# EXPERIMENTAL STUDIES OF GCFR SAFETY PHYSICS PARAMETERS IN THE ZPR-9 CRITICAL ASSEMBLIES

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## ABSTRACT

Physics parameters related to the safety analysis of the Gas-Cooled Fast Reactor (GCFR) have been measured in a series of critical assemblies constructed on ZPR-9. These measurements represent the first full-scale experimental study of GCFR physics. The critical assemblies were modelled after the 300 MWe GCFR Demonstration Plant designed by General Atomic Company. The specific integral parameters studied were the coolant (helium) depressurization worth, the $^{238}U$ Doppler effect, control rod worths and the reactivity worth of materials of importance to GCFR safety. An extensive study was made of the effects of steam entry in a GCFR core. The results showed that the helium depressurization worth is small and considerably overpredicted (by ~35%) by standard methods, and that the GCFR spectrum was harder than corresponding LMFBR spectra as evidenced by the decreased $^{238}U$ Doppler effect and control rod worths and central reactivity worths. Steam entry in the critical assembly was shown to result in a positive reactivity insertion and cause a large change in the magnitudes of the safety related physics parameters. The results provide a basis for validating the methods used for GCFR safety analyses.

## INTRODUCTION

A critical experiments program has been undertaken on the ZPR-9 facility at Argonne National Laboratory to provide an experimental characterization of the neutronic features of a GCFR. The program of measurements was planned in support of the GCFR Demonstration Plant designed by General Atomic Company.[1] The GCFR critical assemblies represent the first complete mock-ups of the GCFR ever constructed and the measurements provide the initial experimental data on GCFR physics parameters. While the critical assemblies were modelled after the 300 MWe GCFR Demonstration Reactor, the results are of more general applicability to the GCFR concept. Results of the measurements of safety parameters are reported in this paper along with predictions made by standard calculational methods.

The GCFR critical assemblies were designed as homogeneous, single core-zone mockups of the four-zoned GCFR Demonstration Plant. The reactor materials including the plutonium fuel were in the form of plates assembled in drawers loaded into the stainless steel ZPR-9 matrix. The pressurized helium coolant of the GCFR was simulated by air at atmospheric pressure contained in stainless steel void cans. Like pressurized helium, air is relatively transparent to neutrons providing an appropriate neutronic simulation of the coolant. The unit cell compositions of the assemblies were designed such that the atom concentration of all important isotopes were matched closely with those of the reference GCFR design. The fissile enrichment (17.3%) and void fraction (53%) of the initial GCFR assembly[2] matched the average enrichment and coolant volume fraction of the Demonstration Plant. In the subsequent assembly[3] the void fraction was reduced to 42% to provide a suitable sized system for the measurement of some of the safety parameters. The radial and axial blankets were composed of $U_3O_8$, depleted uranium and void cans while the reflector was made of stainless steel. Figure 1 gives a pictorial view of the GCFR Phase II assembly showing some of the important dimensions.

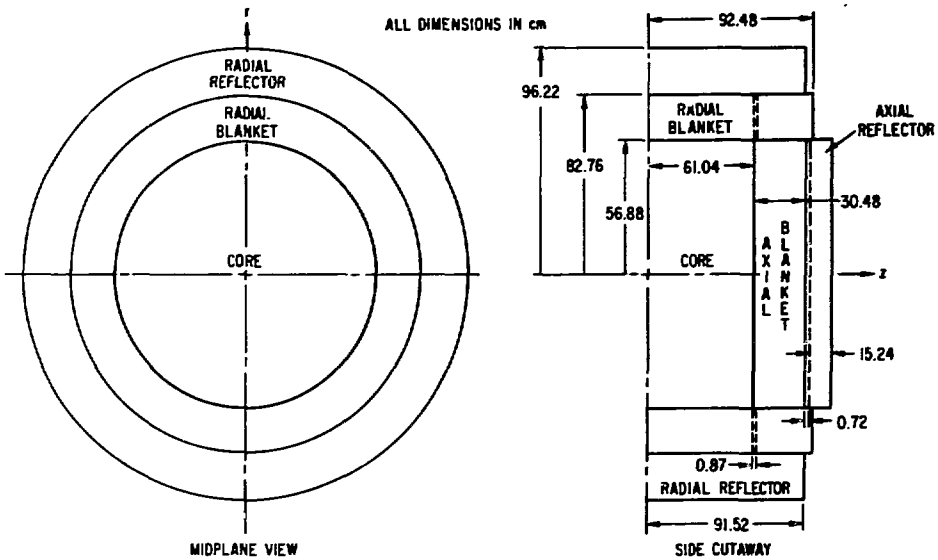


Fig. 1: Sketch of the GCFR Critical Assembly giving the cylindrical dimensions.

## Experimental and Calculational Methods

The helium depressurization worth, the $^{238}U$ Doppler effect and the central reactivity worth measurements were made using variations of the well established sample oscillation-reactivity difference technique. The large reactivity changes involving control rod worths and steam entry worths were determined as the differences of the reactivity worths of two reactor configurations. The configuration reactivity worths were determined by the inverse kinetics rod-drop technique. The worth results presented in this paper have been compared with results of earlier work in LMFBR assemblies.

Analysis of the experiments were performed using ENDF/B-IV nuclear data and two-dimensional diffusion theory methods in a 29 broad group energy structure. Unit cell averaged isotopic cross-sections were generated for all appropriate compositions using the MC$^2$-2/SDX[4,5] codes wherein plate heterogeneity effects were explicitly taken into account. The Benoist[6] method involving directional diffusion coefficients was used to treat the anisotropic effects of neutron streaming within the framework of diffusion theory.

## EXPERIMENTAL RESULTS AND COMPARISON WITH CALCULATIONS

### Helium Coolant Depressurization Worth

One of the important safety features of the GCFR is the absence of the large coolant induced positive reactivity effects comparable to possible sodium void effects in an LMFBR. To gauge the reactivity effect of helium depressurization, a measurement of the worth of a small cylinder containing pressurized helium gas was performed at core center. The measurement was made with aluminum cylinders pressurized to 150 psia and 300 psia with helium. Table I(A) shows the results of the measurement of the worth of the pressurized helium cylinders. The reactivity worth of the gas was determined to be linear with respect to pressure (at least up to 300 psi) and was small in magnitude (170 ± 4 Ih/kg for depressurization). In the analysis of the experiment a perturbation integral transport theory formulation was used to correct for the flux-distortion effects of the pressure cylinder material.

TABLE I. Safety Coefficients Measured in the GCFR Assemblies

A. Helium Depresaurization Worth

| | Experimental, Ih | Calculated, Ih | C/E | Flux Distortion Factor[a] |
|---|---|---|---|---|
| Helium @ (152.4 ± 0.5) psia | -0.161 ± 0.004 | -0.211 | 1.31 | 0.90 |
| Helium @ (299.4 ± 0.5) psia | -0.302 ± 0.005 | -0.411 | 1.36 | 0.90 |

B. Control Rod Worth

| Control Rod Composition | Axial $^{10}B$ Weight per linear inch, g | $^{10}B$ Atom Concentration, $10^{21}$ atoms/cm$^3$ | Worth, Ih/kg | | |
|---|---|---|---|---|---|
| | | | Experimental | Calculated[b] | C/E |
| 1 | 4.63 | 3.59 | -454 ± 1.8 | -481 | 1.06 |
| 2 | 9.25 | 7.17 | -847 ± 2.3 | -920 | 1.09 |
| 3 | 16.2 | 12.5 | -1150 ± 16.8 | -1353 | 1.18 |

C. $^{238}U$ Doppler Reactivity Worth

| Sample | Temperature Range, °K | Experimental Worth, Ih/kg | Calculated Worth, Ih/kg | C/E |
|---|---|---|---|---|
| $^{238}UO_2$ | 300 - 1100 | -0.623 ± 0.009[c] | -0.515 | 0.83 |

[a] The flux distortion factor is the ratio of the worths obtained using the perturbation integral-transport theory formulation to that obtained from first order perturbation theory.

[b] Infinitely dilute $^{10}B$ cross-sections were used in those calculations.

[c] The normalized Doppler worth in the GCFR assembly is $-2.69 \times 10^{-3}$. This compares with a normalized Doppler worth of $-5.21 \times 10^{-3}$ for the FTR-EMC and $-5.81 \times 10^{-3}$ for ZPR-6 assembly 7.

The large C/E ratio is quite typical of light scattering materials. Significant improvement (~11%) in the calculated value has been effected by using bilinear weighted cross-sections and a finer group spectrum calculation. The C/E bias factor for the small-sample worth was applied to the calculated full core depressurization worth, resulting in a value of 99 Ih (31¢) for this event. This result indicates that for an actual GCFR, the loss of He coolant does not result in a large reactivity insertion.

### Doppler Effect of $^{238}U$ at Core Center

A consequence of the predicted harder GCFR spectrum is the reduced $^{238}U$ Doppler effect - an important inherent safety mechanism of fast reactors. The Doppler reactivity worth of a $^{238}U$ sample was measured at core center to Doppler worth measurement for the temperature range 300-1100°K. The reactivity worth, normalized to the $^{239}Pu$ central worth of the assembly, is almost a factor of 2 smaller than the corresponding value for LMFBR assemblies,

indicating the relative hardness of the GCFR spectrum. A modified perturbation theory method was used to calculate the Doppler reactivity worth. Integral-transport theory methods were used to generate the Doppler cross-sections and hot sample/cold core resonance interaction effects were explicitly taken into account. The calculated value was ∿17% lower than the experimental value (C/E = 0.83). This misprediction is considerably larger than that experienced in LMFBR assemblies and the cause of this appears to be the harder spectrum in a GCFR. About 42% of the calculated Doppler effect comes from the unresolved resonance energy range for $^{238}U$ (∿4 KeV-∿40 KeV) in which the calculated Doppler effect is more uncertain than in the resolved energy range. Additionally, the low calculated prediction of the central $^{10}B$ worth (taking into account the central worth discrepancy) lends credence to belief that the low energy flux is computed to be smaller than it actually is. Direct spectrum measurements using proton recoil proportional counters have confirmed this.

## Control Rod Worth Determinations

The GCFR designs call for "gray" control rods. Several possible control rod compositions with different $^{10}B$ linear weights were simulated using $B_4C$ plates. Table I gives the experimental worths of these rods along with calculated predictions. The calculations used infinitely dilute cross-sections for $^{10}B$ and $^{11}B$ and gave C/E values that are typical of earlier experience.

## Small Sample Reactivity Worths

The reactivity worth of a large number of materials of interest to the GCFR program were measured at the core center of the assemblies. Radial and axial distribution of the worths were also determined. The individual isotopic worths reported in Table II can be used to construct the composite worths of fuel, clad, structural and control materials, for accident analyses.

TABLE II. Central Reactivity Worths in the GCFR Critical Assemblies

| Sample or Isotope | Experimental Worth, Ih/kg | Calculated[a] Worth, Ih/kg | C/E | Typical C/E values for LMFBR[b] assemblies | Ratio of normalized[d] Worth in GCFR and normalized worth in LMFBR |
|---|---|---|---|---|---|
| $^{239}Pu$ | 238.08 ± 1.97 | 276.48 | 1.16 | 1.19 | 1.0 |
| $^{240}Pu$[e] | 42.19 ± 0.38 | 51.35 | 1.22 | - | - |
| $^{241}Pu$[e] | 288.04 ± 2.48 | 374.39 | 1.30 | | - |
| $^{242}Pu$[e] | 30.92 ± 0.38 | 41.35 | 1.34 | | - |
| $^{233}U$[e] | 295.38 ± 2.76 | 345.00 | 1.17 | | - |
| $^{235}U$ | 170.45 ± 1.40 | 203.49 | 1.19 | 1.17 | 0.85 |
| $^{238}U$ | -11.26 ± 0.31 | -12.77 | 1.13 | 1.04 | 0.69 |
| $^{232}Th$[e] | -21.37 ± 0.43 | -25.72 | 1.20 | | |
| $^{10}B$ | -3412.3 ± 50.9 | -3398.5 | 1.00 | 1.12 | 0.77 |
| $^{6}Li$[e] | -2520.1 ± 31.8 | -2893.3 | 1.15 | | |
| $CH_2$ Foam | 159.3 ± 6.9 | -273.65 | -1.72 | | |
| C | -21.23 ± 0.72 | -43.78 | 2.06 | | |
| Stainless Steel | -7.64 ± 0.08 | -10.35 | 1.35 | 1.38[c] | 1.38 |
| Aluminum[e] | -13.33 ± 4.92 | -15.15 | 1.14 | - | |
| Oxygen[e] | -16.46 ± 5.60 | -27.64 | 1.68 | - | |

[a] 1% Δk/k = 971.97 Ih.

[b] These results are for ZPR-6 assembly 7, a benchmark LMFBR assembly.

[c] This result is for the FTR-EMC assembly.

[d] All ratios refer to experimental values.

[e] The worths of these materials were measured in an unreflected assembly. Comparisons have indicated that the experimental worths in the unreflected assembly differ by no more than 1% from those in the reflected assembly.

Table II also shows the calculated predictions of the worths obtained for first order perturbation theory methods. The isotopic worths shown were inferred from composite sample experimental worths. The agreement of calculated predictions with the measured worths show the same general features as the results for earlier LMFBR assemblies. The central worth discrepancy is very much in evidence as is the chronic problem with the prediction of the worths of light scatterers. Table II also presents a comparison of the normalized, experimental central worths in the GCFR assembly and a typical LMFBR assembly - the ZPR-6 Assembly 7. The evidence clearly points to a harder GCFR spectrum. Axial and radial worth profiles of some of the isotopes were also measured to provide information for core disassembly accident analysis. Figure 2 shows some typical radial worth profiles.

## Reactivity Worth of Steam Entry

Since the secondary steam pressure in a GCFR is higher than the helium coolant pressure, the hypothetical accident scenario involving the leakage of steam into the core is an important safety consideration. The reactivity effects of such a steam entry were experimentally determined for the first time in this series of measurements.

Polyethylene ($CH_2$) foam was used to simulate steam in these experiments.[9] Foam strips were inserted into the void cans to mock-up the actual entry of steam in the coolant channel in an operating reactor. The steam densities simulated were within the range of possible accident situations as reported by Broido and Rothenstein.[10] The reactivity worth of steam entry was investigated in a small central core zone and also for the entire assembly. In addition, the reactivity worths of small samples of $CH_2$ foam and water were measured at the core center and at various axial and radial locations in the assembly. All these measurements were made in a clean assembly ie. without neutron poisons in the core. The central small sample worths, the large zone worth and the full core steam entry worth were all determined to be positive for every case studied, in contradiction to earlier predictions. The small sample worth calculations were performed with

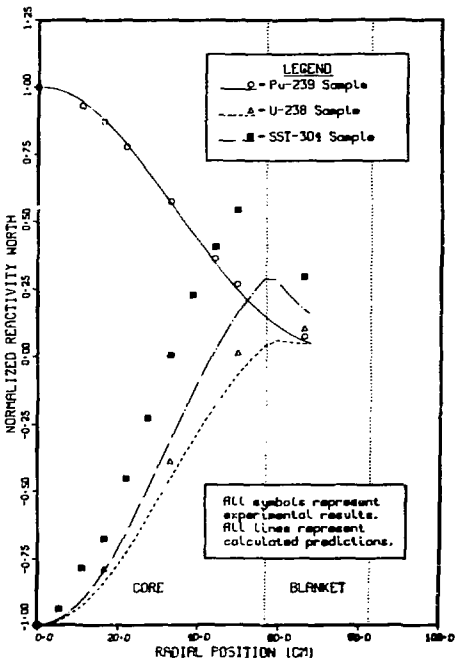


Fig. 2. Radial reactivity worth traverses of $^{239}Pu$, $^{238}U$ and stainless steel-304 samples in the GCFR critical assembly. Both the experimental and calculated values are normalized to the respective reactivity worths at core center.

first order perturbation theory, while the large region steam worth calculations were performed with eigenvalue difference and exact perturbation theory methods. The cross-sections of all isotopes in the steam-filled regions were re-generated to account for effects of spectral softening due to steam entry. The Benoist bi-directional coefficients were also re-generated for the steam-filled regions.

The results of the reactivity measurements are summarized in Table III. The refined calculational methods correctly predicted the sign of the central zone steam entry reactivity effect and reproduced all the trends of the variations of the worth with steam density; however, the worth per unit mass of steam was mispredicted. The sign of the small sample (~0 mass) worth is mispredicted by first order perturbation theory, resulting in a misprediction of the slope of the worth versus steam density curve at the origin. For the whole core steam entry case, the experimental worths are positive, but smaller than anticipated from earlier predictions. The present calculated predictions are negative with the standard methods of analysis. The net reactivity effect of steam entry consists of a balance between the negative effect of the reduced $k_\infty$ of the assembly and the positive effect of decreased leakage. Presence of hydrogen in the assembly causes errors in the eigenvalue calculations as indicated by the consistently poorer C/E ratios for

TABLE III. Summary of Steam-Entry Reactivity Worth Experimental Results

A. Small Central-Zone Steam-Entry Experiments (GCFR Phase-I Assembly)[a]

| No. | Weight of $CH_2$ in Zone, kg | Equivalent steam density, $g/cm^3$ | Reactivity Worth, Ih: Experimental | Reactivity Worth, Ih: Calculated ΔK | Reactivity Worth, Ih: Calculated Exact Perturbation Theory |
|---|---|---|---|---|---|
| 1 | 0.7840 | 0.0217 | 157.2 ± 2.6 | 207.8 | 222.4 |
| 2 | 0.4082 | 0.0113 | 69.0 ± 2.7 | 73.8 | 67.8 |
| 3 | 0.3738 | 0.0103 | 59.9 ± 3.3 | 58.3 | - |
| 4 | 0.1940 | 0.0054 | 26.1 ± 2.9 | 6.6 | 8.0 |

B. Full-Core Steam-Entry Experiments (Core radius 54.79 cm)[b]

| No. | Weight of $CH_2$ in assembly, kg | Equivalent steam density in core, $g/cm^3$ | Experimental Reactivity Worth, Ih | Calculated Reactivity Worth, Ih |
|---|---|---|---|---|
| 1 | 6.03 | 0.0022 | 84.0 ± 10.3 | - |
| 2 | 11.91 | 0.0042 | 204.5 ± 14.3 | - |
| 3 | 23.51 | 0.0082 | 522.1 ± 10.1 | -436.26 |

[a] 1% Δk/k = 976.64

[b] These numbers are all for a clean (unpoisoned) core. For a core radius of 56.10 cm, the steam entry worth went from 484.1 ± 0.8 Ih for a clean core to 357.2 ± 47.1 Ih for a poisoned core - a decrease of 26 %.

steam-filled configurations (∿0.99) compared to corresponding "dry" configurations (∿1.00). Present evidence suggests that the balance between capture and leakage events in a steam-filled system is not computed accurately enough and improvement in processing codes and methods are necessary for the analysis of steam-filled GCFR systems.

Impact of Steam Entry on Physics Parameters

Figure 3 shows the calculated spectra at core center for the dry and steam-filled GCFR Phase II assembly. The dramatic softening of the spectrum results

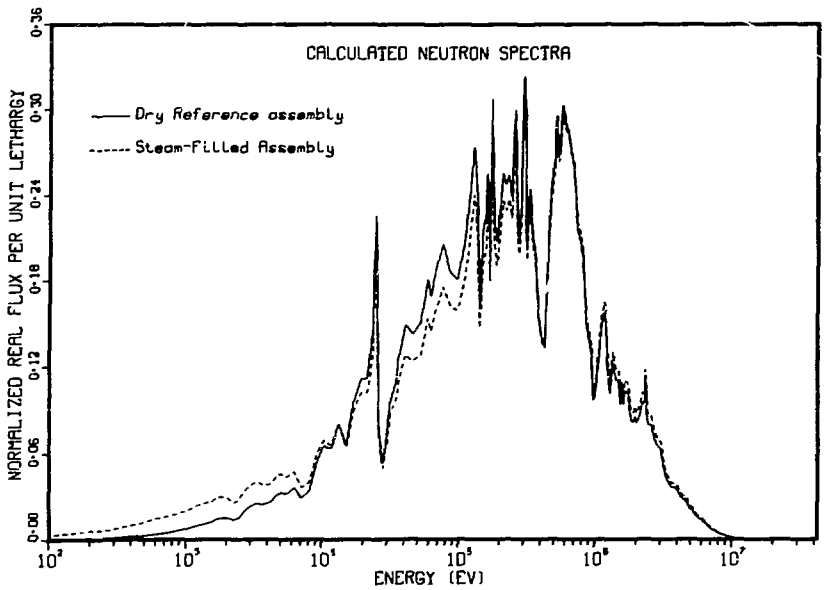


Fig. 3. Comparative neutron spectra at core center for the dry reference GCFR assembly and the steam-filled GCFR assembly.

in a change in the values of the safety physics parameters. The integral parameters were re-measured under the steam flooded condition. Table IV presents a summary of the results of these measurements along with comparisons with calculated values and the ratio of the steam filled to dry values. The central worth ratios show the effect of spectrum softening (eg. the 18% increase in the $^{238}U$ central worth and the 45% increase in the $^{10}B$ central worth). The calculated predictions of the worths are slightly superior to the corresponding values in the dry reference assembly (see Table II). Of particular interest is the fact that the polyethylene foam and water sample worths were predicted to be positive in this case, in agreement with experiment and in contradiction to the calculated results in earlier GCFR assemblies. Table IV(B) shows the Doppler reactivity worth of $^{238}U$ at the center of the steam-flooded core. The worth increased by 92% relative to the dry case and the calculated prediction was considerably better. The normalized $^{238}U$ Doppler worth is comparable to the LMFBR values. Figure 4 shows the experimental Doppler worths in the dry and wet GCFR assemblies as a function of sample temperature.

To study the effect of neutron poisons in the core on the reactivity worth of steam entry, a set of $B_4C$ rod worth measurements were made in the steam-filled and dry assemblies. Columns of $B_4C$ plates were positioned at the core center and also in a ring within the core and the worths were measured relative to void. Table IV(C) summarizes the results of the measurements and corresponding calculations. The $^{10}B$ cross-sections used in the analysis

TABLE IV. Comparison of Integral Safety-Physics Parameters for the GCFR Reference Assembly and the Steam-Filled Assembly

A. Central Reactivity Worth

| Isotope or Material | Steam Filled, Experimental Reactivity Worth, Ih/kg | Calculated Worth, Ih/kg[a] | C/E | Ratio[b] of normalized worth in the steam-filled assembly[c] to that in the dry assembly |
|---|---|---|---|---|
| $^{239}Pu$ | 237.55 ± 2.13 | 272.42 | 1.15 | 1.00 |
| $^{235}U$ | 177.00 ± 1.83 | 211.97 | 1.20 | 1.04 |
| $^{238}U$ | -13.33 ± 0.35 | -15.16 | 1.14 | 1.18 |
| $^{10}B$ | -4934.3 ± 66.1 | -5434.8 | 1.10 | 1.45 |
| $CH_2$ Foam | 328.65 ± 10.58 | 319.57 | 0.97 | 2.06 |
| Stainless Steel | -7.32 ± 0.09 | -9.12 | 1.25 | 0.96 |

B. $^{238}U$ Central Doppler Reactivity Worth

| Temperature Range, °K | Experimental Reactivity Worth, Ih/kg | Calculated Reactivity Worth, Ih/kg | C/E | Ratio of normalized worth in the steam-filled assembly to that in the dry assembly |
|---|---|---|---|---|
| 300 - 1100 | -1.197 ± 0.010[d] | -1.193 | 0.997 | 1.93 |

C. Reactivity Worth of Poison Rods

| | Experimental Value, Ih | Calculated Value,[e] Ih | C/E | Ratio of worth in steam-filled assembly to that in dry assembly |
|---|---|---|---|---|
| 1. Worth of a centrally located $B_4C$ column in the dry reference assembly | -484.18 ± 1.87 | 491.57 | 1.015 | - |
| 2. Worth of centrally located $B_4C$ column in the steam-filled assembly | -544.83 ± 3.71 | 573.96 | 1.053 | 1.13 |
| 3. Worth of ring of 8 $B_4C$ columns in the dry reference assembly | -1934.16 ± 33.85 | -1901.69 | 0.98 | - |
| 4. Worth of ring of 8 $B_4C$ columns in the steam-filled assembly | -2061.16 ± 46.79 | -2242.15 | 1.088 | 1.07 |

[a] 1% Δk/k = 953.98 Ih.

[b] All ratios refer to experimental values

[c] The worths in the dry reference case are listed in Table I.

[d] The normalized Doppler reactivity worth is $-5.19 \times 10^{-3}$ which is comparable in magnitude to the value in the FTR-EMC ($-5.21 \times 10^{-3}$).

[e] Infinitely dilute $^{10}B$ cross-sections were used in these calculations.

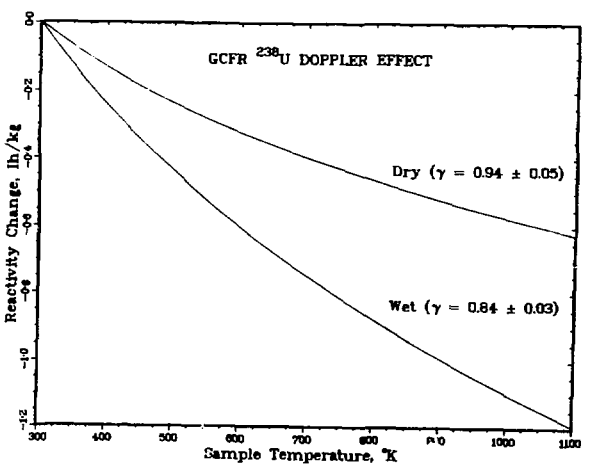


Fig. 4. The central $^{238}U$ Doppler reactivity worth as a function of temperature for the reference and steam-filled GCFR assemblies.

were infinitely dilute (ie. no spatial self-shielding corrections were applied). The agreement between experimental results and calculations is typical of past LMFBR experience. The worth of steam entry was found to be reduced by 26% when poisons were present in the core. This factor also includes the effect of increased worth of the poisons due to spectrum softening.

## CONCLUSIONS

A complete set of GCFR safety physics parameters have been measured for the first time in critical assemblies. The results of the critical experiments provide a set of reference integral data useful in evaluating GCFR safety analysis. The harder spectrum of the GCFR relative to LMFBR assemblies was apparent from the results (e.g., decreased $^{238}U$ Doppler worth and $^{10}B$ worth). Despite the presence of neutron streaming effects the reactivity worths were generally predicted with the same degree of certainty as the LMFBR parameters. The reactivity worth of helium depressurization was inferred to be small based on the gas reactivity worth measurement and the calculational methods gave conservative predictions for this worth. Loss of coolant accidents in a GCFR appear to involve smaller safety consequences than the corresponding sodium voiding accidents in a LMFBR. Standard analytical methods also gave a conservative prediction (by about 17%) for the $^{238}U$ Doppler effect. Finally, the accidental entry of steam in a GCFR was shown to have a positive reactivity effect in the critical assembly environment. The magnitude of the reactivity insertion was found to be sensitive to many core characteristics i.e., steam worth with neutron poisons (control rods and/or fission products) present in the core. The calculations of the reactivity effects of steam entry provide a very stringent test of the methods of analysis. The results of the experiments suggest that improvements are necessary in the methods. Finally, it was shown that the increased $^{238}U$ Doppler effect and the control rod and poison worths with steam entry would mitigate the positive reactivity effects of steam entry in a GCFR.

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## REFERENCES

1. B. Pellaud, "The Physics Design of the Gas-Cooled Fast Breeder Reactor Demonstration Plant," USAEC Report GA-10509, Gulf General Atomic, August 29, 1971.

2. S. K. Bhattacharyya, "An Experimental Study of the Neutronics of the First Gas Cooled Fast Reactor Benchmark Assembly (GCFR Phase I Assembly)," ANL-76-36, Argonne National Laboratory, to be published.

3. R. B. Pond, "Reactor Physics Studies in the GCFR Phase II Critical Assembly," ANL-76-108, Argonne National Laboratory, to be published.

4. H. Henryson II, B. J. Toppel and C. G. Stenberg, "MC$^2$-2: A Code to Calculate Fast Neutron Spectra and Multigroup Cross-Sections," ANL-8144, Argonne National Laboratory, June 1976.

5. W. M. Stacey et al., "A New Space-Dependent Fast Neutron Multigroup Cross-Section Preparation Capability, " *Trans. Am. Nucl. Soc.*, 15, 292 (1972).

6. P. Benoist, "Streaming Effects and Collision Probabilities in Lattices," *Nucl. Sci. Eng.* 34, 285-307 (1968).

7. R. G. Bucher and E. F. Groh, "Reactivity Worth of Helium Gas in a GCFR Assembly," *Trans. Am. Nucl. Soc.*, 23, 563 (1976).

8. R. B. Pond and S. K. Bhattacharyya, "Measurement of $^{238}$U Doppler Effect in GCFR Critical Assemblies," to be presented at the ANS Winter Meeting in Washington, D. C. (1976).

9. S. K. Bhattacharyya and R. D. McKnight, "Experimental Study of the Reactivity Effect of Steam Entry in a Simulated GCFR Assembly," *Trans. Am. Nucl. Soc.*, 23, 561 (1976).

10. J. H. Broido and M. P. Rothstein, "The Effect of Steam Entry on the Gas-Cooled Fast Breeder Reactor Demonstration Plant," Gulf-GA-A12041, Gulf General Atomic (1972).