OPERATING EXPERIENCE WITH URANIUM-MOLYBDENUM FUEL IN PULSED REACTORS*

J. A. Horak,** J. A. Reuscher, and D. J. Sasmor

Sandia Laboratories
Albuquerque, New Mexico 87115

The first planned pulsed operation of a fissile system was achieved at Los Alamos on January 8, 1945. The temperature increase produced in the fuel was 0.001°C by the yield of approximately $2 \times 10^{11}$ fissions (1). Since that initial pulse there has been an ever increasing emphasis on higher yields of neutrons per pulse and shorter pulse widths; at the present time the yields are up to values as high as $5 \times 10^{18}$ fissions/pulse and the pulse widths are as short as 24 μsec (2). The strains and resultant stresses produced in the fuel are a function of the temperature rise and the rate of rise in the fuel, and since temperature is a linear function of the energy released by the fissions produced in a pulse, this emphasis on higher yields has produced more stringent demands on the thermomechanical properties of the fuel utilized in pulsed reactor systems. Shorter pulse widths also increase the maximum dynamic stresses induced in the fuel components during a pulse. During the first 15 years of pulsed reactor operations unalloyed uranium was used as the fuel for these reactors. However, by 1960 the stresses produced during a pulse exceeded the yield and ultimate stresses of unalloyed uranium and almost all

* This work was supported by the United States Atomic Energy Commission.

** Also Nuclear Engineering Department, University of New Mexico, Albuquerque, New Mexico 87106.
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
fast pulsed reactors built since 1960 use a uranium-molybdenum alloy as the fuel. Two pulsed reactors utilize α phase U-Mo alloy and five use γ phase U-Mo alloy. Table I contains the relevant parameters for the seven reactors. All but VIPER are homogeneous all metal annular cylinders of the dimensions given in Table I. All achieve prompt criticality by inserting fueled control rods and all are shut down by thermal expansion of the fuel; VIPER also uses Doppler effect for shut down (3).

This paper presents the operating experience obtained with U-Mo fuel in pulsed reactors. The presentation is in ascending order of the operational temperature rise induced in the fuel per pulse.

**Alpha Phase U-Mo Alloys**

**Godiva IV**

The Godiva IV reactor at Los Alamos Scientific Laboratory uses cast U-1.5 w/o Mo fuel (2). The 1.5 w/o Mo provides a fine grain size, which eliminates surface roughening upon thermal cycling and/or irradiation and minimizes the anisotropy of the mechanical and physical properties of the uranium α phase; it provides some strengthening and an increased oxidation resistance relative to unalloyed uranium. As shown in Fig. 1 Godiva IV consists of six annular fuel rings held together with three external "C" clamps made of maraging steel. All fuel components are plated with aluminum to reduce oxidation of the fuel and to inhibit fission product release from the fuel.

Godiva IV has been pulsed approximately 400 times with maximum fuel temperatures ($\Delta T_{\text{max}}$) of 200-250°C; the average fuel temperature ($\Delta T_{\text{avg}}$**) produced in these pulses was 100-125°C. During early operation to high yields that produced $\Delta T_{\text{max}}$ of 500-550°C the second fuel plate from the top failed by cracking, the cracks radiating from the control rod clearance holes to the outside fuel plate surface. The cracking was attributed to insufficient radial clearance between the second fuel plate from the top and the central fuel region shown in Fig. 1 (2). This problem

* $\Delta T_{\text{max}}$ is the maximum temperature rise measured in the core.

** $\Delta T_{\text{avg}}$ is the average core temperature.
## TABLE I

Design, Capability, Fuel Geometry and Performance Information
for Uranium Molybdenum Alloy Fueled Pulsed Reactors

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Fuel w/o No</th>
<th>Fuel Plate Dimensions, Inches</th>
<th>Internal Cavity Dimensions, Inches</th>
<th>Fissions Per Pulse ((10^{17}))</th>
<th>Pulse Width (\mu\text{sec})</th>
<th>(\phi \ 10^{19} \frac{n}{\text{cm}^2 \text{sec}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Godiva IV</td>
<td>1.5</td>
<td>3.50 ID x 7.00 OD</td>
<td>9/16 dia x 3 long</td>
<td>1</td>
<td>24</td>
<td>4</td>
</tr>
<tr>
<td>VIPER</td>
<td>1.25</td>
<td>0.4 OD x 11.4 long</td>
<td>2 dia x 3 long</td>
<td>3.5</td>
<td>400</td>
<td>0.25</td>
</tr>
<tr>
<td>HPRR</td>
<td>10</td>
<td>3.5 ID x 8 OD</td>
<td>2 dia x 9 high</td>
<td>1.8</td>
<td>48</td>
<td>2</td>
</tr>
<tr>
<td>Super Kukla</td>
<td>10</td>
<td>18 ID x 30 OD</td>
<td>18 dia x 2 high</td>
<td>20-50</td>
<td>600</td>
<td>0.25</td>
</tr>
<tr>
<td>FBR</td>
<td>10</td>
<td>4 ID x 8 OD</td>
<td>1.25 dia x 5 high</td>
<td>0.6-1.0</td>
<td>50</td>
<td>0.82</td>
</tr>
<tr>
<td>APRF</td>
<td>10</td>
<td>4.2 ID x 8.9 OD</td>
<td>1-1/2 dia x 8 high</td>
<td>2.2</td>
<td>50</td>
<td>1.8</td>
</tr>
<tr>
<td>SPR II</td>
<td>10</td>
<td>1.6 ID x 8 OD</td>
<td>1-1/2 dia x 8 high</td>
<td>1.6</td>
<td>40</td>
<td>2</td>
</tr>
</tbody>
</table>

---

* All of these reactors, except VIPER and Super Kukla, use fully enriched uranium. For VIPER the enrichment is 37%, and for Super Kukla the enrichment is 20%.

* The internal irradiation cavity in pulsed reactors is usually referred to as the "glory hole".
was eliminated by providing increased clearance between the central fuel region and the second fuel ring. No further fuel failures have occurred since this modification was made.

**VIPER**

The VIPER (ALRE-Aldermaston, England) reactor began pulsed operation in August, 1967. Through April of 1973 the reactor has been pulsed approximately 500 times. Of these pulses approximately 250 were between 75 to 100% of the maximum yield of $3.5 \times 10^{17}$ fissions ($3.4$). A pulse to this yield produces a $\Delta T_{\text{max}}$ in the fuel of 480°C and a $\Delta T_{\text{avg}}$ of 250°C. The maximum temperature to which the reactor may be pulsed is limited by the temperature that the epoxy resin moderator may be heated to before it begins to decompose. Figure 2 is a vertical section of the VIPER core (3). Between adjacent fuel elements are alternating plates of copper and of aluminum loaded epoxy resin. The epoxy resin is present for moderation and the copper is used as a reflector.

The fuel elements of the VIPER reactor most closely resemble those of a power reactor or a steady state research reactor as shown in Fig. 2. The fuel rods are 11.4" long and 0.400" in diameter. The fuel is clad with 0.015" thick type 304 stainless steel with helium cover gas. In addition to protecting the fuel from oxidation and inhibiting the release of fission products into the atmosphere, the cladding also serves to support each fuel pin at its longitudinal midplane. The cladding is pinched around the circumferential groove in the fuel pin. Supporting the fuel at its centerline results in the forces developed during a pulse being transmitted equally upward and downward in the fuel pin. By this method of support the strains produced in the fuel are reduced significantly over those that would be produced in the fuel if it were supported at the bottom only.

Twenty five fuel pins are removed at periodic intervals and radiographed to determine if irradiation growth and/or dimensional instability have occurred. After the approximately 500 pulses the maximum length increase is 0.005" in the 11.4" fuel rods (3). No distortion or cracking have been detected.

Because of the aluminum-epoxy moderator and copper reflector in VIPER the pulse widths are approximately 400 µsec (full width at half maximum). This results in very low stress levels in the fuel. The calculated maximum stresses are 6,600 psi at the center support region and an average of 3,000 psi in the remainder of the fuel. From the low stress levels produced in the fuel it is easy to see why the fuel has performed very well and why there have been no fuel failures to date.
Because of the low temperature produced at the fuel surface, < 250°C, there have been no compatibility problems between the stainless steel cladding and the fuel. It requires 1,000 pulses of the maximum yield to achieve a fluence of $1 \times 10^{18}$ n/cm² which produces a burnup of only 0.0001%. This burnup level is too small for swelling or even radiation induced growth to be of concern. In addition, a fluence of $1 \times 10^{18}$ n/cm² is still an order of magnitude below the neutron exposure where an appreciable decrease in the ductility and a significant increase in the yield strength is observed for the fuel and the cladding.

**Gamma Phase U-10 w/o Mo Alloy**

Most of the pulsed reactors built in the past decade have used γ phase U-10 w/o Mo as the fuel (1). The γ phase was selected because of the isotropy of the mechanical and physical properties. Molybdenum was selected as the alloying agent because of the following reasons.

1. Molybdenum is at least twice as effective in stabilizing the gamma phase as is niobium. For U-5 w/o Mo the nose of the TTT diagram is at approximately 20 minutes; for uranium-niobium alloys 10 w/o of Nb must be added to U for the nose of TTT diagram to be at 20 minutes (5,7). For U-10 w/o Mo the nose of the TTT diagram is at 400 minutes (5,7). Therefore, less non-fissile diluent is required in U-Mo alloys than in U-Nb alloys to stabilize the γ phase. The lower concentration of diluents in the fuel provides for shorter neutron pulses and a "harder" neutron spectrum in the experimental cavity of the reactor.

2. Uranium-molybdenum alloys exhibit the slower transformation kinetics for the $\gamma \rightarrow \alpha + 5$ reaction upon heating to 300-570°C which is the temperature region of operation of the current pulsed reactors (6). This prevents, or at least retards, transformation of the γ phase due to the stress and temperature pulses generated within the fuel during reactor operation.

3. Molybdenum provides more solid solution strengthening of the uranium γ phase than does niobium. This results in the stronger fuel for pulsed reactor applications. The yield strengths of several U-Mo alloys are greater than 130,000 psi and the ultimate tensile strengths are in excess of 140,000 psi (7,8).
4. Considerable metallurgical research on the casting, fabrication, phase equilibria and irradiation stability of uranium-molybdenum alloys has been conducted within the USAEC fast breeder reactor program. This research provides a broad base of information on U-Mo alloys that is extremely useful in developing the technology of fuels for pulsed reactors.

A Mo content in excess of 5 w/o is required for retention of the γ phase to room temperature and to provide sufficient stability of the γ phase during reheating to 300-570°C to avoid decomposition of the γ to α + δ during reactor operation. For Mo contents in excess of 10 w/o the alloy is extremely difficult to cast, to fabricate, and to machine; and possesses little, if any, ductility. In addition, a Mo content in excess of 10 w/o (20 a/o) adversely affects the neutron spectrum and pulse widths desired for pulsed reactors. For these reasons U-10 w/o Mo has been used in all of the recent pulsed reactors that have been designed primarily for high yield pulses.

The reactors using U-10 w/o Mo fuel are discussed in the order of increasing operational temperatures and greater stresses generated in the fuel components.

HPRR

The Health Physics Research Reactor, HPRR, (Oak Ridge National Laboratory, Oak Ridge, Tennessee) Fig. 3, was the first pulsed reactor to use a fuel other than unalloyed uranium. The ten fuel plates of HPRR are held together with nine bolts that are also made of U-10 w/o Mo; the reactor is held together by threading the nine bolts into the bottom fuel disc. Each of the nine bolts is hollow to provide reactivity adjustments by inserting U-10 w/o Mo plugs into the hollow bolts. All of the fuel components of HPRR are nickel plated.

Since its initial operation, 1962, the HPRR has been subjected to 490 pulses. The maximum temperature rise achieved in any pulse was 315°C; however, almost all of the pulses have been to only slightly above room temperature. The reactor is used principally in the low-power steady-state mode for health physics radiation detector work. The fuel has performed very well under these conditions. The reactor still operates with the original fuel components except for the bottom plate that contains the threaded bolt holes. During a routine inspection of the core a crack was detected in the bottom fuel plate. The crack emanated from one of the threaded bolt holes. It has been attributed to the galling of the U-10 w/o Mo bolt in the U-10 w/o Mo plate. To circumvent the two identical materials being in intimate contact, Type 304 stainless
steel helicoils have been placed in the bolt holes. Since the end plate and the bolts are at relatively low temperature (< 100°C) during pulsed or steady state operation there have been no compatibility problems between the U-10 w/o Mo and the stainless steel. The nickel has remained intact on all of the components except for the one cracked fuel plate.

Super Kukla

Super Kukla, Fig. 4, was developed by Lawrence Livermore Laboratory (LLL) and is operated by LLL at the Nevada Test Site.

Physically, Super Kukla is the largest fast pulsed reactor ever built and has produced the highest neutron yield ever achieved, 2-5 x 10^{18} fissions per pulse. Pulsing to a yield of approximately 2 x 10^{18} fissions produces a fluence of 1.5 x 10^{15} n/cm^2 per pulse within the experimental cavity. However, because of the long time duration of the pulse width of approximately 600 μsec, the stresses produced in the fuel are very low; and a ΔT_{max} of 140°C was generated in a pulse of approximately 2 x 10^{18} fissions.

Under these conditions the fuel has performed well; however, some more stringent conditions have been encountered under which the fuel has been damaged. In one experiment the glory hole was filled with polyethylene to determine its effectiveness as a moderator. Because of the close coupling between the fuel and polyethylene an extremely high fission density was achieved on the inside fuel surface. This resulted in temperature rises in the fuel that ranged from 500-600°C. The stresses produced during this pulse resulted in two fuel plates being cracked from the inner fuel surface to the bolt holes and control rod holes. In addition, the other seven fuel plates have surface cracks that are approximately 1/4" deep. The cracks are currently being examined; the only information available at this time is that the cracks follow the grain boundaries in the fuel. After this incident the reactor has continued to be used. As long as the outer surface is held intact by the bolts the reactor can still be pulsed. The reactor has been pulsed a total of 1,230 times with approximately 250 high yield pulses. In high yield operation the ΔT_{max} produced during a pulse is approximately 360°C with the ΔT_{avg} being approximately 180°C.
**WSMR-FBR**

The White Sands Missile Range Fast Burst Reactor,* WSMR-FBR, Fig. 5, is used in both the steady state and the pulsed modes. The typical sequence is a week of pulsed operations followed by a week of steady state operation. This operational sequence was established to satisfy experimental needs and at the same time optimize the reactor use; although this sequence was not chosen in order to prolong the useful life of the core, the choice may have been most fortuitous. The temperatures attained during steady state operation are capable of relieving any residual stresses from the pulse mode of operation, while the temperatures are still sufficiently low that long range diffusion and transformation of the $\gamma$ to $\alpha + \delta$ should not occur (6).

The initial core loading performed satisfactorily from 1955 to 1971. During this period the reactor was used for 3,426 operations, of which 935 were in the pulsed mode and the remainder in the steady state mode. In this mode the reactor operates at 5 to 6 kw with a core temperature of 290°C to 350°C, with most of the operations conducted at a fuel temperature of approximately 250°C. In the pulsed mode, almost all of the pulses were to a $\Delta T_{max}$ of less than 200°C, with a yield of approximately $6 \times 10^{16}$ fissions in approximately 50 μsec (F.SMR). The number of pulses to higher temperatures has increased in recent years as the need to obtain information of the effects of higher fluences has developed.

There have been some failures of the fuel components of the WSMR-FBR. One of these is shown in Fig. 6, which is a photograph of a fuel plate that experienced 3,426 pulses and 935 steady state operations. There are cracks from the inner surface of the plate to two of the control rod holes, another crack from one of these holes to the outer surface, and one third of the boss has been broken away from the top of the fuel. The crack on the outer surface was detected during a routine inspection. A review of the FBR operational data does not indicate the existence of any major indicators to which one can attribute the development of the cracks in the ring. One of us (J. A. Horak) has suggested that the initial damage was the result of the reactor excursion during the test of the modified core (9).

---

* Fast pulsed reactor and fast burst reactor are terms often used interchangeably to describe highly enriched, all metal systems where fission is predominantly with fast neutrons.
A new core was put into operation in June 1972, and it appears to be performing satisfactorily. All components of the new core were fabricated and aluminum ion plated at Y-12 and nondestructively examined at Sandia Laboratories prior to assembly of the reactor (10).

The Army Pulsed Radiation Facility, APRF, Fig. 7, is located at the Aberdeen Proving Ground, Maryland, and essentially a second generation HPFR (11). The U-10 w/o Nb fuel components are aluminum ion plated and the reactor is operated in a dry nitrogen environment to minimize the possibility of stress corrosion cracking. This reactor is also operated in both the pulsed and steady state modes. A normal pulse to $1.5 \times 10^{17}$ fissions in approximately 50 μsec produces a $\Delta T_{\text{max}}$ of 365°C and a $\Delta T_{\text{avg}}$ of 180°C (15). Maximum fuel temperature during steady state operation at 4.5 kW is approximately 300°C.

During early testing operations of the reactor a pulse was experienced that produced $6.09 \times 10^{17}$ fissions in a pulse width of approximately 26 μsec which is three times larger than the maximum planned operational yield (12). As a result of this pulse, portions of the core reached 1150°C. The center one third of the safety block melted; the fuel plates near the axial center of the core were distorted and cracked from the inner surface to the bolt holes and control rod holes (12). The U-10 w/o Nb bolts were stretched and bent but they did not fracture. The pulse rod, regulating rod, and mass adjustment rod were also slightly bent. All of these components had to be repaired or replaced before the reactor could be made operational.

In October 1972, a crack was observed in the safety block that had been in the core for 29 months (13). This crack was observed at the longitudinal midplane of the block and it traversed over 90° of the outer circumference of the block. After the block was removed from the reactor a fine crack was detected that traversed the entire inner circumference of the block; also at the longitudinal midplane of the block. The inner crack is at an undercut in the threaded region of the block (13). The block is currently being examined in an attempt to determine the reason for the cracking. It has not been established whether the cracks are due to the operation at the fairly high average yields or to the relatively few pulses at $\Delta T_{\text{max}} > 350°C$ which occurred between February and October 1972. A new safety block has been installed with the undercut in the threaded region eliminated. The core was inspected in March 1973, and no cracks or any form of damage were detected. The components of the core, other than the new safety block, have produced approximately 1,000 pulses with no apparent damage (13).
The Sandia Pulsed Reactor II (SPR II) is operated by Sandia Laboratories in Albuquerque, New Mexico, and began operation in May 1967. This reactor, shown in Fig. 8, has produced more than 4,600 pulses. Experience with SPR II has shown that severe demands are placed on the thermomechanical properties of the fuel which requires emphasis on the quality of the fuel with respect to chemical purity, impurity inclusions, casting voids, and design considerations such as stress concentrations.

Several fuel component failures occurred during the initial operation of SPR II. The pulse behavior and dynamic mechanical response of the reactor were measured with the protective shroud removed. Upon pulsing to a maximum fuel temperature rise of 509°C, a loud report similar to a rifle shot was heard over the intercom and a shower of sparks between the two halves of the core was observed on the closed circuit television monitor. Since there was no visible damage to the core, several additional pulses in excess of 50°C were produced. For the largest pulse with a maximum temperature rise of 606°C, another loud report and shower of sparks was observed. After this pulse, one of the control rods would not function properly so the core was disassembled.

The control rod that malfunctioned had broken in a thread relief area and was separated from the rod drive mechanism. A crack in the top fuel plate of the lower half of the core was observed as shown in Fig. 9 after dye penetrant was applied to the plate. This crack extends outward from the glory hole along a radial thermocouple hole. The control rod was modified by changing from male to female threads and increasing the rod length. The core was reassembled and operated at lower yields for another 850 pulses. Then the core was again disassembled and more cracks were observed in the plate shown in Fig. 9, as well as in three other plates. Some of the cracks in the plate shown in Fig. 9 were in a low stress region near the bolt holes and have been attributed to stress corrosion (14).

Because of the cracking near the glory hole surface and the suspected stress corrosion in the original core, two changes were made in the reactor design. The coolant was changed from dry air to dry nitrogen, off gas from boiling liquid N . The four central fuel plates in the core were slotted to reduce the hoop stress induced by a pulse at the glory hole surface. Four 0.020 inch slots were cut through the plates from the glory hole to the four control rod holes and radial thermocouple holes were eliminated. Expansion measurements conducted on the unslotted and slotted plates showed a considerable reduction in the hoop stress. For example, a maximum temperature rise of 500°C induced a peak tensile stress of 106 ksi in the unslotted plate; for the slotted plate this stress was reduced to 27 ksi. Fuel performance and the duty factor of the reactor have been greatly increased after these design changes.
More recently there have been failures due to cracking in one fuel plate after only 33 pulses; the last pulse was to a $q_{\text{max}}$ of 531°C. Two control rods have fractured after approximately 1,000 and after 2,000 pulses respectively. The cracks in the plate are shown in Fig. 10, and are 180° apart in the boss areas of the plate. A detailed examination that included x-ray radiography, optical and scanning metallography* and chemical analyses was performed on the fuel plate in an attempt to determine the cause, or causes, for the failure after so few pulses.

The x-radiography did not reveal any major anomalies or defects that would have led to the cracking. In addition to the large cracks at the two bosses, there were some small cracks in two of the control rod holes and around the glory hole. Figure 11 shows the microstructure of the region near the glory hole. This region was examined because, to the unaided eye, it appeared to contain some small cracks and/or surface imperfections. As Fig. 11 shows, the apparent cracks are actually a series of voids that are closely spaced and/or interconnected to produce the same effect on the mechanical properties as a crack. Note that some of the voids intersect the glory hole. The micrograph also shows that the grain boundaries are outlined with an almost continuous phase that has been analyzed to be composed of UC-U$_2$N$_3$-U$_2$Mo.

Figure 12 shows the microstructure after etching with citric acid which preferentially attacked the grain boundaries and subgrain boundaries. The subgrains appear to be outlined with UC that precipitated on the subgrain boundaries during homogenization and during cooling from the homogenization treatment. At the homogenization temperature of 950°C the carbon content in the alloy exceeded the solubility limit for C in $\gamma$ phase U-10 w/o Mo. This resulted in precipitation of the carbon at the grain boundaries and subgrain boundaries. In addition, during the cooling from 950°C the solubility of carbon in the U-Mo solid solution decreases with decreasing temperature. As the carbon atoms are rejected from the solid solution they precipitate on the energetically most favorable sites. Within the grains the most energetic sites are the subgrain

* The reactor materials laboratory at Sandia did not possess the facilities for metallographic examination of irradiated fuel material; therefore, the fuel was sent to Argonne National Laboratory (ANL) for optical and scanning electron metallography. The metallographic examination was conducted by H. V. Rhude and J. E. Sanecki of ANL; and the most important results of this examination are shown in Figs. 11-14.
boundaries which are rather stable arrays of dislocations having slight orientation differences from array to array. Since there are many of these arrays within each grain the carbon atoms do not have to diffuse very far during the time of cooling to find a favorable site for precipitation. It is this precipitation of carbon to form UC at the subgrain boundaries that provides the structure within the grains that is shown in Fig. 12. Note also in Fig. 12 that there is little or no outlining of the subgrain boundaries near the primary grain boundaries. Near the primary grain boundaries the carbon which is rejected from solid solution upon homogenization and cooling diffuses to these boundaries since they possess a greater surface energy than the subgrain boundaries. Since a surface must be created for the formation and growth of the UC, this process occurs more rapidly at the grain boundaries than at the subgrain boundaries. This leaves little or no carbon left to diffuse to the subgrain boundaries in this area and as a result, little or no precipitation of carbon occurs in the subgrain boundaries in the region near the primary grain boundaries as illustrated in Fig. 12. The grain boundaries contained a semicontinuous to continuous brittle phase of the aforementioned UC + U_3C + U_6C. This phase has a higher elastic modulus and lower coefficient of thermal expansion than the matrix and produces stress risers (especially for sharp edged particles) during the temperature increases experienced during pulsed operation.

Figure 13 shows that the grain boundary structure is composed of two dimensional dendrites which provide an almost continuous path for crack propagation. The "fern leaf" appearance of the dendrites in the grain boundaries is typical of dendrites that are restricted to two dimensional growth. The presence of the dendrites in the grain boundaries indicates that it was the last phase to form during solidification. The highest freezing point composition nucleated first to form the γ grains; the material with the lowest freezing point was pushed to the grain boundaries by growth of the advancing γ grains. At the grain boundaries the lowest melting phases form and their growth is limited to two dimensions since the γ grains are already solid and they resist physical impingement and/or verмяtation by the newly forming grain boundary phase. Hence, the dendrites are restricted to the two dimensional growth as shown in Fig. 13.

Chemical analyses were made to determine if the Mo and/or C contents in the regions of the bosses that cracked were significantly different than those in other regions of the plate and whether or not the Mo and C contents were within the specified limits. The Mo and C contents were found to be uniform over the entire plate. The Mo content ranged from 9.7 w/o to 10.03 w/o which is within the specified values of 9.50 to 10.50 w/o. However, the carbon content ranged from 646 to 670 ppm which is more than three times the upper
specified limit of 200 ppm. Examination of this plate is continuing with ion surface scattering, decoration of grain boundary, and sub-grain boundary phases with selenium sulfide to determine whether any composition variations exist within these phases; and with Auger spectroscopy to determine whether As, P or Cu have segregated to the grain boundaries since, under certain conditions, each of these elements has been determined to result in embrittlement of bcc alloys (15,16,17,18,19).

The control rod which had failed after 1,000 pulses has been subjected to the same examination as the fuel plate which had failed. The Mo content ranged from 9.57 to 9.58 w/o; however, the carbon level ranged from 360 to 380 ppm which is almost a factor of two higher than the specified maximum. Metallographic examination revealed that almost every grain was outlined with a second phase very similar to that of the fuel plate shown in Fig. 12. There are several microcracks present in or adjacent to the grain boundary phase, as shown in Fig. 14. There are two major cracks in the control rod that appear to have initiated at the root of the control rod thread and then follow the grain boundary phase.

It appears that the high carbon levels in both the fuel plate and control rod resulted in an almost continuous brittle grain boundary phase that provide easy paths for crack initiation and propagation. The fuel plate also contained regions of microvoids. The premature failure of the fuel plate is attributed to cracking along the grain boundary phase and along the microvoids. Fracture of the control rod is attributed to the presence of the brittle grain boundary phase plus stress concentration due to the sharpness of the thread roots.

The control rod that failed after 2,200 pulses is currently undergoing metallographic examination. The SEM images reveal fatigue striations, Wallner lines, ductile fracture, and brittle fracture. The fracture initiated at the root of a sharp thread and was enhanced by the presence of several microvoids in the material just below the thread root.

By working with the fuel vendor, the shrinkage porosity appears to have been eliminated by adding 10% more material to the melt and maintaining the casting at high temperatures for longer time to allow sufficient molten metal to flow into the shrinkage areas. All pulsed reactor fuel components are now being made from special melts of low carbon enriched uranium. The authors have also initiated a nondestructive testing, NDT, program for pulsed reactor fuels. This program is providing valuable pre-irradiation information on the fuel components so that the effects of pulsing, temperature and radiation may be accurately assessed.
A new reactor, SPR III, is being planned and designed at Sandia. It is intended that SPR III utilize all, or as much as possible, of the information obtained from the operating experience presented in this paper. The fuel for SPR III is fully enriched \( \gamma \) phase U-10 w/o Mo. There are no control rod holes, no bolt holes and no sharp corners in the plates. All of these design features are to reduce thermomechanical stresses in the fuel components.

**Summary**

The failures of U-10 fuel components early in the history of pulsed reactors have been attributed to (1) stress corrosion cracking, (2) design problems, (3) fuel material quality, and (4) accidents. The stress corrosion of the \( \gamma \) phase U-10 w/o Mo has been eliminated, or at least minimized, by providing a cover gas of dry nitrogen (obtained from liquid nitrogen boil off) over the reactor. The acquisition of data relative to the response of the fuel components under the dynamic conditions present in these reactors has resulted in design correction. Operations of the pulsed reactors to inner core temperature rises of the order of 300°C are routine. For high yield pulses, with temperature rises in the range of 300 to 500°C, the performance of the fuel components is directly related to the quality of the fuel. The properties of the fuel material is very dependent on minor element chemistry, i.e., carbon, and manufacturing history.

To satisfy the ever increasing demands for higher yields which produce \( \Delta T \)'s of 500–600°C per pulse and/or shorter pulse widths, fuel of the highest quality is required. A metallurgy program and an NDE program have been established to produce fuel of the quality required to achieve these goals and to maximize fuel performance in pulsed reactors.

**Acknowledgements**

The authors are extremely indebted to the following individuals that contributed to this paper in the manner indicated.

<table>
<thead>
<tr>
<th>Person</th>
<th>Affiliation</th>
<th>Assistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>C. E. Johnson</td>
<td>Argonne National Laboratory</td>
<td>Ion surface studies and helpful discussions on thermodynamics of UC and UN systems.</td>
</tr>
<tr>
<td>Person</td>
<td>Affiliation</td>
<td>Assistance</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>M. H. McTaggart</td>
<td>Atomic Weapons Research Establishment, Aldermaston, England</td>
<td>Helpful discussions and correspondence on VIPER.</td>
</tr>
<tr>
<td>A. H. Kazi</td>
<td>Aberdeen Proving Ground</td>
<td>Helpful information on ATRF.</td>
</tr>
<tr>
<td>O. L. Kruger</td>
<td>Battelle Columbus Laboratories</td>
<td>Helpful discussions on the thermodynamics and phase relationships in the UC, UN, U_{2}Mb systems.</td>
</tr>
<tr>
<td>T. F. Wimett</td>
<td>Los Alamos Scientific Laboratory</td>
<td>Helpful information on Godiva IV.</td>
</tr>
<tr>
<td>L. R. Peterson</td>
<td>Lawrence Livermore Laboratory</td>
<td>Helpful information on Super Kukla.</td>
</tr>
<tr>
<td>L. B. Holland</td>
<td>Oak Ridge National Laboratory</td>
<td>Helpful information on HPRR.</td>
</tr>
<tr>
<td>P. D. O'Brien</td>
<td>Sandia Laboratories</td>
<td>Careful review of this manuscript.</td>
</tr>
<tr>
<td>T. R. Schmidt</td>
<td>Sandia Laboratories</td>
<td>Careful review of this manuscript.</td>
</tr>
<tr>
<td>A. De La Paz</td>
<td>White Sands Missile Range</td>
<td>Helpful discussions and correspondence on FBR.</td>
</tr>
<tr>
<td>T. Luera</td>
<td>White Sands Missile Range</td>
<td>Helpful discussions and correspondence on FBR.</td>
</tr>
</tbody>
</table>
References


References
(cont'd)


List of Figures

1. Godiva IV

2. VIPER

3. Health Physics Research Reactor (HPRR)

4. Super Kukla

5. White Sands Missile Range Fast Burst Reactor (WSMR-FBR)

6. WSMR-FBR Cracked Plate
List of Figures (cont’d)

7. Army Pulsed Radiation Facility (APRF)
8. Sandia Pulsed Reactor II (SPR II)
9. SPR II Cracked Plate
10. Cracks in Modified SPR II Plate
11. Micrograph Section of Modified SPR II Plate (50X)
12. Micrograph Section of Modified SPR II Plate (200X)
13. SE! Section of Modified SPR II Plate (500X)
14. Microcracks in SPR II Control Rod (500X)
Godiva IV
PLUGGED HOLE FOR
SAMPLE INSERTION

BOLTS A FULL PLUG
(U-Ma)

MASS ADJUST ROD
(U-Mа)

HEATING ROD
(U-Mа)

CENTER PLUG
(St)

THERMOCOUPLES

SAFETY BLOCK
(U-Mа)

SAFETY TUBE (St)

Health Physics Research Reactor
(HPRR)

Super Kukla

UPPER CORE HALF
SPRING SUPPORTS (4)
STEEL SUPPORT PLATE
LOWER CORE HALF
BASE PLATE
SHOCK ABSORBERS
UPPER CROSSHEAD
BRAKE

SHIM ROD
BURST ROD
SAMPLE CONTAINER
HYDRAULIC CYLINDER
BURST ROD DRIVE
White Sands Missile Range Fast Burst Reactor
(WSMR-FBR)
Army Pulsed Radiation Facility
(APRF)

Sandia Pulsed Reactor II
(SPR II)
Cracks in Modified SPR II Plate

SPR II Cracked Plate
Micrograph Section of Modified SPR II Plate (50X)

Micrograph Section of Modified SPR II Plate (200X)
SEM Section of Modified SPR II Plate (500X)

Microcracks in SPR II Control Rod (500X)