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SUBJECT: PRELIMINARY REPORT ON RESULTS OF MSRE ZERO-POWER EXPERIMENTS

TO: Distribution

FROM: P. N. Haubenreich

ABSTRACT

The MSRE first attained criticality on June 1, 1965 with a ^{235}U concentration within 1% of the predicted value. Initial critical conditions were 1181°F, fuel circulation stopped, one control rod inserted 0.03 of its worth and 65.4 kg of ^{235}U in the loop (plus 4.2 kg in a drain tank). Subsequently the reactor was held at 1200°F while the $^{235}UF_4$ concentration was increased by the addition of 79 enriching capsules containing 6.6 kg ^{235}U. During these additions, experiments were done to measure rod sensitivity and total worth, ^{235}U concentration coefficient of reactivity, temperature coefficient, pressure coefficient, and effect of circulation on reactivity. Dynamics experiments gave information on system transfer functions and separated prompt (fuel) and delayed (graphite) temperature coefficients. Nuclear power was restricted to a nominal 10 watts, except during transients, when 10 kw was permitted. The experiment was concluded on July 3 and the salt was drained to permit preparations for high-power operation.

There were no mechanical difficulties of any consequence during the experiment. Salt analyses showed practically no corrosion. Analysis of the reactor physics data, although incomplete, has shown that all the observed parameters are in good agreement with predicted values.

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INTRODUCTION

Preliminary testing of the Molten Salt Reactor Experiment began in the fall of 1964. The salt systems were heated to 1200°F, purged with helium to remove moisture, and 66 LiF-34 BeF_2 salt was charged into the fuel and coolant systems. Salt was circulated for 1000 hr in the fuel system and 1200 hr in the coolant system as most of the non-nuclear testing was completed. This run, designated PC-1, was concluded in March, 1965.

In the shutdown after PC-1, final preparations were made for "zero-power" nuclear operation. These included installation of the sampler-enricher, completion of the nuclear instrumentation and controls, and operator examinations and certification.

The salt which had been circulated through the fuel system was processed to remove oxide, then was isolated in the flush-salt tank for future use. The basic fuel salt, lacking only the enriched uranium to bring it to the final composition, was charged into a drain tank. The fuel system was heated and this "carrier" salt was circulated for 10 days in Run PC-2. Analysis of the salt showed no abnormalities, all equipment operated well, and all was in readiness for the nuclear experiments.

Addition of $^{235}UF_4$-LiF to the salt began on May 24, and on June 1 criticality was first attained. Following this experiment, more ^{235}U was added to bring the concentration up to the level required for power operation. While the extra ^{235}U was being added, experiments were done to measure the nuclear characteristics of the system. This series of experiments was completed on July 3, the fuel salt was drained and the system was flushed, concluding Run 3.

This report describes the preliminary findings of the nuclear experiments, the chemical behavior of the fuel salt and the performance of the mechanical components.

Final preparations for high-power operation are presently being made. These include inspection, maintenance, installation of shielding, and sealing and testing the containment.

NUCLEAR EXPERIMENTS

Initial Critical Loading

The purpose of this experiment was to provide a check on the calculations of critical concentration under the simplest conditions: the core isothermal, rods fully withdrawn, and the fuel stationary. It also served to establish the basepoint from which the ^{235}U additions necessary to reach the operating concentration could be made with confidence.

The fuel salt composition specified for power operation is 65 LiF-29.2 BeF_2-5 ZrF_4-0.8 UF_4 (expressed as molar percentages). The total uranium content is considerably above the minimum required for criticality if highly enriched uranium were used, and was chosen for reasons of chemistry.

The critical ^{235}U concentration was predicted by calculations using a multi-group, one-dimensional diffusion code, MODRIC, with thermal-group cross sections obtained from cell calculations by the THERMOS code and fast-group cross sections calculated by GAM-2.[1,2] The geometrical approximations were checked by using a two-group, two-dimensional code, Equipoise-3, with group constants for each region from MODRIC. It was predicted that the reactor would be critical at 1200°F, rods out, fuel static with 0.256 mole % $^{235}UF_4$ (0.795 mole % total UF_4).

Instead of using 32%-enriched uranium to make up the fuel salt, we decided to start with depleted uranium in the salt and add the required amount of ^{235}U as highly enriched uranium (93% ^{235}U). This permitted preliminary operation with uranium in the salt before the beginning of nuclear operation and also facilitated the manufacture of most of the uranium-bearing salt. The salt was prepared in three lots: the carrier salt, containing the beryllium, zirconium and most of the lithium fluorides; 73 LiF-27 UF_4 eutectic containing 150 kg of depleted uranium; and eutectic containing 90 kg of ^{235}U in the highly enriched form.

Thirty-five cans of carrier salt and two cans of eutectic containing the depleted uranium were blended as they were charged into a drain tank in April. This mixture of salt was then circulated for 10 days at 1200°F while the sampler-enricher was tested and 18 samples were analyzed to

establish the initial composition. The critical experiment then consisted of adding enriched uranium in increments to bring the ^{235}U concentration up to the critical point.

Nuclear instrumentation for the experiment consisted of two fission chambers, two BF_3 chambers and an ^{241}Am-^{242}Cm-Be source, located as shown in Fig. 1. The fuel salt itself also constituted a neutron source, due to reaction of ^{234}U alphas with beryllium and fluorine.

The enriching salt was added in two ways: by transfer of molten salt from a heated can into a drain tank, and by lowering capsules of frozen salt into the pump bowl via the sampler-enricher. The latter method was limited to 85g ^{235}U per capsule, only 0.0012 of the expected critical loading. Therefore the bulk of the ^{235}U was added in 4 additions to the drain tank. After each addition the core was filled and count-rate data were obtained to monitor the increasing multiplication.

The amount of ^{235}U expected to make the reactor critical was calculated to be 68.7 kg, using the volumetric concentration from the criticality calculations and the volume of salt thought to be in the fuel loop and drain tank. (The value of salt density which was used to get the volume from the known weight of salt is now believed to be erroneous. See later discussion.)

Before the addition of enriched uranium, count rates had been determined with barren salt at several levels in the core. Then as the core was filled after each ^{235}U addition, the ratio of count rates at each level was used to monitor the multiplication. (Fig. 2 shows elevations; count rates were determined with salt at 0.4, 0.6, 0.8, and 1.0 of the graphite matrix and with the vessel full.)

Count-rate ratios with the vessel full after each of the four major additions are shown in Fig. 3. Each addition, fill, and drain took between one and two days, so only four major additions had been planned. After the third addition, with 64.54 kg ^{235}U in the salt, the projected critical loading was 70.0 ± 0.5 kg ^{235}U. (The 1-inch BF_3 chamber located in the thermal shield, whose count rates extrapolated to a higher value was known to be strongly affected by neutrons coming directly from the source.) The fourth addition was intended to bring the loading to about

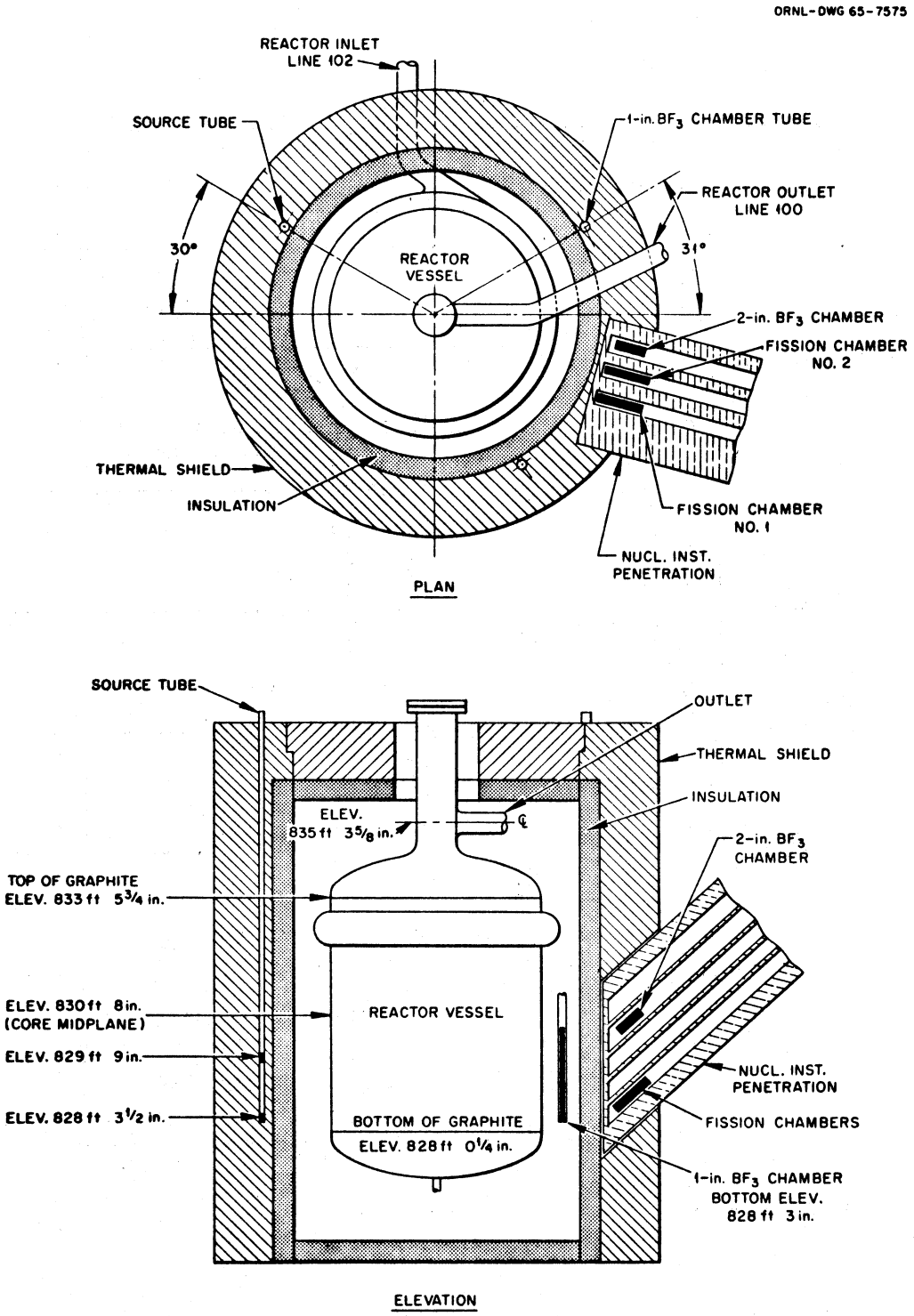

Fig. 1. Source and Instrumentation in Initial Critical Experiment.

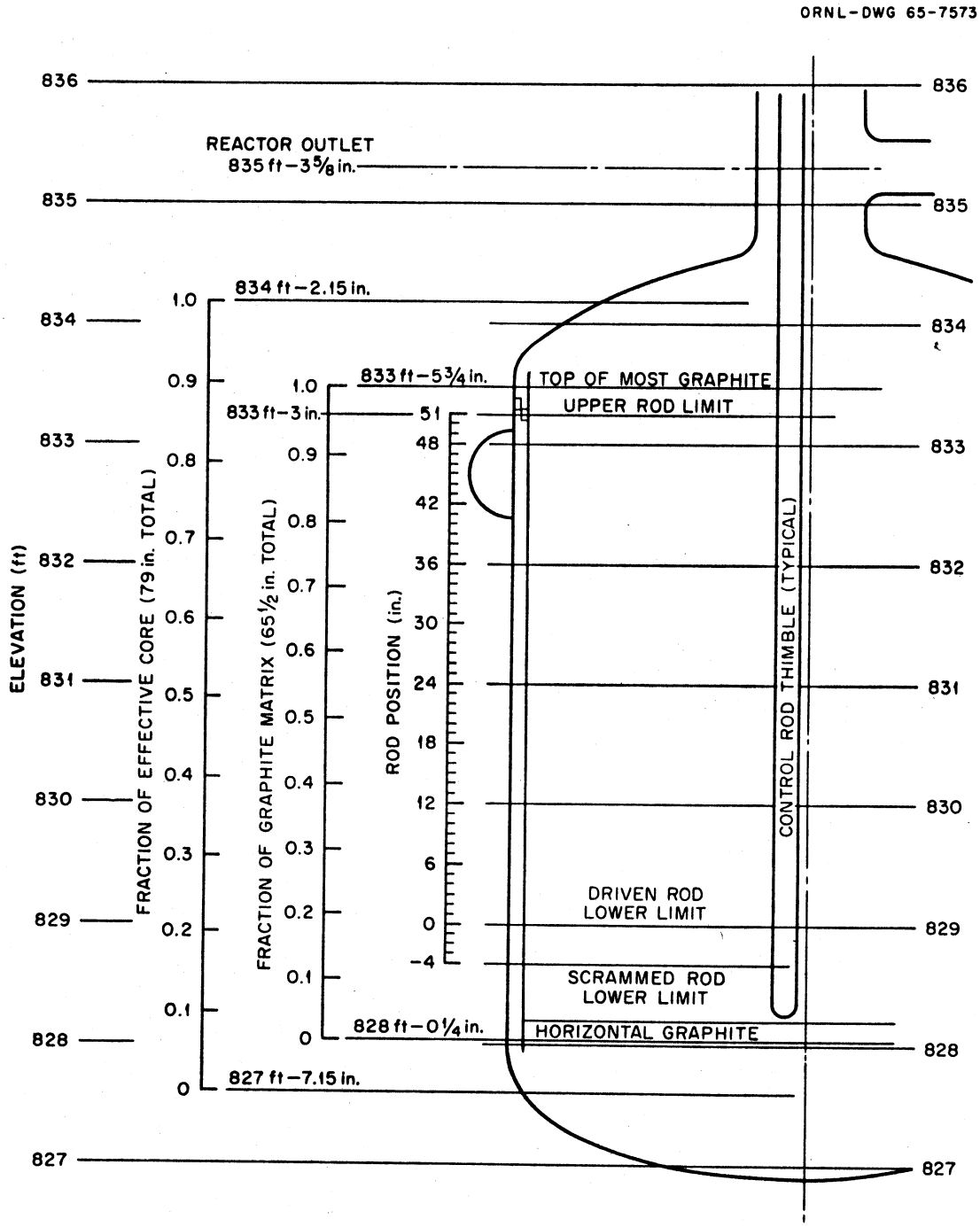

Fig. 2. Relation of Rod Position and Levels in Reactor Vessel.

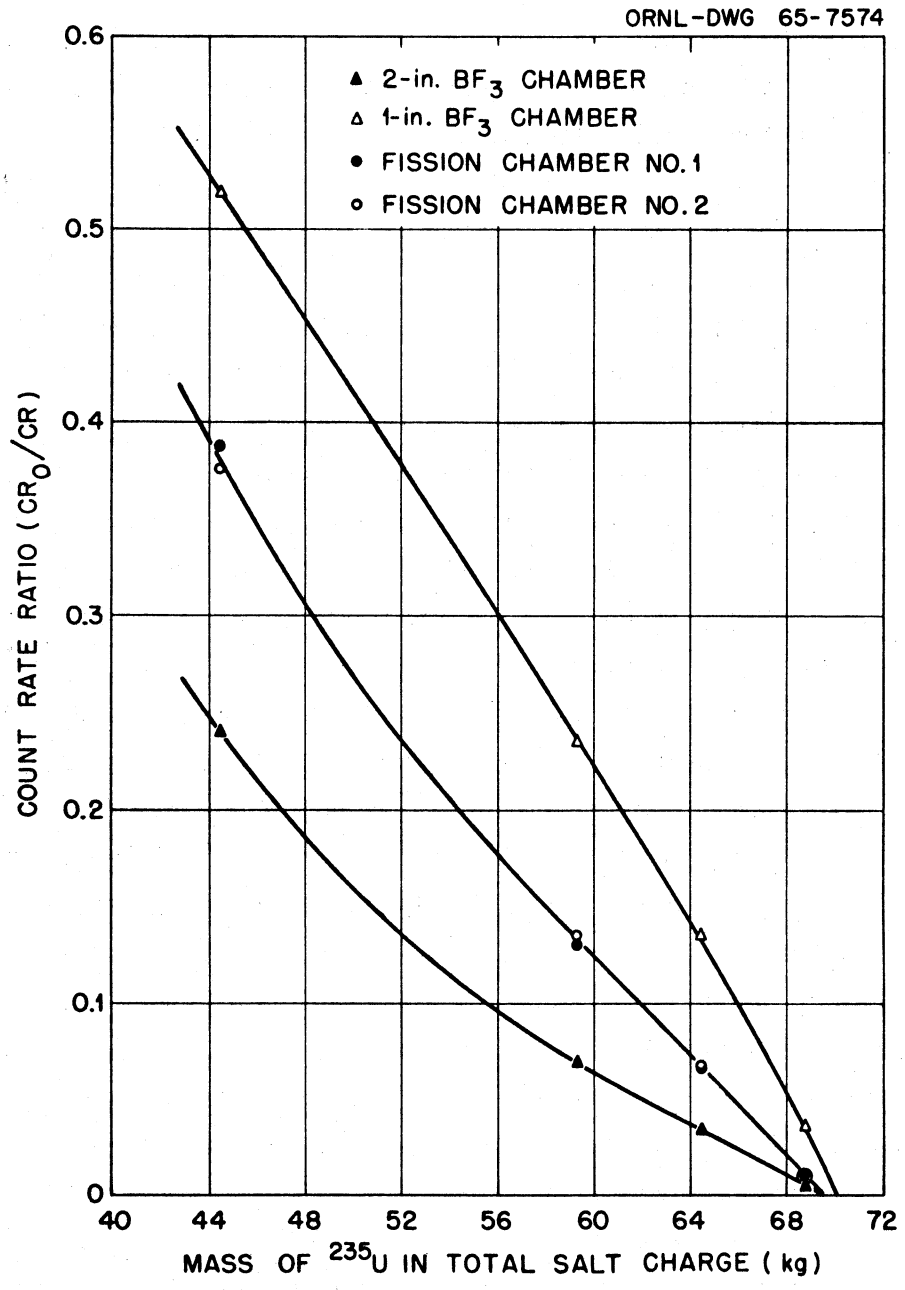

Fig. 3. Count Rate Ratios After First Four Additions of ^{235}U. (Vessel full, rods at 51 in., Source at 829'-9", chamber locations as in Fig. 2.)

1 kg below the critical point. (This was not as bold as it has seemed to some; the minimum critical loading at which we were shooting was only a checkpoint before subsequent additions. No question of safety was involved if there had been an overshoot.) 4.38 kg of ^{235}U was added and the count rates showed the loading was within 0.8 kg of critical when the rods were withdrawn and circulation was stopped. Preliminary estimates of rod worth and circulation effect, based on changes in subcritical multiplication, were approximately the expected values.

In the final stage, enriching capsules were added through the pump bowl to bring the loading up 85g at a time. After each addition circulation was stopped, the rods were withdrawn and count rates were measured. The external source was withdrawn for some of the measurements to see the relative strength of the internal and external source. With the reactor within 0.2% $\delta k/k$ of critical, slight variations in temperature caused considerable changes in multiplication. (Variations in the voltage of the area power supply change the heater inputs slightly, requiring fine adjustments of the heater controls to keep the temperature precisely at a specified temperature.) After 7 capsules, it appeared that after one more, the reactor could be made critical. The eighth was added, circulation was stopped and the rods were carefully withdrawn. At 6:00 PM, June 1, the reactor reached the critical point, with two rods at full withdrawal and the other inserted 0.03 of its worth. Criticality was verified by leveling the power at successively higher levels with the same rod position. The ^{235}U loading was 69.6 kg.

Predicted and observed ^{235}U requirements for criticality are compared most logically on the basis of volumetric concentration. The required volumetric concentration is nearly invariant with regard to the fuel-salt density (unlike the mass concentration, which varies inversely with density) and depends not at all on system volume or total inventory.

The "observed" ^{235}U concentrations are on a weight basis, obtained from either inventory records or from chemical analyses. These weight concentrations must be converted to volumetric concentration by multiplying by the fuel-salt density. The amounts of ^{235}U and salt weighed into the system gave a ^{235}U weight fraction of 1.42% at the time of the initial criticality. The chemical analyses during the precritical operation and