A DETAILED STUDY OF THE STEAM ENTRY EFFECT OF A GCFR

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1. Introduction

In a gas cooled fast reactor (GCFR) a restricted amount of steam could enter into the reactor core as a consequence of a steam generator leak. The reactivity effect of such an incident is an important safety parameter. Because of large compensating effects steam entry is difficult to calculate and a detailed physical understanding is particularly important.

In this paper the results of detailed steam entry calculations for a realistic reactor model are reported. From an additional perturbation theory analysis, and an analysis of one group cross section changes for different nuclides new insight into the physics of the steam entry effect can be obtained.

2. Calculational Methods

The calculations were performed for a GCFR which conforms to the General Atomic 300 MWe design (1). A two-dimensional R-Z model with 4 core zones and radial and axial blanket zones was used. The reactor model is shown in Fig. 1.

The calculations proceeded in two steps. First, burnup calculations were performed to obtain the nuclide concentrations for the middle of the equilibrium cycle (MOEC). These concentrations were then used as input for the subsequent steam entry calculations. Fig. 2 illustrates the calculational procedure in more detail. The cross sections were derived from the British FGL5 data set. Fundamental mode spectrum calculations and subsequent cross section condensations were performed with MURALB to obtain zone dependent 37 group constants.

- Burnup calculations:

  Burnup was calculated in two-dimensional R-Z geometry using 10 energy groups. The group condensation scheme allowed for interactions between zones by averaging the 37 group cross sections with zone integrated fluxes from a one-dimensional radial reactor calculation. A 360 day equilibrium cycle was calculated assuming an average thermal power of 830 MW, a load factor of 0.7, and a fuel residence of 3 cycles. This corresponds to an average burnup of 74 400 MWd/t HM of the fuel. For the radial blanket a 6 cycle residence was assumed. The plutonium enrichment of the fuel was adjusted to give $k_{eff}=1$ without boron control at the end of the equilibrium cycle.

- Steam entry calculations:

  For each reactor zone "dry" (no H_2O) and "wet" (0.03 g/cm^3 H_2O in the coolant channels) 37 group cross sections were calculated. The "dry" and "wet" microscopic cross sections were appropriately mixed for intermediate steam densities. Finally the mixed cross sections were used as input for 37 group two-dimensional diffusion and perturbation theory calculations.

3. Integral Reactivity Effect

3.1. Middle of the Equilibrium Cycle

For the middle of the equilibrium cycle (MOEC) the steam entry effect was calculated for steam densities of 0.01, 0.02 and 0.03 g/cm^3 in the coolant channels, the maximum steam density corresponding approximately to the H_2O inventory of all steam generators. The boron control in core zones 1 and 3 was adjusted to give $k_{eff}=1$ for the dry reactor at MOEC, i.e. the reactor was assumed to be critical when the steam ingress occurs.

The results are shown in Fig. 3. The total reactivity effect was calculated to be negative in the whole range of interest. The maximum negative effect amounts to -1.0 % near 0.02 g/cm^3 H_2O. At the steam density of 0.03 g/cm^3 the reactivity effect is still -0.8 %.

A replacement (simulation) of the boron control by a buckling imposed overall leakage would lead to a positive steam entry effect of 0.7 % for a H_2O density of 0.03 g/cm^3. This illustrates that the steam entry reactivity effect is very sensitive to the method used for adjusting the reactor for criticality. An adjustment by a buckling imposed leakage, as it is customary in fundamental mode calculations, leads to a pessimistic value.

At General Atomic the steam entry reactivity effect for the fresh unrodded core at operating temperature was calculated to be -1.85 $ (-0.65 %) for a steam density of 0.0075 g/cm^3 in the coolant channels, Ref. (2) p. 13. Since this value corresponds to different reactor conditions an accurate comparison with the EIR result cannot be made easily. However, the General Atomic and the EIR calculations appear to be consistent.

3.2. Beginning of Life

At the beginning of life (BOL) the steam entry reactivity effect was calculated for an H_2O density of 0.03 g/cm^3. The excess reactivity of the dry reactor was compensated by the following alternative methods:

1. By reducing the Pu enrichment of all core zones such that the reactor is critical at the end of the first cycle and compensating the remaining excess reactivity of the beginning of the cycle with B10.
2. By B10 poisoning alone.

The first method is the more realistic method. In the first case a steam entry effect of -0.6 % was obtained, i.e. a value similar to that for the MOEC. In the latter case an effect of -2.8 % was obtained. This, again, demonstrates that the steam entry effect is extremely sensitive to the method used for compensating the excess reactivity to obtain criticality before steam ingress occurs. This is especially true at BOL where the excess reactivity is relatively large.

4. Perturbation Theory Analysis

To get the contributions of the different reactor zones exact perturbation theory calculations in 37 energy groups were performed for a steam entry of 0.03 g/cm^3. The results are shown in Table I. The total reactivity change $\Delta\rho$ is represented as the following sum:

$\Delta\rho = \delta SCAT + \delta LEAK + (\delta PROD + \delta ABS)$

- The scattering term $\delta SCAT$ contains the reactivity change due to changes in the scattering properties resulting from the additional hydrogen and oxygen atoms. It includes also the entranced reaction probabilities of the neutrons scattered down into lower energy groups (the main spectrum effect). The contributions from core zone one and three containing B10 to the scattering term are negative. The contributions of core zone two and four on the other hand are positive but smaller compensating 1/3 of the original negative value. Particularly interesting are the large negative contributions of the blankets accounting for 70% of the total negative scattering effect.
- The leakage term $\delta LEAK$ accounts for the fact that the neutron mean free path is reduced by steam. The leakage term has approximately the same size in core zones 1,2 and 3 but increases towards the outer zones. The total leakage effect compensates half of the total scattering effect.
- The production term $\delta PROD$ and the absorption term δABS are the reactivity contributions due to perturbation of neutron producing and neutron absorbing materials. For a steam entry it should in principal be small and mainly due to the hydrogen absorption. In our case however, the contribution amounts to 27 % of the total reactivity effect. The reason is the spectrum change within the individual 37 energy groups which leads to production gains and absorption losses. This spectrum change was taken into account by calculating new wet cross sections (compare paragraphe 2). The big contribution of the $(\delta PROD+\delta ABS)$-term shows that the 37 energy group structure would not be adequate enough to calculate the steam entry effect using only one single (dry) cross section set.
- The total reactivity contributions $\Delta\rho$ of the different reactor zones show:
  1. The blankets contribute considerably (72 %) to the total negative effect.
  2. Core zones with a high plutonium enrichment and no control absorbers give raise to positive contributions.
  3. In the core positive and negative zonal contributions are compensating each other to a considerable extent.
  4. The reactivity change of the whole reactor, $\Delta\rho = -0.82$ %, is consistent with direct diffusion theory calculation.

5. Sensitivity to Fuel Composition

The sensitivity of the steam entry reactivity effect to the composition of the fuel can be studied using one-group cross-sections (Normalised zone dependent reaction rates). The representation in Table II is convenient for estimating the influence of small changes in the nuclide concentrations on Δk_{eff} ("wet" - "dry").

It can be seen that changes in the isotopic composition of the plutonium can give rise to important effects. The replacement of pure 239Pu by an equivalent amount of typical LWR grade plutonium, for instance, can be expected to give a positive net effect, the negative 240Pu contribution being overbalanced by the positive 241Pu contribution.

The figures show that 237Np can considerably improve steam entry reactivity. For fuel loaded with a small amount of 237Np (237Np/Pu=0.1) burnup and subsequent steam entry calculations for the MOEC were performed. The obtained steam entry reactivity curve decreases with increasing steam density reaching -1.9 % at 0.03 g/cm^3. This is more than twice the negative effect obtained with normal fuel for the same steam density. Under normal reactor conditions the reactivity loss due to the addition of 237Np is small because the 237Np absorption losses are compensated by 237Np fission gains and to some extent also by a spectrum hardening effect. In our case,e.g., replacement of 238U by 237Np in the fresh core caused a reactivity loss of 1% and no reactivity loss at all at the end of the equilibrium cycle (238Pu breeding). The deteriorating of breeding gain due to the replacement of 238U by 237Np is small because 237Np capture produces 238Pu which can be regarded as fissile in a GCFR. Therefore 237Np is a better material to improve steam entry reactivity than a pure absorber as e.g. Gd.

The figures for the blankets indicate that the blanket steam entry values can be affected by Pu breeding.

6. Conclusions

The calculations lead to the following main conclusions:

1. Our calculations predict that the effect of steam entry into a 300 MWe GCFR fueled with normal Pu mixed oxide fuel is negative in the whole range of interest.
2. The effect is very sensitive to the method used for compensating the excess reactivity to obtain criticality before steam ingress occurs. This is especially true at BOL where a relatively large excess reactivity has to be compensated.
3. The blanket zones contribute significantly to the total negative steam entry effect.
4. Steam entry reactivity is sensitive to fuel enrichment and boron control which can cause positive contributions from core zones with high Pu enrichment and no boron control.
5. Changes in the isotopic compositions of Pu can give raise to important changes of the steam entry effect (240Pu and 241Pu in LWR-Pu)
6. A small amount of 237Np added to the fuel can considerably improve steam entry reactivity without noticeably deteriorating breeding ratio or affecting reactor operation.

7. Literature

(1) R.A. Moore, "A Critical Program for the 300 MWe Gas-Cooled Fast Breeder Reactor",
Gulf-GA-A12780, pp. 3-18, Gulf General Atomic (1973).

(2) A.L. Hess, C.J. Hamilton, "Steam Ingress Reactivity Effects in the GCFR",
Technical Review Proceedings of Gas-Cooled Fast Reactor Program, Helium Breeder Associates Department of Energy (1979).

Table I: REACTIVITY CONTRIBUTIONS OF DIFFERENT ZONES, NORMAL FUEL

Middle of the Equilibrium Cycle
Steam Density = 0.03 g/cm^3

Reactor Zone	Steam Entry Reactivity (%)			
	δSCAT	δLEAK	δPROD + δABS	$\Delta\rho$
Core Zone 1	-0.19	+0.07	-0.07	-0.19
Core Zone 2	+0.05	+0.06	-0.05	+0.06
Core Zone 3	-0.33	+0.07	-0.04	-0.30
Core Zone 4	+0.11	+0.11	-0.02	+0.20
Rad. Blanket	-0.27	+0.11	-0.01	-0.17
Ax. Blanket	-0.55	+0.16	-0.03	-0.42
Total Reactor	-1.18	+0.58	-0.22	-0.82

Table II: SENSITIVITY OF STEAM ENTRY EFFECT TO DIFFERENT NUCLIDES

Nuclide	$(\nu\sigma^f - \sigma^a)_{wet} - (\nu\sigma^f - \sigma^a)_{dry}$ [b]					
	Core Zone 1	Core Zone 2	Core Zone 3	Core Zone 4	Radial Blanket	Axial Blanket
U 238	-0.05	-0.05	-0.04	-0.04	-0.06	-0.11
Np 237	-0.92	-0.86	-0.66	-0.69	-1.88	-3.08
Pu 238	-0.10	-0.09	-0.03	-0.05	-0.36	-0.63
Pu 239	+0.51	+0.46	+0.35	+0.37	+1.19	+2.16
Pu 240	-0.24	-0.22	-0.15	-0.15	-3.91	-8.76
Pu 241	+1.69	+1.56	+1.18	+1.26	+3.69	+6.23
B 10	-1.71	—	-1.26	—	—	—

MOEC, Steam Density = 0.03 g/cm^3

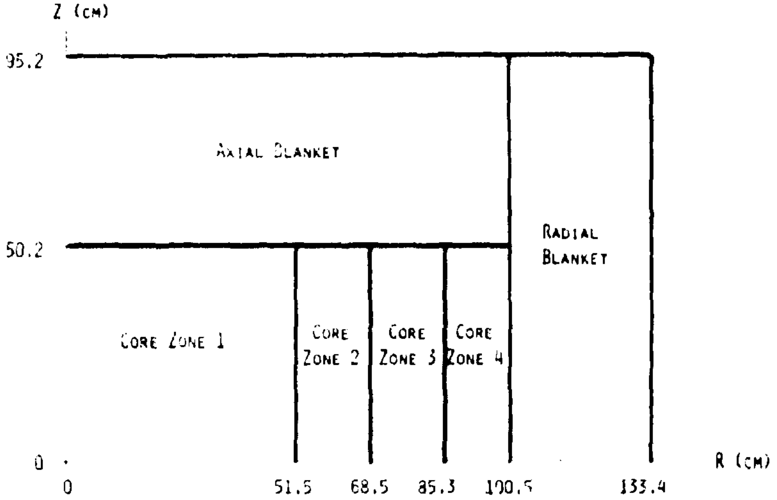

Fig. 1 Model of the Reactor

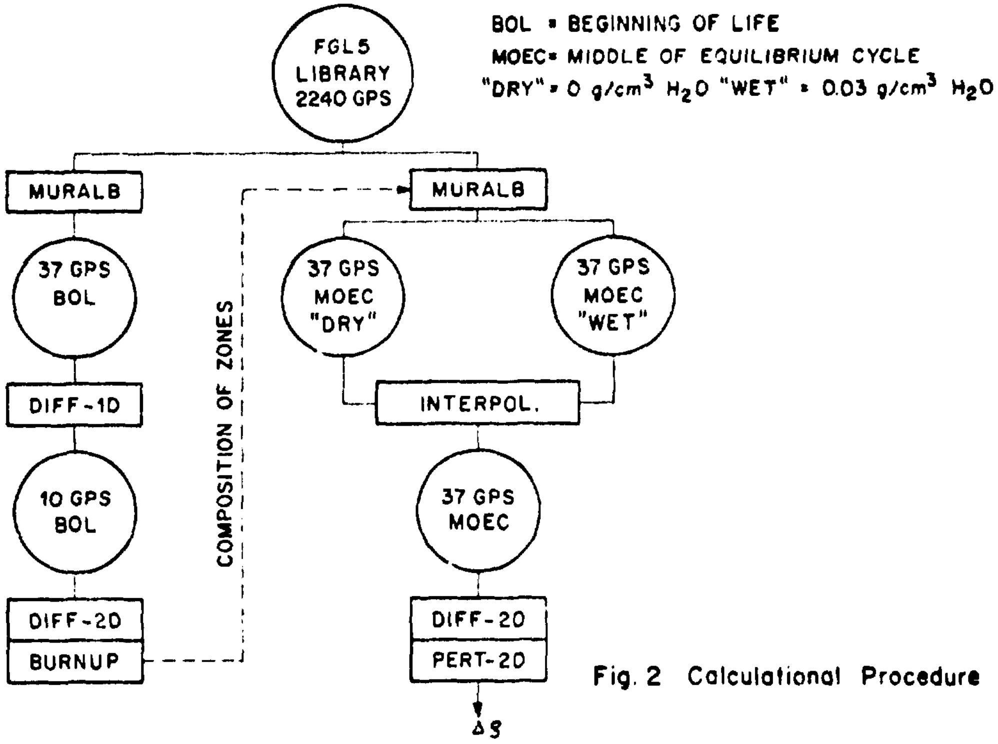

Fig. 2 Calculational Procedure

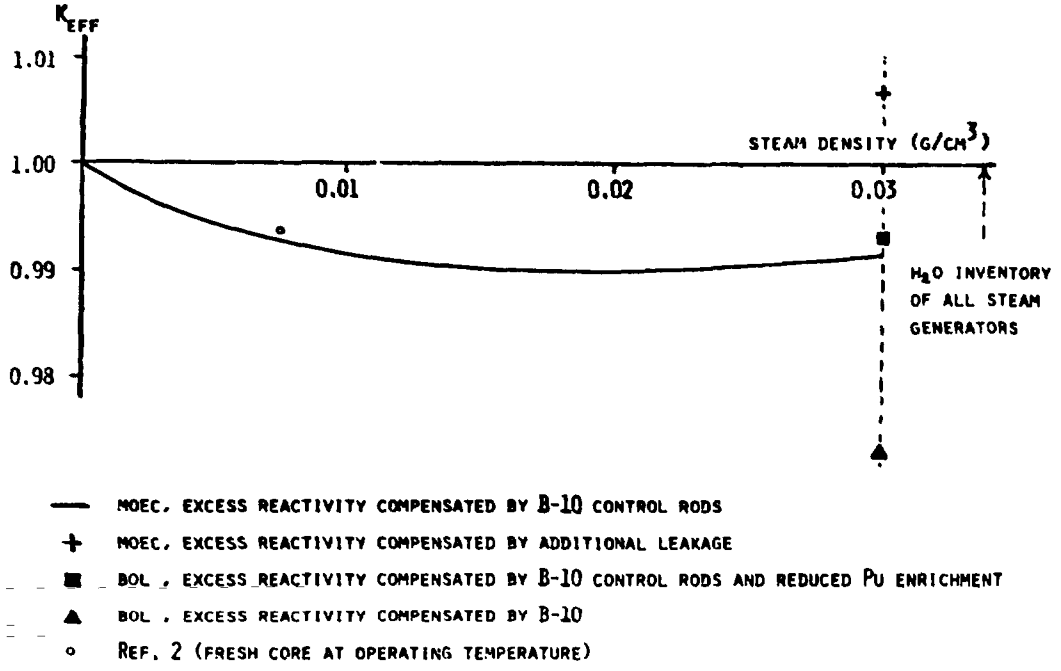

FIG. 3 REACTIVITY EFFECT OF STEAM ENTRY IN A 300 MWE GCFR

PRESSURE TRANSIENTS ANALYSIS OF A HIGH-TEMPERATURE GAS-COOLED REACTOR WITH DIRECT HELIUM TURBINE CYCLE

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Abstract

The direct coupling of a gas cooled reactor with a closed gas turbine cycle leads to a specific dynamic plant behaviour. This behaviour will be described and illustrated through results gained from computer analyses performed at the Swiss Federal Institute for Reactor Research (EIR) in Wurenlingen within the scope of the Swiss-German HHT project.

The specific dynamic plant behaviour may be summarized as follows:

a) Any operational transient involving a variation of the core mass flow rate causes a variation of the pressure ratio of the turbomachines and leads unavoidably to pressure and temperature transients in the gas turbine cycle.

b) Very severe pressure equalization transients initiated by unlikely events such as the deblading of one or more turbomachines must be taken into account.

Among the operational transients, two cases will be presented: a generator loss of load followed by plant stand by operation and a plant emergency shut down. In both cases a compressor