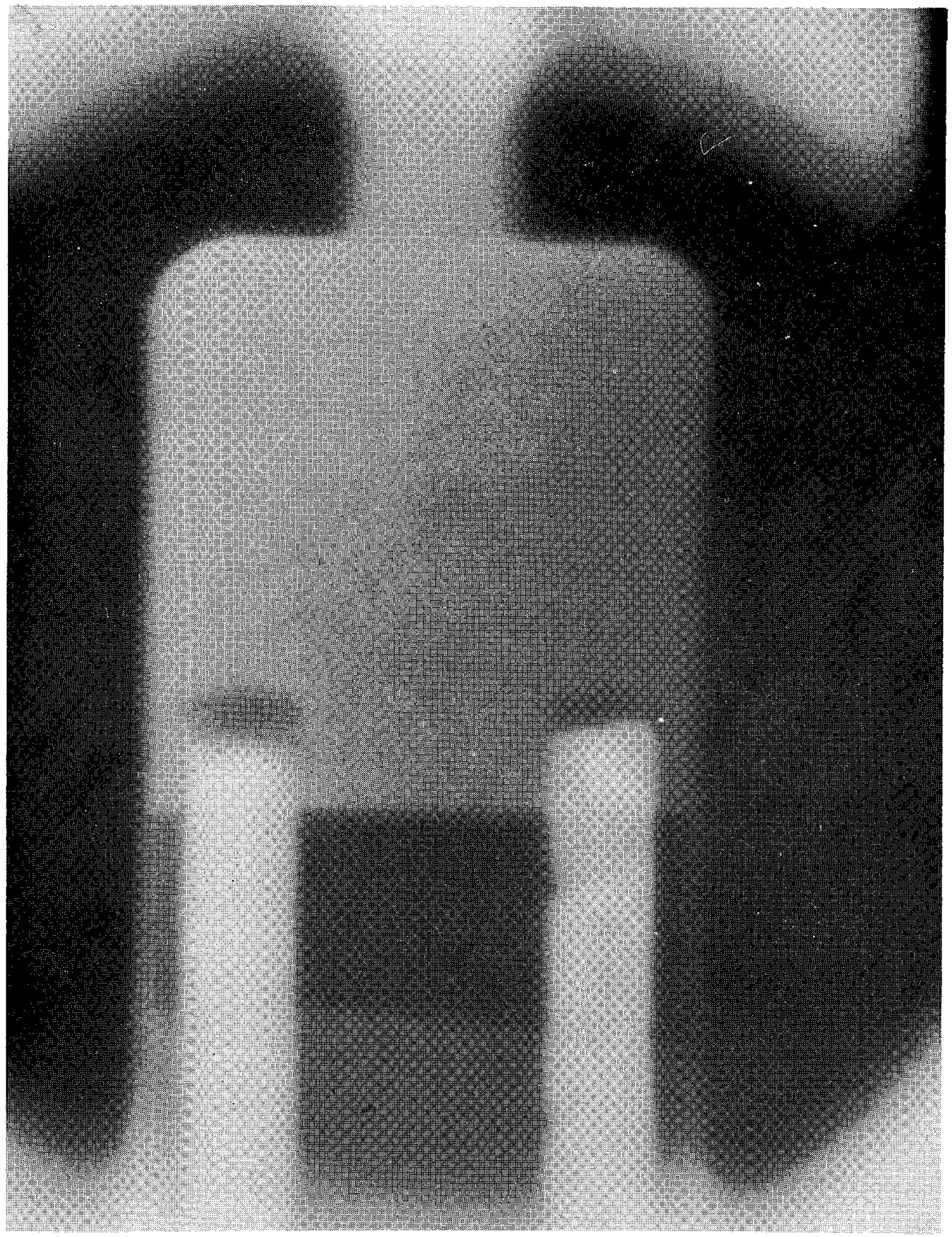
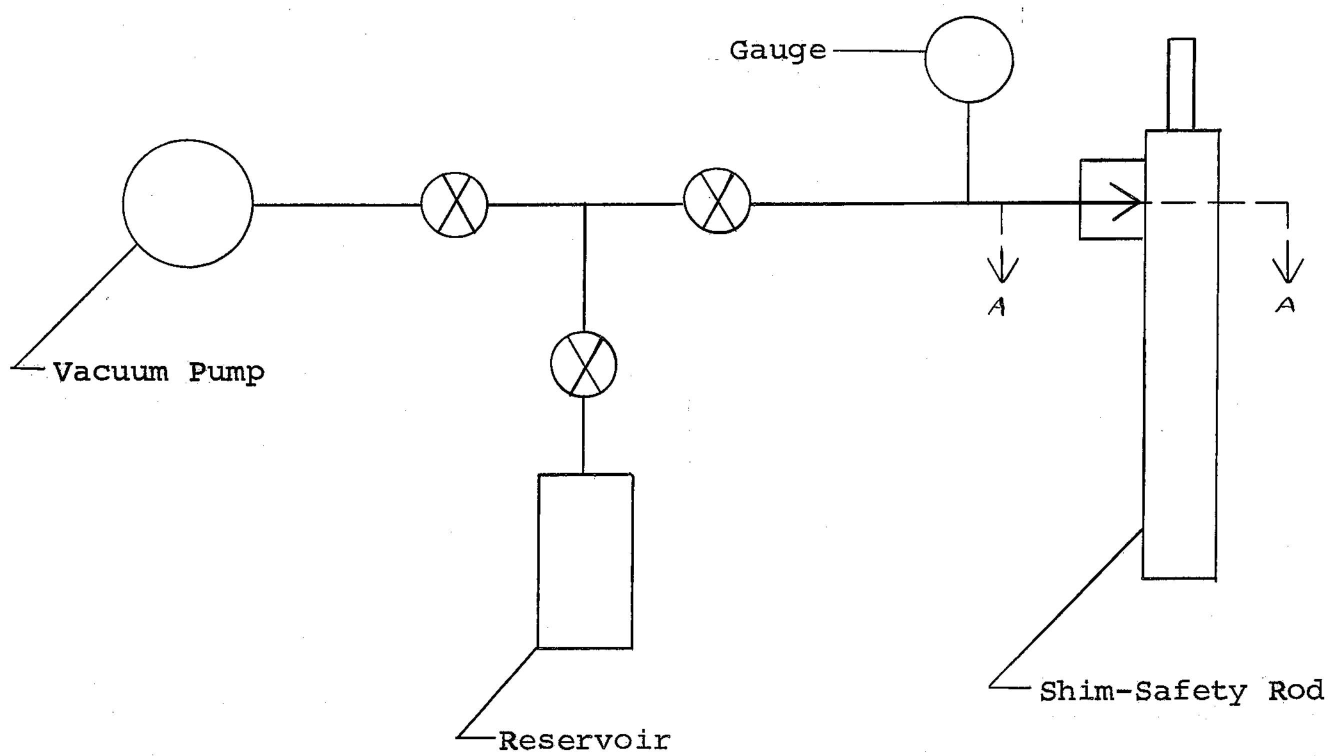
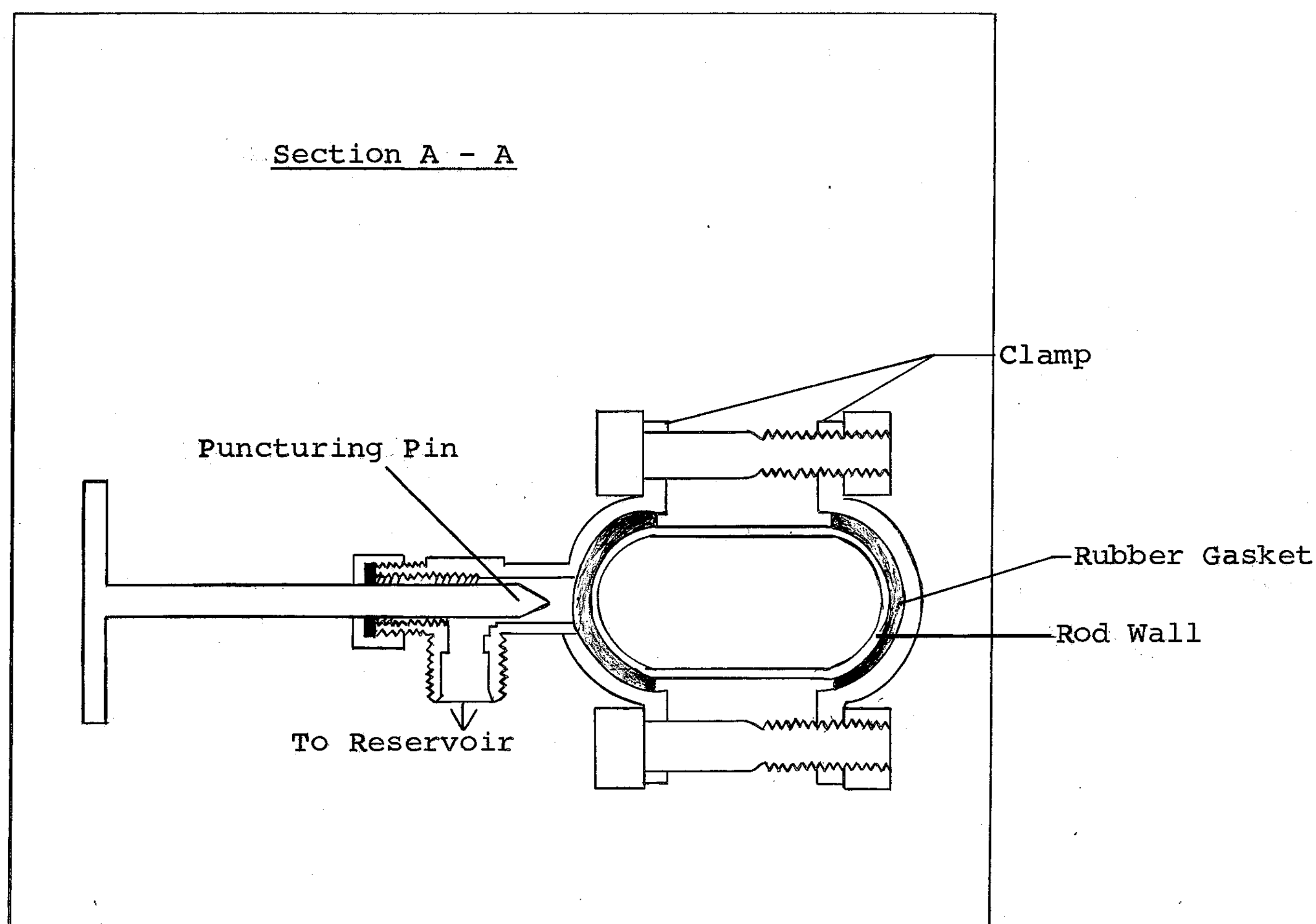


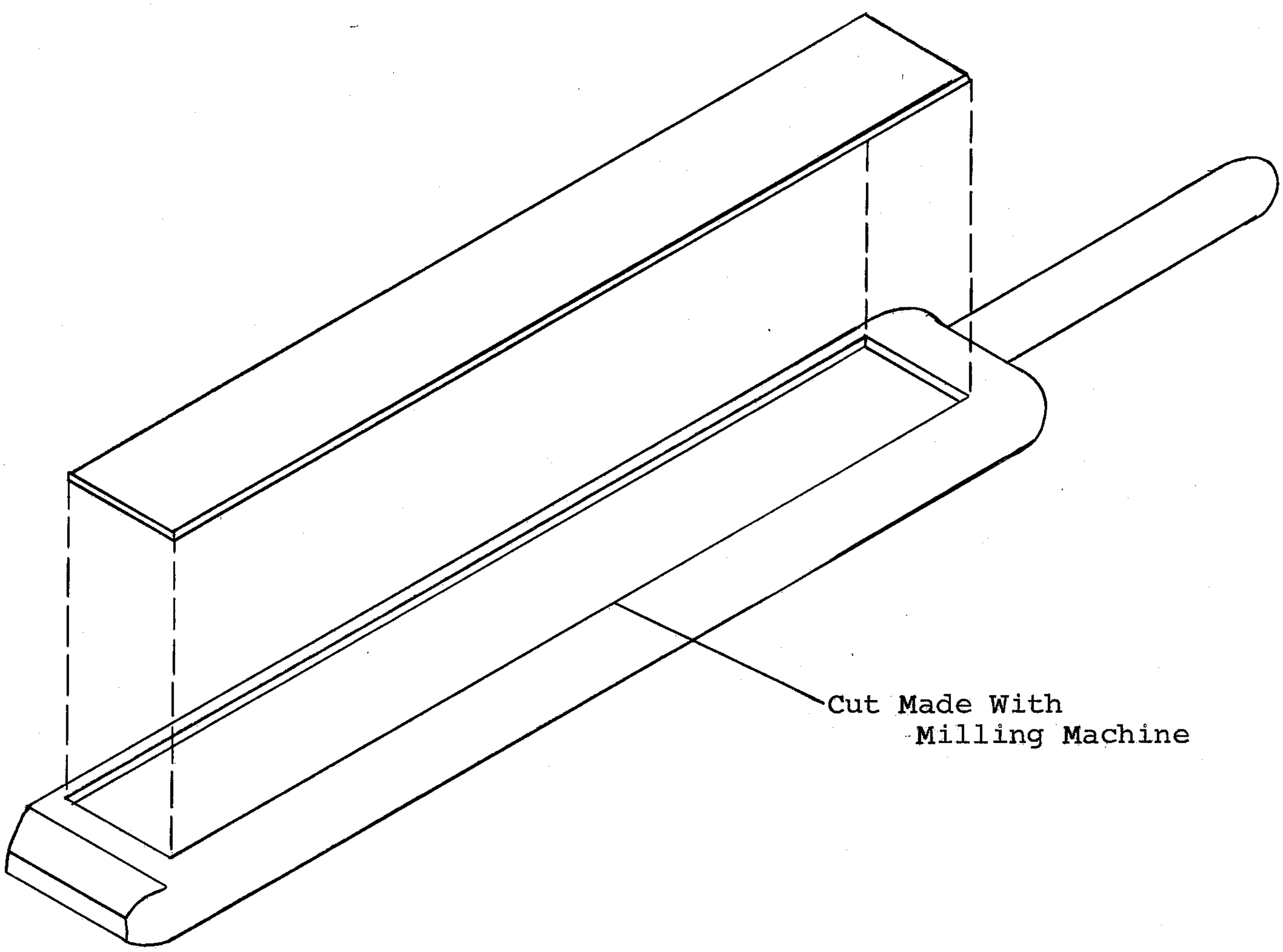
PLATE II - RADIOGRAPH OF THE TOP END OF A SHIM-SAFETY ROD

The light vertical rods are lead filled ballast tubes. The darkest area between the two tubes represents the void above the powder.




SKETCH II - GAS REMOVAL APPARATUS




SKETCH III - ROD SECTIONING DIAGRAM

The results are as follows:

Gas Analyses
(in Mole Per Cent)

Rod 1-A Rod which jammed

Rod 1-B "Normal rod"

Rod 2-C Rod which off-gassed

| Gas | 1-A | 1-B | 2-C |
|---|---|---|---|
| $H_2$ | 36.42 | 78.6 | 39.47 |
| $O_2$ | 36.00 | 0.4 | 14.98 |
| $N_2$ | 23.23 | 15.4 | 44.54 |
| $CO_2$ | 1.70 | 4.6 | 0.15 |
| A | 0.29 | 0.35 | 0.71 |
| He | 0.0 | 0.7 | 0.0 |

Note that the hydrogen-oxygen concentrations observed in 1-A and 2-C are in the detonable range.

## Analysis of $B_4C$ Powder and Inspection of Rod Interiors

When rod 1-B was opened, the $B_4C$ powder was dry and lightly packed. The interior walls of the rod were not corroded. The powder removed from the lower portion of the rod was radioactive and had a total beta-gamma activity of about 3 mr/hr/gram on contact. A gamma spectral analysis indicated the presence of $Mn^{54}$, $Zn^{65}$, and $Co^{60}$. Analyses of the $B_4C$ by emission spectroscopy showed the most predominant impurities to be Al, Cu, Fe, Zn and Mn. The supplier of the $B_4C$ powder reports 98.79% B, 1.08% C, 0.10% Si, 0.02% Se and 0.02% N.

The $B_4C$ in rod 1-A, the deformed rod, was found to be in a caked rather than a powdered form as in rod 1-B. The hard layer was concentrated between the ballast rods along the lower six inches of the shim rod. This cake had a grayish appearance unlike the characteristically black color of $B_4C$ powder. The powder removed from the lower portion of rod 1-A was found to contain approximately 5 weight per cent water.

Oxidation was prevalent on the interior walls at the lower end of rod 1-A. A crust of $Al_2O_3$ surrounded the lead filled aluminum ballast rods.

The water found in rod 1-A indicated a leak had occurred. However, the 40 psig pressure test before sectioning failed to show such a leak. Therefore, another attempt was made to locate a leak in rod 1-A with the powder removed and the inner surface cleaned. This was done by replacing and rewelding the removed section and pressurizing to 40 psig. Under these conditions a 30 cc/hr leak was noted at the top of the rod where the endpiece is welded to the extruded tube. The gas leaked from a very small hole which looked much like the pits revealed by the dye penetrant test.

The leakage rate was reduced drastically by evacuating and then re-pressurizing the rod. It appeared that the leak was capable of a valve-like action which was dependent on the internal pressures of the rod.

## IV. POSSIBLE EXPLANATION OF DEFORMATION

Consideration has been given to the possible causes of the swelling of rod 1-A. The deformation of rods 2-A, 2-B and 2-C, although not as great as that of 1-A, was also considered.

The hypotheses are:

A. Mechanical stresses resulting from expansion of wet $B_4C$ powder.

B. Internal gas pressure generated by:

1. $B^{10}$ $(n, \alpha)$ $Li^7$ reactions
2. Chemical reactions between $B_4C$ and $H_2O$
3. Chemical reactions between $Li^7$ and $H_2O$
4. Radiolysis of $H_2O$

Several experiments and calculations have been made to assist in evaluating these hypotheses.

A. The hypothesis that the deformation of the rod was a result of volumetric changes in wetted $B_4C$ powder appears to be without foundation. Radial measurements of a polyethylene bottle containing wetted $B_4C$ at room temperature showed no dimensional changes during an eight week period of observation.

B-1. It has been demonstrated that a pressure of approximately 110 psig is required to obtain the degree of deformation observed for rod 1-A. Calculations indicate that the generation of this pressure by helium as a result of $(n, \alpha)$ reactions on boron is extremely doubtful. Further, the gas analysis of rods 1-A and 1-B showed a relatively low concentration of helium.

B-2. The hypothesis involving a chemical reaction between $B_4C$ and $H_2O$ has been given little consideration since the reaction rate constant is small even at temperatures of 400°C. (Reference 1)

B-3. Significant pressures from the $Li\text{-}H_2O$ reaction are unlikely in view of the low lithium concentrations from the $B^{10}$ $(n, \alpha)$ $Li^7$ reactions.

B-4. Present data strongly indicates that the necessary pressure to cause the observed rod deformation can be generated inside the rod by the radiolytic decomposition of water into gaseous hydrogen and oxygen. To produce free $H_2$ and $O_2$, this reaction requires free radical scavengers which could well be the $B_4C$ powder itself, impurities in the powder, impurities in the water or the component parts of the rod (References 2, 3, 4, 5 and 6). The generation of gases was not the only prerequisite for the rod deformation. In addition, either the hole which allowed water to get into the rod and which allowed gas to escape must have closed off at some time or, the gas generation rate far exceeded the gas leakage rate.

The possibility of having water present at the time the rods were sealed in the fabrication process was considered since a small amount of water is capable of causing rod deformation. This is especially significant since $B_4C$ powder is naturally hygroscopic.

In the case of the deformed rod, the above possibility was discounted in favor of an external leak since the rod was in the reactor for a long period of time before jamming occurred. However, this possibility exists for rods 2-A, 2-B and 2-C. It is therefore imperative that the $B_4C$ powder used in fabricating shim-safety rods be dried and subsequently handled in humidity controlled environments.

In an attempt to demonstrate the feasibility of generating significant quantities of gas in reasonably short periods of time, an experiment was designed which would simulate the conditions that were suspected within the jammed rod. Two small, aluminum sealed vessels, one containing water and the other water and $B_4C$ powder were installed adjacent to the reactor core in a thermal flux of $5 \times 10^{12}$ neutrons per square centimeter-second and a gamma field of $5 \times 10^7$ roentgens per hour. Pressures in these chambers were monitored over a period of three days during which time the reactor operated at a power level of one megawatt for 50 hours. The pressure in the chamber containing water and $B_4C$ powder increased linearly with respect to reactor operating time at a rate of 1.2 psig per hour. See Graph I, page 19. This test chamber had a volume of 295 cc and contained 10 grams of water and 25 grams of $B_4C$ powder. The pressure in the chamber containing water only was 1.1 psig after 50 hours of reactor operation as compared to 60 psig in the chamber containing both water and $B_4C$ powder.

Analysis showed that the gas generated in the water-$B_4C$ chamber contained predominantly a hydrogen-oxygen gas mixture in a 2:1 ratio, similar to the finding for rod 2-C.

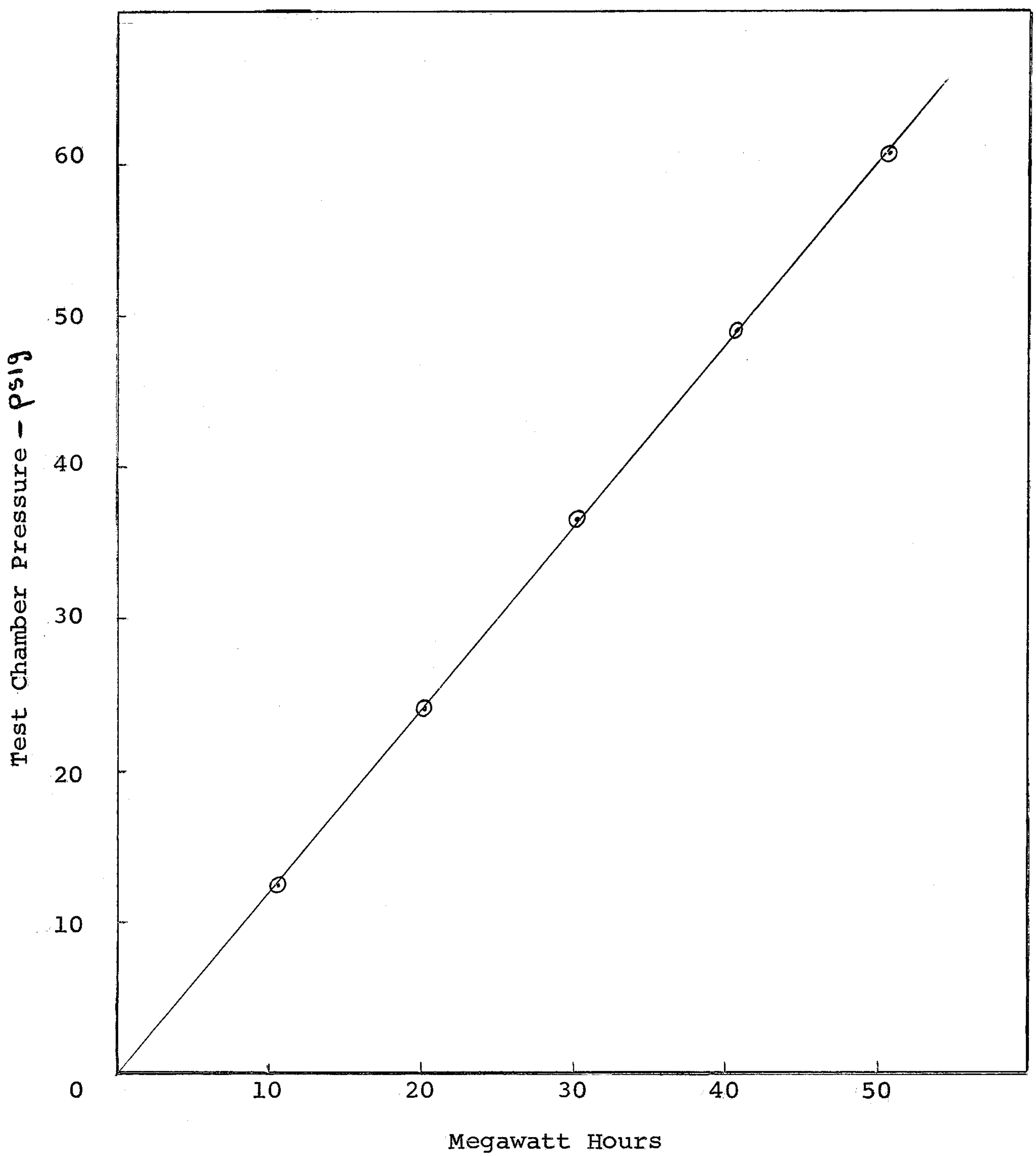
## V. RECOMMENDATIONS

Deformation of shim-safety rods because of internal pressure could lead to the following dangerous conditions:

1. Withdrawal of a special fuel element during start-up. Any subsequent release and drop of this special fuel element could result in a large and rapid increase in the positive reactivity of the reactor.

2. Jamming of the rods during reactor operation. In such an event, it would not be possible to insert the deformed

GRAPH I - TEST CHAMBER PRESSURE VS MEGAWATT HOURS



rods into the reactor when unsafe conditions exist or even for routine shut down. This is a particularly serious possibility in reactors which operate at power for long periods of time.

3. Detonation of the hydrogen-oxygen gas mixture contained in the shim-safety rods. This could cause damage to the reactor core in addition to rupturing the rod. Although such a detonation appears to be improbable, it is nevertheless a potential hazard that needs further investigation, especially in strong radiation fields.

## Operational Recommendations

In view of the important function of shim-safety rods, a detailed inspection should be made of all rods before installation in a reactor. Records of these inspections, especially weights in water and dimensional measurements, should be maintained for reference purposes. A careful survey of the surface conditions of the rods including all welds is extremely important. Radiographs have proved valuable in determining internal conditions of reactor rods.

In addition to the initial tests, shim-safety rods should undergo periodic inspections. The FNR is presently on a schedule calling for rod inspection every 320 megawatt hours of operation. This inspection requires the rods to be removed from the reactor, the dimensions measured directly and the surface observed for corrosion or any other indication of damage, such as off-gassing.

Close attention should also be given to the potential hazards that exist when water containing free-radical scavengers is present in any sealed experiment or device located in a radiation field.

## Recommendations for Design and Fabrication

Consideration should be given to the design of new shim-safety rods which would avoid the possibility of the generation of gases leading to high pressures. Further, consideration should be given to the design of the special fuel elements for these rods which would minimize the possibility of jamming. Any arrangement of element and rod which would make dimensional changes easily and readily detectable would be a decided improvement over our present system.

In the fabrication of shim-safety rods similar to those presently used on the FNR, it is extremely important that all substances capable of producing gases in the presence of radiation be held to a minimum. These substances include volatile degreasing agents, water used for rinsing and any water contained in the $B_4C$ powder.

## Proposed Investigations

As a result of this investigation of the shim-safety rod incident, it has become evident that the following subjects should be investigated more thoroughly.

1. The internal pressures necessary for shim-safety rod deformation.

2. Gas and pressure generation in shim-safety rods located in a reactor core as a function of water content in $B_4C$ powder.

3. The effect of alpha particles and lithium recoils from $B_4C$ powder on the radiolytic process.

4. The sources of free-radical scavengers which are required in the radiolytic process.

5. Possible sources of ignition energy for the detonation of hydrogen-oxygen gas mixtures.

Recognizing the importance of the above problems, these investigations will be undertaken at the Phoenix Memorial Laboratory. Financial assistance will be required for a thorough investigation of these problems.

From an operational point of view, the removal of shim-safety rods from their special fuel elements and the reactor for dimensional tests is a time consuming and complicated manipulation. In an attempt to simplify these inspections a study of "in situ" rod inspection techniques will be undertaken. Further, the criteria for the frequency and technique of inspection for shim-safety rods will be re-evaluated in light of the results of the aforementioned experimental investigations.

## VI. REFERENCES


1. F. F. Mikus, Reactor Technology Quarterly Report No. 6 KAPL-2000-3, 48-49 (1958).

2. J. B. Hoag, Nuclear Reactor Experiments, D. Van Nostrand Co., Inc., Princeton, New Jersey 346-347 (1958).

3. E. J. Hart and P. D. Walsh, Proc. 2nd Intern. Conf. Peaceful Uses of Atomic Energy, Geneva 29, P/763 38-42 (1958).

4. A. O. Allen and H. A. Schwarz, Proc. 2nd Intern. Conf. Peaceful Uses of Atomic Energy, Geneva 29, P/1403 30-37 (1958).

5. E. J. Hart, et al, Proc. 2nd Intern. Conf. Peaceful Uses of Atomic Energy, Geneva 7, P/839 593-598 (1955).

6. C. B. Senvar and E. J. Hart, Proc. 2nd Intern. Conf. Peaceful Uses of Atomic Energy, Geneva 29, P/1128 19-23 (1958).