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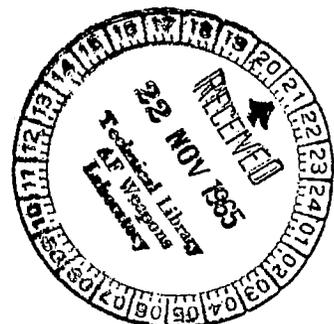
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CRITICAL MASS STUDIES WITH NASA ZERO POWER REACTOR II

I-CLEAN HOMOGENEOUS CONFIGURATIONS

*by Thomas A. Fox, Robert A. Mueller,
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SUMMARY

The NASA Zero Power Reactor II (ZPR-II) has been used to determine experimentally the critical masses for more than a tenfold range of highly enriched (93.2 percent U^{235}) aqueous uranyl fluoride fuel concentrations in clean cylindrical geometries. The ZPR-II reactor tank permits the assembly of cylindrical cores 76.2 centimeters (30 in.) in diameter and with lengths (heights) up to 90 centimeters either bare or radially reflected by about 15 centimeters (6 in.) of water. The specific range of fuel concentrations was from hydrogen to uranium²³⁵ atom ratios of about 150 (167 g U^{235} /liter of fuel solution) to 1650 (15 g U^{235} /liter).

In addition to the critical masses, data are presented on the temperature coefficient of reactivity and the incremental reactivity worth at criticality for a similar range of concentrations. Some of the physical properties for the fuel concentrations are presented, based on measurements made at the Lewis Research Center. A brief description of the ZPR-II and the experimental procedures used are also included.

INTRODUCTION

The NASA Zero Power Reactor II (ZPR-II) was designed and built by the NASA Lewis Research Center to provide a tool for the study of heterogeneous inserts in solution critical systems. This reactor uses aqueous solutions of highly enriched (93.2 percent U^{235}) uranyl fluoride salt (UO_2F_2) in a cylindrical tank with a diameter of 76.2 centimeters (30 in.) that is either unreflected or radially reflected by about 15 centimeters (6 in.) of water. A range of critical assemblies can be achieved by varying the fuel solution concentration. Control consists solely of solution height manipulation, thereby clean cylindrical geometries for criticality determinations are provided.

Much previous work has been reported involving critical systems that use uranyl fluoride solution fuel (e.g., see refs. 1 and 2). This study represents new parametric information because of the particular reactor vessel geometry involved. The criticality data for clean homogeneous configurations are presented; in addition, solution temperature coefficients and incremental height

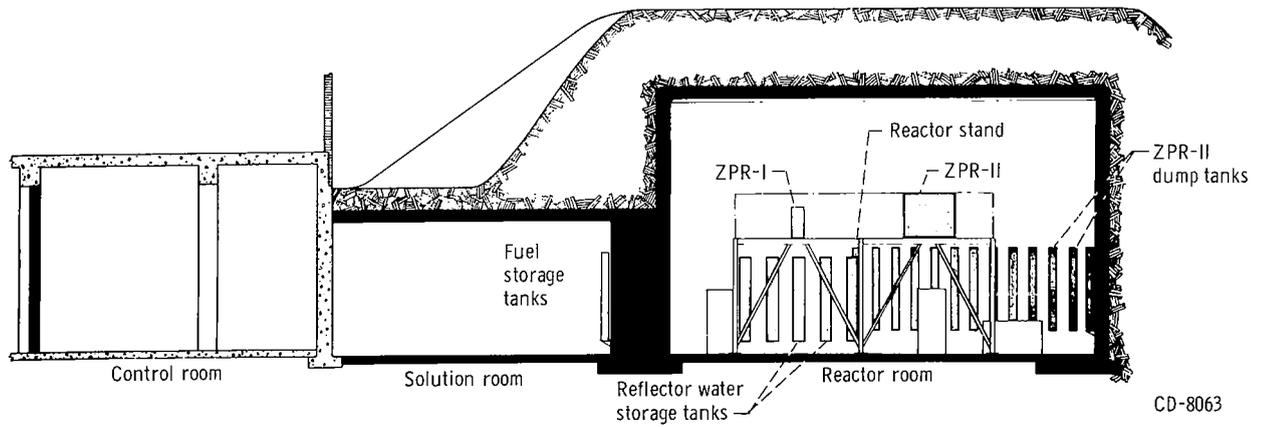
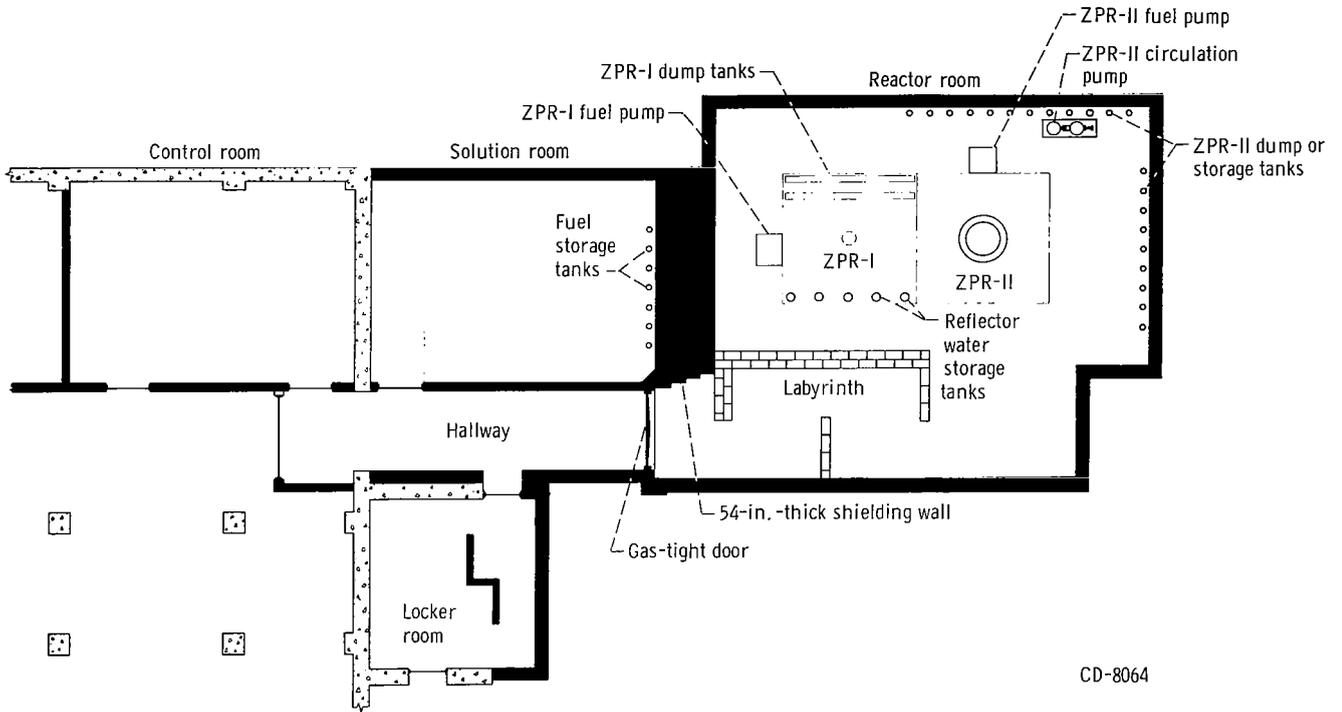


Figure 1. - ZPR facility.

reactivity worth measurements for the systems studied are also included.

DESCRIPTION OF NASA ZPR-II

The ZPR-II is one of two critical systems making up what is presently known as the NASA Zero Power Reactor Facility (ZPRF). The layout of the ZPRF is shown in figure 1. The facility proper includes a control room, reactor room, solution room, locker room, and a connecting hallway. The reactor room or test cell is constructed of reinforced poured concrete and is located underground to minimize shielding problems. A 54-inch-thick (137 cm) wall is provided between the reactor room and the solution room to permit access to the solution room at all times.

The ZPR-II shares the reactor room with the Zero Power Reactor I (ZPR-I), a schematically similar but much smaller and separate system that uses the same kind of fuel. Both reactor vessels are mounted on a stand, so that the reactor midplane is about midway between the floor and the ceiling of the reactor room. The reactors are also located approximately at epicenters of the reactor room (see plan view in fig. 1(a)). These locations are intended to keep wall effects in all directions to a minimum. The reactors use a single control console and instrumentation system to assure operation of only one reactor at a time. The fuel piping systems for the two reactors are separate and independent, but both are connected to the solution room storage system and the vacuum distilling apparatus used to concentrate fuel solution.

The ZPR-I and ZPR-II are both solution critical systems. Each consists essentially of a geometrically safe fuel storage system, a reactor tank where various different configurations may be assembled, and a solution manipulating system that enables the experimenter to assemble remotely the critical reactor in a controlled manner. The assembly takes place with the reactor room closed to provide a sealed test cell, which gives both adequate shielding from direct radiation and protection from the airborne activity associated with the operation of such systems.

The ZPR-II fuel storage system consists of 21 polyethylene tanks with 5-inch (12.7 cm) inside diameters located on 18-inch (45.72 cm) centers along part of the east and north walls of the reactor room (see figs. 1(a) and 2). These are connected by a common manifold and makeup a storage and dump tank system of approximately 550-liter capacity. A custom-made positive-displacement type pump is used to transfer the fuel from the dump tanks to the reactor vessel. The only reactor control is the fuel height manipulation possible with this variable-speed pump, although safety devices in the form of a cadmium safety blade and two dump valves are incorporated.

The reactor vessel is constructed basically of two concentric aluminum cylinders welded to a common bottom plate. This configuration provides a central core region about 76.2 centimeters in diameter by 106 centimeters in height surrounded radially by an approximately 15-centimeter-thick annular region that may be used for a water reflector, (see fig. 3). The system is unreflected axially and is open to the atmosphere at the top. Fuel solution and reflector water are inserted into and removed from the vessel through

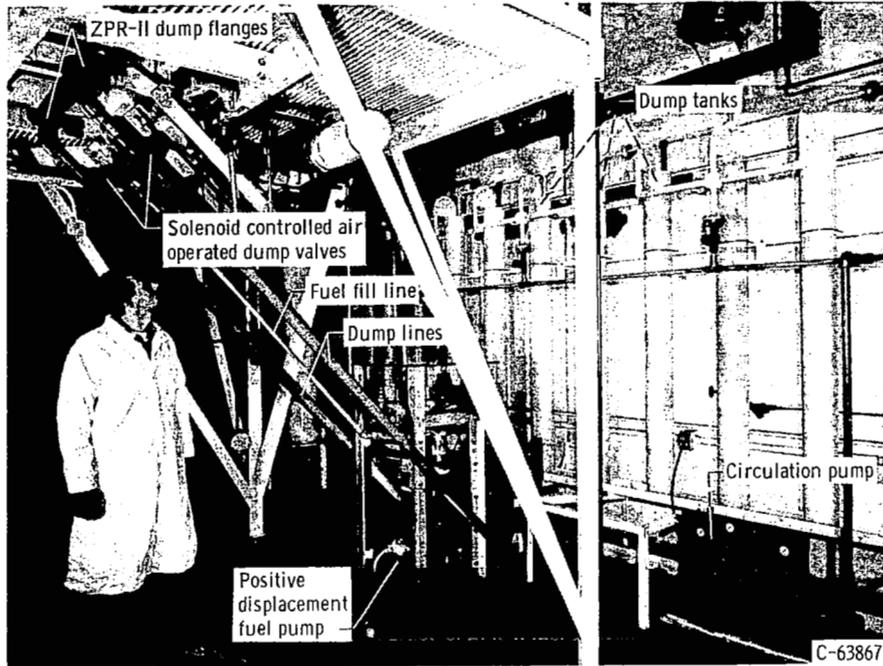


Figure 2. - Portion of ZPR-II fuel system.

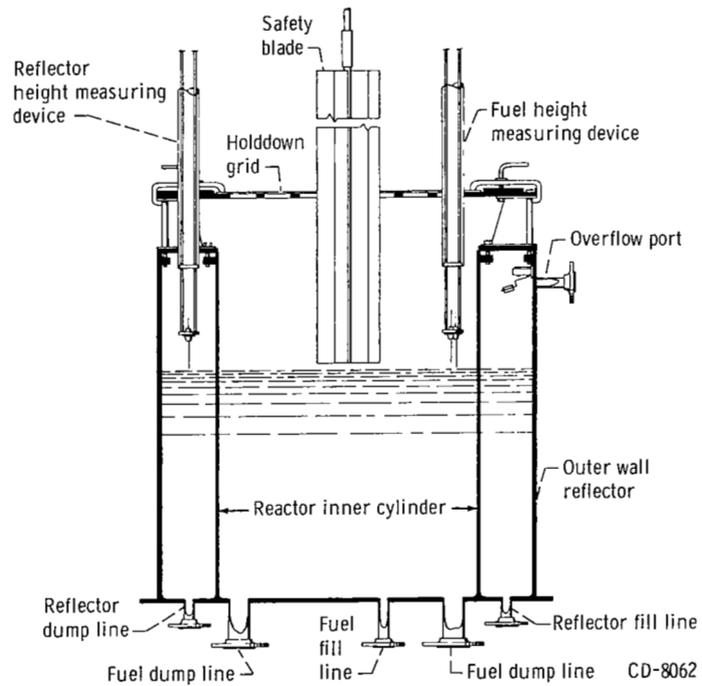


Figure 3. - ZPR-II reactor tank.

TABLE I. - DIMENSIONS OF ZPR-II VESSEL

Component	Inside diameter, cm	Outside diameter, cm	Wall thickness, cm
Reactor inner cylinder: 15 cm from bottom Near top (out of roundness)	76.152±0.013 76.137±0.076	77.559±0.025	0.704±0.018
Reactor outer cylinder	107.95±0.64	110.5±0.64	1.27
Reactor bottom, core region			1.270±0.064
Reactor bottom, reflector region			1.270±0.157

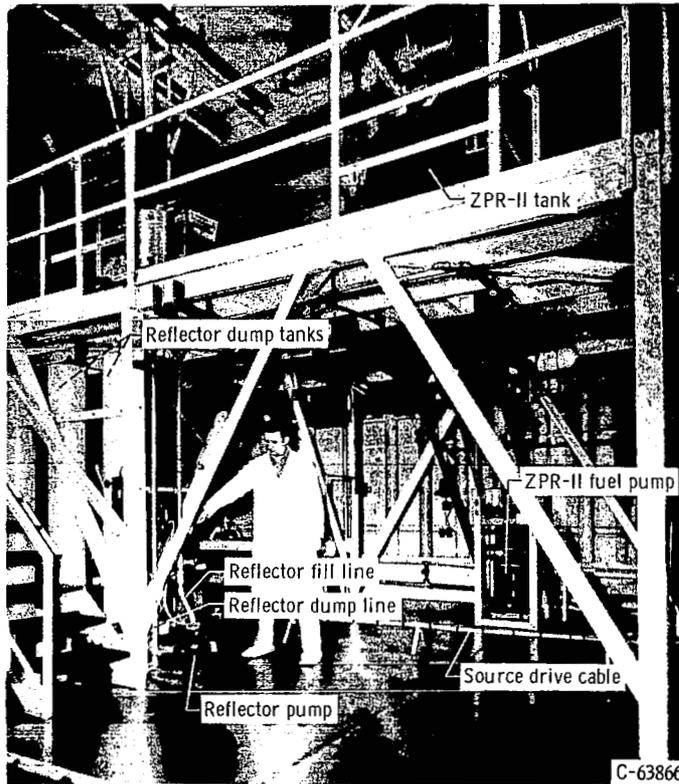


Figure 4. - General view of reactor room showing portion of ZPR-II installation.

penetrations in the bottom plate. The structure is extended above the top of the vessel to permit the secure positioning of the various heterogeneous arrays of voids and absorbers while retaining the open upper surface property of the critical reactor. The precise dimensions of the vessel are given in table I.

Special efforts are made in the choice of construction materials to minimize corrosion. In addition to the polyethylene tanks in the storage system, polyvinyl chloride piping and valves are used throughout; Teflon bellows are used on the fuel pump. The reactor tank is made of aluminum that has been covered with a thin coating of Glyptal to prevent corrosion. Any additional

items coming in contact with the fuel are either corrosion resistant or protected in some similar fashion from the fuel solution.

A reflector water system consisting of polyethylene storage tanks, a canned rotor pump, the appropriate control valves, and piping can be seen in figure 4. This system has a capacity of about 450 liters.

The height of the fuel solution is measured by a direct current probe arrangement. This probe is actually a very fine platinum-iridium wire that is attached to the end of a precision lead screw that is motor driven and manually controlled from the control console. When the probe makes contact with the upper surface of the fuel solution, a meter deflects on the control console. At the same time a selsyn arrangement provides a position readout from the lead screw. The height measuring device is designed to read solution heights to the nearest 0.0025 centimeter (0.001 in.). This value is not to be mistaken as the accuracy of the absolute height measurements. Because of inherent difficulties in calibrating the zero height at the reactor tank bottom on a regular basis, as well as the tolerances in the tank dimensions, the absolute accuracy of the height measurements is of the order of ± 0.075 centimeter.

The fuel solution temperature is measured by an iron-constantan thermocouple swaged in a stainless-steel jacket for protection from solution corrosion. The reference junction for the thermocouple is a demineralized water-ice bath. The output from the thermocouple is measured with a precision potentiometer and galvanometer to the nearest 0.005° C. These measurements are relative since the thermocouples are not calibrated for absolute measurements. Comparison checks with a calibrated thermometer indicate agreement of the order of $\pm 0.25^{\circ}$ C. A more precise measurement of the temperature has not been necessary for the experimental work conducted to date at the ZPRF.

EXPERIMENTAL PROCEDURES

The basic measurement involved in these studies has been the determination of the critical mass of uranium 235 in the 76.2-centimeter-diameter cylindrical vessel. An accurate experimental determination of critical mass is dependent on the precision to which several variables, associated with the steady-state critical system, can be measured. These variables include concentration, volume, and temperature of the fuel solution at the steady-state critical condition and the determination of the steady-state critical condition itself. The determination of the steady-state critical condition is the basic operation around which the other measurements are centered.

Preparation of Fuel Solution

In any given experiment, the fuel solution of desired concentration is prepared first by adding or removing water from the existing solution. Fuel dilution or a decrease in concentration is accomplished by adding demineralized water to a particular concentration and mixing. Water removal to increase fuel concentration is more difficult and is accomplished by evaporating water from a given solution. A vacuum evaporator-condenser arrangement is used to achieve

the desired water removal at a low temperature to minimize the corrosion effects on the heating and cooling elements and to ensure the integrity of the polyethylene container used.

A very important step in any fuel preparation is the thorough mixing of the fuel solution. The multitank array of long, small-diameter cylinders is not conducive to easy mixing. However, two methods for mixing are used in the ZPR-II fuel system: the first is the circulation of the fuel solution within the storage tank array; the second is the transfer of all the fuel solution to be used from the storage system to the reactor tank (loaded with poison absorbers to prevent criticality) and back several times. In the latter method, mixing was more readily obtainable. By either method the fuel solution was mixed prior to operation, and the fuel concentration was determined from a sample obtained as quickly after operation as practicable.

Reactor Operation

The startup procedures for the ZPR-II are those typical for solution critical systems. The fuel is assembled in a controlled manner in the presence of a neutron source. In this case a 1-curie plutonium-beryllium neutron source is located externally at the reactor tank bottom. With each increment of fuel addition there is an increase in the neutron flux due to multiplication of the original source neutrons. When the critical condition is approached closely (i.e., within a few centimeters of the critical height) the actual critical height can be predicted quite accurately from multiplication measurements. For the experimental arrangement associated with ZPR-II the multiplication must be of the order of 2 or more to have meaning, and a good prediction of critical height is generally obtainable with a multiplication of the order of 10 or more. When the reactor reaches criticality, the neutron source is withdrawn from the vicinity of the core and returned to its storage container to ascertain if the system is truly self-sustaining. If a reflected system is being operated, the water level is adjusted to match the fuel solution height at criticality.

In order to determine the steady-state condition accurately, a constant self-sustaining neutron level is maintained for 15 minutes or longer in an effort to assure that all factors which contribute to nonequilibrium in the system have been allowed to stabilize. These factors include surface waves, structure vibrations, reactor system kinetics, and gaseous voids due to gas evolution and pump agitation. The magnitude of the neutron level used is such that the signal-to-noise ratio is high on the associated control instrumentation. The power level providing such a condition will vary depending on the particular configuration and the immediate electrical noise conditions, but it is generally no greater than 1 watt thermal. Once the steady-state condition is considered to exist, it is deliberately disturbed by putting the reactor on long positive and long negative periods that bracket the steady-state condition closely. This procedure assures that the steady-state condition is real and reproducible.

Measurement of Fuel Solution Concentration

The experimental variable that has proved to be the limiting one when making most critical mass determinations is that of fuel solution concentration. (For some short "pancake" reactors the error in critical mass associated with height determination may be greater.) In discussing highly enriched aqueous fuel solutions, the parameter most universally used to designate concentration is the hydrogen to uranium 235 atom ratio H/X . This parameter presents a problem because the hydrogen atom concentration is difficult to determine precisely. Inasmuch as the hydrogen atom density in the range of H/X studied has much less effect on criticality calculations than the uranium atom density, the latter is used as the primary index for this work. The H/X ratio is also presented because this parameter is more universally used.

Since the basic properties of the fuel concentration are of fundamental importance to all critical mass studies at the ZPRF, a careful investigation of some of the solution properties has been carried out. This report presents only the physical properties determined for the fuel concentrations directly involved in this study. A brief discussion of the methods used is also presented. Capability has been developed to measure fuel solution concentration by two different methods at the ZPRF. The first method makes use of the solution density properties of the fuel. Measurement of the fuel solution density, though simple in principle, requires great care in performance and prior knowledge of certain physical properties of the fuel solution such as those given in reference 3. This method is favored in many cases because it is the most direct, does not alter the form of the fuel, and requires a minimum investment in equipment. The actual density measurement has been done by two different techniques at the ZPRF. The first is by a precision hydrometer that gives an accuracy (maximum error) of about ± 0.1 percent in solution density. A better density measurement, with a maximum error of about ± 0.03 percent, can be obtained by using calibrated volumetric flasks of high quality. There is a fundamental limitation in the density measuring method that is best illustrated by an example. A tenfold change in H/X from 150 to 1500 results in a solution density change from about 1.21 to 1.02 grams per cubic centimeter. Thus, density is a rather insensitive index of the fuel concentration.

The second method of determining fuel concentration makes use of a chemical analysis to determine the uranium content of a known volume of fuel solution. A gravimetric method was chosen for analysis in this case because of the absence of any elements in the $UO_2F_2-H_2O$ solution that would interfere with such an analysis. The procedure involves addition of ammonium hydroxide to a known volume of fuel. A precipitate, ammonium di-uranate, is formed and subsequently separated by filtration. The precipitate is then converted to uranium oxide (U_3O_8) by igniting the filter paper and heating the precipitate in a muffle furnace for about an hour at $1000^\circ C$. The residue U_3O_8 can then be weighed with precision. This method, described in greater detail in reference 4, is advantageous because it does not require previously acquired data. Good agreement with the fuel solution data reported in reference 3 was obtained by using this analysis technique.

Temperature and Temperature Coefficient

The need to measure temperature is associated with two interrelated properties essential to the critical mass determination. These properties are fuel solution density and temperature coefficient of reactivity. The general practice at ZPRF is to correct all data to a single temperature of 20° C (68° F). To this end, all solution density measurements are made at 20° C, and all critical mass studies are corrected to this temperature. To correct the critical height to the base temperature, a study has been made of temperature coefficient at several values of H/X from about 150 to 1600. The temperature span used in the measurements is of the order of 5° C, which is considered adequate to cover the anticipated experimental program.

The ZPR-II is operated at very low power and therefore undergoes no temperature change as the result of heat generation within the core. The variation of fuel temperature is caused by the change in the reactor room air temperature. Since the reactor room is underground, this temperature change is primarily a matter of seasonal rather than short term changes. The reactor room is provided with a heating system and an exhaust fan for ventilation but not with any air-conditioning equipment. The general practice has been to achieve conditions that will give short time periods at nearly constant temperature and to let the long term variations occur naturally. By measuring the temperature and knowing the temperature effects, it is possible to make the necessary corrections and eliminate the need for any closer control of the environment.

The actual experimental measurement of temperature coefficient makes use of the effect of room air temperature on fuel solution temperature to get the necessary fuel solution temperature changes. The general procedure is to raise the room air temperature enough to achieve a fuel temperature increase of about 2° to 5° C and then to determine the critical height at this fuel temperature. The fuel temperature is then reduced and the critical height determined at the lower temperature. It has been found that the temperature coefficient is a constant over the temperature range involved within the accuracy of the measuring technique.

Inhour Technique for Determining Reactivity Worth

The reactivity worths associated with small changes in the core height at criticality have been determined by making use of the inhour formula

$$\rho = \frac{\lambda}{\Lambda k_{\text{eff}}} + \sum_{i=1}^6 \frac{\beta_i}{1 + \lambda_i T}$$

where

ρ reactivity

λ mean prompt neutron lifetime, sec

T reactor period, sec

k_{eff} effective multiplication factor

β_i fraction of total number of fission neutrons belonging to i^{th} delay group

λ_i radioactive decay constant for that group, 1/sec

The technique involves perturbing the steady-state condition of the critical system by a small amount and measuring the associated period. From this period the reactivity is determined by using the value 0.0064 for the delayed fraction β and the values for β_i and λ_i reported in reference 5.

The delayed neutrons have a lower energy spectrum than the prompt neutrons and therefore have a lower probability of leaking from a finite system. The effective worth per neutron of the delayed neutrons consequently is greater than that of the prompt neutrons. Hence, for each reactor there is an effective value of the delayed neutrons (β_{eff}) which is greater than β by an amount depending on the configuration involved. The ratio β_{eff}/β is applied as a single correction to the entire delayed neutron source so that the inhour equation is now

$$\rho = \frac{\lambda}{Tk_{eff}} + \frac{\beta_{eff}}{\beta} \sum_{i=1}^6 \frac{\beta_i}{1 + \lambda_i T}$$

The experimental technique consists of adding a small increment of fuel to the steady-state critical system to place the reactor on a long positive period. This period is determined from data obtained from boron trifluoride (BF_3) counting channels by the usual method of plotting the neutron count rate against time on semilog paper. A series of reactivity values are obtained from reactor periods at different increments in height. The reactivity as a function of the increase in fuel height above critical can then be determined. The function is linear for the range of periods down to at least 200 seconds and probably as short as 100 seconds. For this range of periods the first term in the inhour equation can be neglected.

Water Evaporation Correction

Since the ZPR-II is assembled in a tank open to the atmosphere, water evaporates from the upper surface of the fuel solution; therefore, the actual critical height can drift with time and require correction to the data. The actual increase in fuel concentration resulting from the water evaporation is so small that it generally cannot be measured by the methods previously described; however, the change in critical height can be significant in some cases.

No attempt has been made to control this evaporation in ZPR-II; rather, it has been the procedure to date to evaluate the effect for each situation and make the necessary correction. In cases where it is important, the procedure

generally resolves itself into running a standard critical case at the beginning and end of the particular measurements and into assuming that the change in critical height due to evaporation is a linear function of time during the experiment. Measurements requiring evaporation corrections usually are limited to a single work day.

Miscellaneous Reactivity Effects

Determining the absolute critical mass in a system such as the ZPR-II necessitates the consideration of the following small effects: (1) neutron reflection due to the reactor tank, support stand structure, instrumentation chamber housing, and reactor room walls, (2) the nuclear effect of the reactor tank protective coating, (3) interaction between fuel in the reactor tank and in the storage tanks, and (4) fuel in fill and dump lines adjacent to the bottom of the core.

The reactivity effect of neutron reflection from the support stand structure and reactor room walls cannot be satisfactorily determined but is generally considered to be negligible. The worth of aluminum in the tank can be accounted for analytically and has not been measured experimentally. The reactivity worth of a sample of the Glyptal coating has been experimentally measured in ZPR-I as essentially that due to the displacement of fuel. The interaction between fuel in the reactor and storage tank can be inferred from solid angle calculations and has also been considered on the basis of past work to be small enough to be neglected. The one item that had not been evaluated in any manner previous to this work was the reactivity effect associated with the fuel in the dump and fill lines adjacent to the bottom of the core. The effect was measured to be worth at most about 0.040 centimeter in critical height. This effect is not considered in the data reported since it involves a separate correction measurement for each concentration.

Most of the miscellaneous effects discussed are of little concern to the research programs planned for ZPR-II because most of the experimental work is of a nature in which relative data are being determined. Any errors beyond the error limits specified in the results should reflect a constant bias from effects present at all times and not be of a random nature.

RESULTS AND DISCUSSION

The experimental data presented in this report include critical mass determinations, temperature coefficient measurements, and reactivity worth determinations carried out by using the NASA ZPR-II. The critical mass studies represent data obtained for uranyl fluoride solution systems with a different geometry than previously reported. The other data are of general interest for safety and operating considerations.

Critical Mass Studies

Critical mass determinations were made by using the ZPR-II for a range of

TABLE II. - EXPERIMENTAL CRITICAL MASS DATA FOR URANYL FLUORIDE SOLUTIONS WITH A 76.2-CENTIMETER-DIAMETER CYLINDRICAL TANK

Fuel concentration (20° C), H/X	Density (20° C), gm/cm ³	Critical height, cm		Critical mass, kg	
		Bare	Reflected	Bare	Reflected
151.6	1.20884	13.77	-----	10.52	-----
151.8	1.20855	13.82	13.67	10.54	10.43
324	1.09844	15.67	15.47	5.68	5.61
438	1.07260	17.04	16.79	4.59	4.51
482	1.06580	17.78	17.53	4.34	4.28
484	1.06558	17.83	17.58	4.34	4.28
493	1.06434	17.96	17.68	4.29	4.23
636	1.04958	19.94	19.58	3.70	3.63
650	1.04844	20.27	19.91	3.68	3.61
718	1.04374	21.34	-----	3.51	-----
789	1.03966	22.81	22.35	3.41	3.35
870	1.03581	24.40	23.88	3.31	3.24
908	1.03424	25.27	24.69	3.29	3.21
993	1.03118	27.38	-----	3.26	-----
1001	1.03090	27.61	26.85	3.26	3.17
1082	1.02848	29.97	29.06	3.27	3.18
1217	1.02514	35.05	-----	3.41	-----
1225	1.02495	34.98	33.61	3.38	3.25
1247	1.02449	36.12	34.64	3.43	3.29
1394	1.02172	45.87	43.12	3.89	3.66
1490	1.02021	52.27	48.44	4.15	3.85
1500	1.02007	55.47	50.98	4.38	4.02
1600	1.01871	71.58	-----	5.30	-----
1650	1.01809	-----	71.46	-----	5.13
1659	1.01798	-----	74.10	-----	5.29

H/X values approximately from 150 to 1650. The geometric configurations include both unreflected systems and systems reflected radially with water. The core region was a 76.2-centimeter-diameter cylinder with a nominal 90-centimeter-height operating limit. The annular reflector region was about 15 centimeters thick. For water this approaches infinite thickness in terms of reactivity effect.

The data for the critical mass studies are given in table II. The critical height and critical mass of both the unreflected and reflected cases are listed as a function of solution concentration. Since the value of H/X is regarded as somewhat lacking in precision, the experimentally determined fuel solution density is also reported. As noted in the table, all data are at a temperature of 20° C.

In the interest of completeness and convenience in analyzing the data, the best values of the following physical properties are given in table III for the concentrations reported in table II:

TABLE III. - ATOM CONCENTRATIONS FOR URANYL FLUORIDE SOLUTIONS

Fuel concentration (20° C), H/X	Solution density (20° C), gm/cm ³	Atom concentration, N/cm ³					Uranium 235, g/liter
		Hydrogen	Uranium 235	Uranium 238	Oxygen	Fluorine	
151.6	1.20884	6.5189×10 ²²	4.2998×10 ²⁰	0.3133×10 ²⁰	3.3517×10 ²²	9.2261×10 ²⁰	167.74
151.8	1.20855	6.5192	4.2938	.3128	3.3517	9.2133	167.51
324	1.09844	6.6026	2.0405	.1487	3.3450	4.3783	79.60
438	1.07260	6.6217	1.5135	.1103	3.3433	3.2474	59.04
482	1.06580	6.6268	1.3749	.1002	3.3429	2.9501	53.64
484	1.06558	6.6269	1.3704	.0999	3.3429	2.9404	53.46
493	1.06434	6.6278	1.3452	.0980	3.3428	2.8863	52.47
636	1.04958	6.6387	1.0445	.0761	3.3418	2.2411	40.74
650	1.04844	6.6396	1.0213	.0744	3.3417	2.1913	39.84
718	1.04374	6.6430	.9256	.0674	3.3414	1.9861	36.11
789	1.03966	6.6460	.8425	.0614	3.3411	1.8078	32.87
870	1.03581	6.6489	.7642	.0557	3.3408	1.6397	29.82
908	1.03424	6.6500	.7322	.0534	3.3407	1.5712	28.57
993	1.03118	6.6522	.6700	.0488	3.3405	1.4376	26.14
1001	1.03090	6.6524	.6643	.0484	3.3405	1.4254	25.92
1082	1.02848	6.6542	.6151	.0448	3.3403	1.3198	23.99
1217	1.02514	6.6567	.5472	.0398	3.3401	1.1740	21.34
1225	1.02495	6.6568	.5433	.0396	3.3401	1.1657	21.19
1247	1.02449	6.6572	.5339	.0389	3.3400	1.1456	20.83
1394	1.02172	6.6592	.4776	.0348	3.3398	1.0248	18.64
1490	1.02021	6.6603	.4469	.0325	3.3397	.9589	17.44
1500	1.02007	6.6604	.4440	.0323	3.3397	.9528	17.33
1600	1.01871	6.6613	.4164	.0304	3.3396	.8935	16.25
1650	1.01809	6.6618	.4038	.0294	3.3396	.8664	15.75
1659	1.01798	6.6619	.4016	.0293	3.3396	.8616	15.66

- (1) Fuel solution density
- (2) Hydrogen atom density
- (3) Uranium 235 atom density
- (4) Uranium 238 atom density
- (5) Oxygen atom density
- (6) Fluorine atom density
- (7) Grams of uranium 235 per liter of solution

All properties reported are for a solution temperature of 20° C. The values assume that the solution contains no constituents other than UO₂F₂ and water.

The reporting of the experimental data to high resolution is indicative of relative sensitivity rather than absolute accuracy. The estimated error in

critical mass varies from about 0.5 percent at an H/X of 150 to 1.5 percent at an H/X of 1500. It is estimated that the absolute critical height has error limits of ± 0.075 centimeter attributable largely to dimension tolerances. The critical heights relative to each other are felt to be in error by no more than ± 0.025 centimeter, which implies that a small constant bias error in the critical height due to reactor vessel dimensional tolerances could exist. The measurement of solution density is accurate (95 percent confidence limit) to ± 0.00025 gram per cubic centimeter at all densities. Thus different error limits will be obtained for the H/X values and critical mass values depending on the concentration. For example, an error limit of ± 0.00025 in density corresponds to values of H/X of 150.0 ± 0.2 , 500 ± 2 , 1000 ± 8 , or 1600 ± 20 .

These limits are borne out in general by the reproducibility achieved during the studies. For example, although the data listed at values of H/X of 151.6 and 151.8 were obtained at a difference in time of 6 months and involved significantly different fuel temperature corrections, they are still in good agreement. The data at several other values of H/X such as 482 and 484 are also separated in time and temperature. These data are not in as good agreement but are within the error limits.

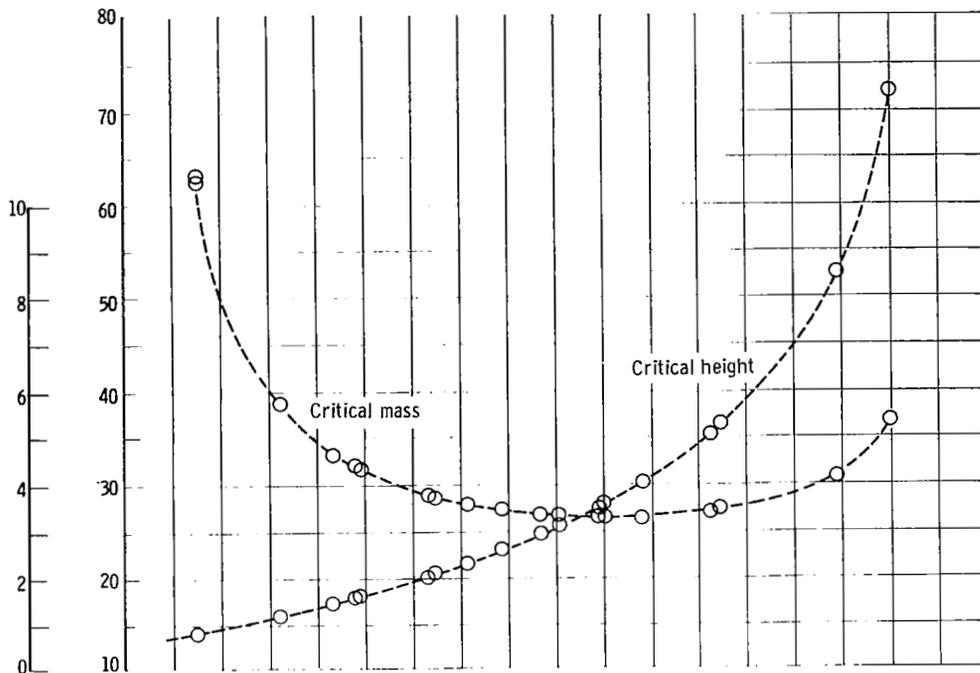
The data of the bare critical heights and critical masses are plotted as a function of fuel concentration in figure 5(a). Similarly, the data for the reflected cases are plotted in figure 5(b). It is of interest to note that the minimum critical mass is found at about a value of H/X of 1000 for both the bare and reflected systems.

Temperature Coefficient

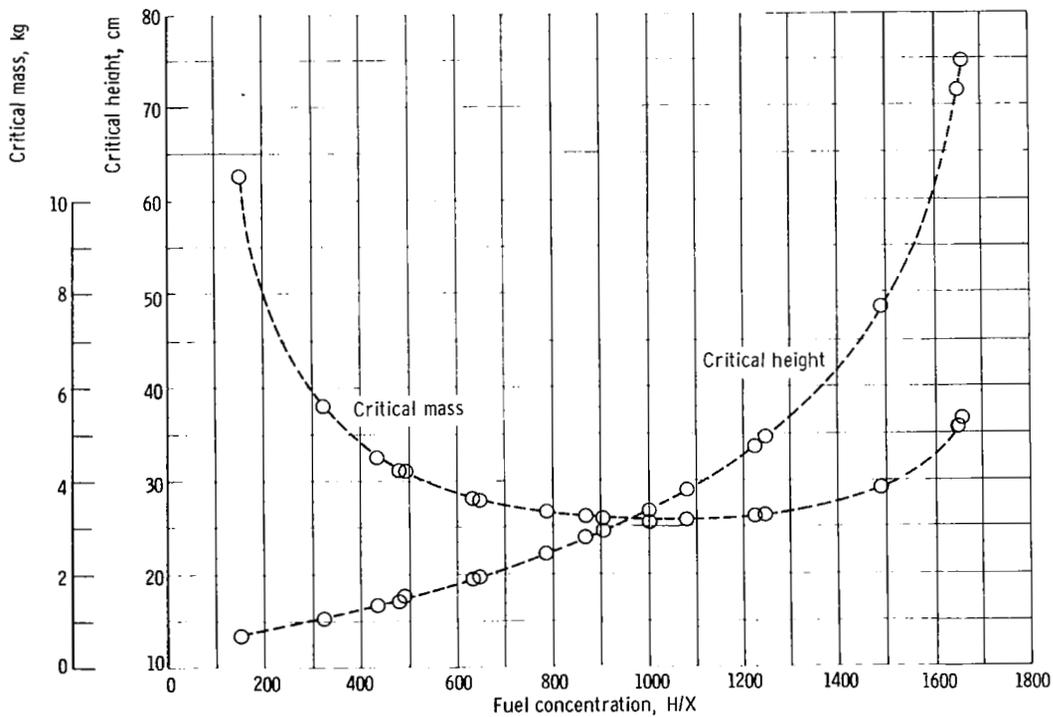
The temperature coefficient has been measured over the range of H/X from about 150 to 1600 although not for all the concentrations run. This measurement is time consuming and in many cases approaches the limit of resolution in the reactivity measuring technique. It is therefore difficult to assign error limits to the data that are somewhat limited. The estimated error in these data is ± 20 percent although the data when plotted (see fig. 6) appear to fall more closely than that to the fitted curve. These data also are tabulated in table IV. The negative sign is used because an increase in temperature results in a loss in reactivity. The values used to make the corrections in the critical mass data were taken from the curve in figure 6 and not from the individual data points.

The temperature coefficient data reported have been limited to bare systems. Enough experimental data for reflected systems have been obtained, however, to observe that an approximate correlation of the temperature effect as a function of critical height exists between the bare and reflected systems. This correlation is used, therefore, for the temperature correction of the reflected data.

To make the temperature coefficient more universally applicable it is reported also in terms of reactivity in figure 7. To do this, it is necessary to make use of the incremental reactivity worth data described in the next section. The product of temperature coefficient in terms of $\Delta H/\Delta T$ and the



(a) Bare cores.



(b) Cores radially reflected by 15 centimeters of water.

Figure 5. - Experimental criticality data for uranyl fluoride solution systems with 76.2-centimeter-diameter-cylindrical cores.

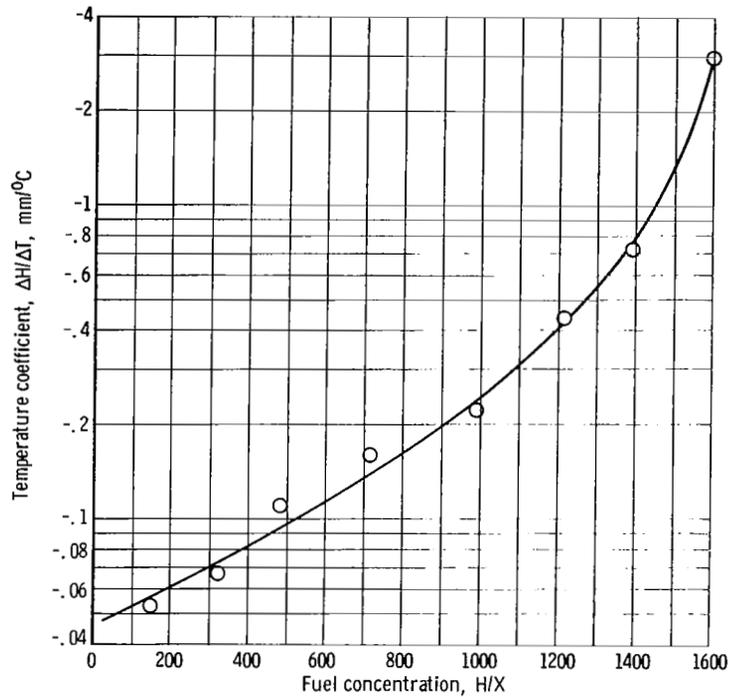


Figure 6. - Temperature coefficient data for uranyl fluoride solution systems having 76.2-centimeter-diameter cylindrical bare cores.

TABLE IV. - TEMPERATURE COEFFICIENT AND INCREMENTAL WORTH DATA FOR URANYL FLUORIDE SOLUTION SYSTEMS WITH 76.2-CENTIMETER CYLINDRICAL BARE CORES

Fuel concentration, H/X	Temperature coefficients, $\Delta H/\Delta T$, mm/°C	Incremental worth, $\Delta\rho/\Delta H$, cents/mm
152	-0.053	65.0
324	-0.067	52.1
482	-0.110	38.0
500	-----	44.5
718	-0.160	30.7
993	-0.222	17.1
1217	-----	10.0
1225	-0.441	10.2
1394	-0.727	5.2
1600	-2.970	1.53

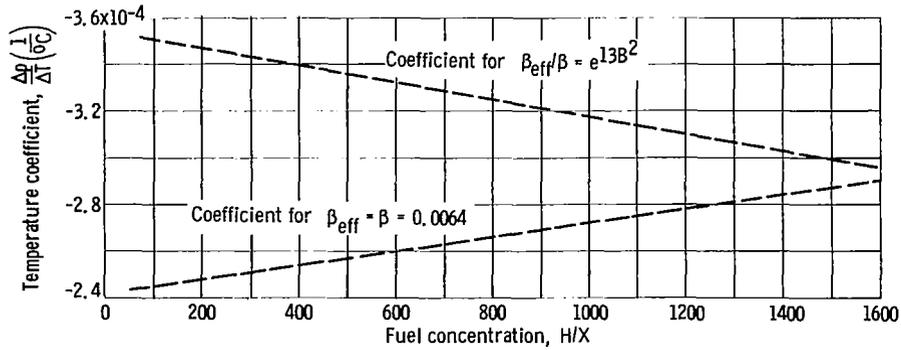


Figure 7. - Reactivity temperature coefficients for ZPR-II bare systems.

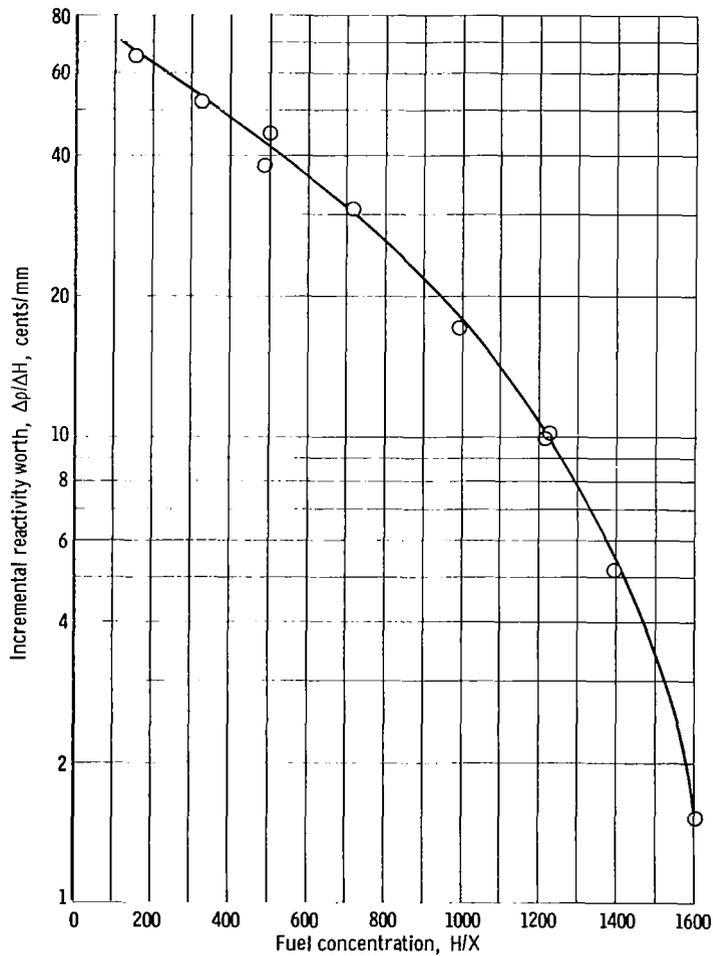


Figure 8. - Incremental reactivity worth at criticality for uranyl fluoride solution systems having 76.2-centimeter-diameter cylindrical bare cores.

incremental reactivity worth $\Delta\rho/\Delta H$ gives the temperature coefficient in terms of $\Delta\rho/\Delta T$.

The lower curve of figure 7 is a plot of reactivity worth per $^{\circ}\text{C}$ against H/X , which was obtained by taking the product of the values from the curves in figures 6 and 8 and applying the appropriate conversion factor. Multiplying the reactivity values expressed in cents by the delayed neutron fraction 0.0064 yields the reactivity worth in terms of the effective multiplication factor for a β_{eff} of 0.0064. The data follow a straight line within the error limits described.

The upper curve in figure 7 is obtained by using a calculated value of the effective delayed neutron fraction rather than 0.0064 at each fuel concentration. The ratio of β_{eff}/β for the ZPR systems is approximated by $\exp(13B^2)$, where the B^2 used in this case is the geometric buckling obtained from the dimensions of the bare critical systems. This calculational method is similar to the method described in reference 6. The coefficient of 13 has been derived by applying this method to unpublished experimental data for β_{eff} measured with the ZPR-I system. It should be noted that more precise values of β_{eff} are not essential to this study, because the primary objective is to show the typical trend of the data. The curves in figure 7 are dashed to show that they should not be used for working curves.

The principle effect to be noted from figure 7 is the relatively constant reactivity values for the temperature coefficient that were found for this range of fuel concentration studies. The value for temperature coefficient appears to be of the order of 3×10^{-4} in $\Delta\rho$ per $^{\circ}\text{C}$ for ZPR-II systems. This value is in good agreement with unreported data obtained for the ZPR-I system over a range of H/X from about 300 to 550.

Reactivity Worth Measurements

In determining the reactivity insertion rates at criticality or the reactivity worth at criticality of a small perturbation to a critical system, it is desirable to have a convenient method to measure the effect. For solution criticals in cylindrical tanks, the most convenient parameter is cylinder height, which has been calibrated in the ZPR-II to give values for reactivity worth per unit increase in fuel height at criticality for bare systems. The units of reactivity are cents based on the use of $\beta = 0.0064$ in the inhour equations; however, for the reactor periods involved in the measurements reported herein, the reactivity in cents is independent of the value of β that is used. The periods are long enough that the prompt term in the inhour equation approaches zero and can be neglected. Thus, a unit of cents represents 1 percent of β regardless of what the value of the delayed fraction actually is.

The data on incremental reactivity worths at criticality as a function of fuel concentration are plotted in figure 8 and given in the third column of table IV. These data are the compilation of measurements made over a large period of time and are not necessarily indicative of the best values that would be possible with present capability. No error limits are given, but it is felt

that the curve fit of the data is a good representation of the values involved and that the accuracy is quite adequate for the purposes of this report.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 18, 1965.

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