Nuclear Safety Parameters of TRIGA Reactor

M. Ravnik

The purpose of this presentation is physical explanation of most important nuclear safety parameters:

- power peaking factors
- temperature and void reactivity coefficient.

Results are directly applicable to TRIGA reactor operation and safety analysis.

More detailed explanation is found in the following references:

1. M. Ravnik, Nuclear safety parameters of mixed TRIGA cores, Workshop on reactor physics calculations, 12 February to 13 March 1990, ICTP, Trieste, Proceedings: p. 399-421, World Scientific,1991.

2. M. Ravnik, PWR Core design calculations, Workshop on reactor physics calculations, 17 February to 21 March 1986, ICTP, Trieste, Proceedings: p. 157-186, World Scientific,1986.

1. Power peaking factors

Fuel power density must be limited due to temperature, thermal-hydraulics and mechanical design limitations. In TRIGA, temperature limitation (1100^0C) is imposed by internal hydrogen pressure due to temperature dissociation of Zirconium-hydride.

Power density distribution in a realistic reactor is neither continuos nor smooth, due to

core heterogeneity

- leakage and reflector effects
- differences in fuel composition, uranium concentration, enrichment, burnable absorbers, burn-up, control rod effect,…
- non-fuel parts of the core: empty positions, water gaps, irradiation channels, control rods

fuel rod heterogeneity

- power distribution inside fuel rod

1.1. Leakage and reflector effects

Even if the core is homogeneous and compact the flux and power density is affected at the core/reflector boundary (**Fig. 1**)

Note:

flux distribution is continuos function of position in the reactor
power density distribution, proportional to product of flux and macroscopic fission cross-section, is not continuos

Inherent effect due to leakage in finite reactor systems:

Flux distribution in radial direction normally peaked in the center with radial power peaking factor typically 1.65 (in TRIGA)

Theoretical radial distribution for homogeneous bare cylinder: Bessel function
Real cores: distorted by core heterogeneity (**Fig. 2**)

Flux distribution in axial direction also peaked in the center with axial power peaking factor typically 1.3 (in TRIGA)

Theoretical axial distribution for homogeneous bare cylinder: cosine
Real cores: much less distorted than radial distribution (**Fig. 3**)

1.2. Core composition

Core is normally loaded with fuel elements that are (practically) identical in

geometry
mechanical design
thermal-hydraulics design
but may significantly differ in
uranium concentration
enrichment
burn-up
burnable poison concentration.

These design features are normally applied to reduce power density variations induced by leakage (e.g. by using more enriched fuel elements at the core periphery, 'Low Leakage Loading Pattern'). However, if they are not properly used, the effect may be opposite.

Radial power peaking factor in mixed core normally increased compared to uniform core (**Fig. 4**)

Effect of burn-up and burnable poison is similar but normally not so strong as effect of design variations in enrichment or uranium concentration.

1.3. Non-fuel parts of the core

empty positions
water gaps
irradiation channels
control rods

Influence of irradiation channel on power density in nearest fuel elements is illustrated in **Fig. 4** and **Fig. 5**.

1.4. Power distribution inside fuel rod

Particularly important for pulsing, when fuel temperature immediately after the pulse proportional to power distribution due to too short time for heat diffusion.

Relative radial power distribution in TRIGA fuel rod is presented in **Fig.6**.

Summary:

Total power peaking factor is conservatively product of several partial peaking factors, depending on conditions

radial x axial x irradiation channel x inside fuel rod x … = total

For pulsing with compact uniform TRIGA core with Standard 20% enriched fuel containing one irradiation channel:

1.6 x 1.3 x 1.17 x 1.20 = 2.92

Maximum power density is approximately three times bigger than the average

For pulsing with mixed TRIGA core with 20% and 70% enriched fuel containing one empty (water filled) position:

2.0 x 1.3 x 1.45 x 1.50 = 5.65

Maximum power density is almost two times bigger than in uniform core without empty positions

Obviously: To reduce power density peaking avoid

- mixed core (use one type of fuel elements)
- water gaps, empty positions, irradiation channels (use compact core configuration).

2. Fuel temperature reactivity coefficient

Two main effects contribute to fuel temperature reactivity effect:

- Doppler broadening
- thermal spectrum shift (spectrum hardening).

Doppler effect is result of increased resonance capture reaction rate in U-238 due to resonance broadening (the same effect as in low enriched uranium power reactors). In TRIGA Doppler effect contributes less than half to total fuel temperature reactivity effect.

Spectrum hardening is dominating effect in TRIGA. The effect is as follows:

Increasing of fuel temperature results in shift to higher energy and deformation of Maxwellian spectrum in fuel. Spectrum in water is only slightly affected due to smaller increase in water temperature. Fission reaction rate in fuel is reduced due to harder spectrum in fuel, absorption reaction rate (sum of absorption in fuel and water) is less reduced. Ratio of fission reaction rate and absorption reaction rate (p.d. equal to multiplication factor) is reduced. Reactivity effect is negative.

Temperature reactivity coefficient α_f in TRIGA reactors is sensitive to neutron spectrum due to spectrum hardening effect.

For this reason α_f depends on

enrichment (also affects Doppler effect, directly through U-238 concentration)
uranium concentration
burn-up
temperature.

Examples for two fuel types with different enrichment and different uranium concentration are presented in **Fig. 7 and 8** in dependence of burn-up and temperature.

3. Void reactivity coefficient

Reducing effective water density in reactor by

temperature expansion (temperature increase) or
void (steam or air bubbles, void irradiation channels)

directly affects moderation in water. This may affect reactivity in negative or positive way, depending on fuel/water volume ratio (reactor overmoderated or undermoderated). TRIGA reactors are designed as undermoderated. Decreasing water/fuel ratio normally results in reducing reactivity. However, effect depends also on the position of void in the reactor:

void in fuel region inside core reduces reactivity
void in water gap between core and reflector may increase reactivity.

Negative void effect of the core is prevailing considering water density changes due to heating or cooling. **Water temperature reactivity coefficient** is for this reason negative.

4. Power reactivity coefficient, which is a "superposition" of fuel temperature reactivity and water temperature reactivity coefficient is also negative. Prevailing contribution is fuel temperature reactivity effect, because Doppler and spectrum hardening contribute more to negative reactivity than reduced moderation density in water.

Conclusion

Power peaking factors and temperature reactivity coefficients are the most important reactor parameters for normal operation and transient safety analysis in research as well as in power reactors. They form the basis for technical specifications and limitations for reactor operation such as loading pattern limitations for pulse operation (in TRIGA).

Figures

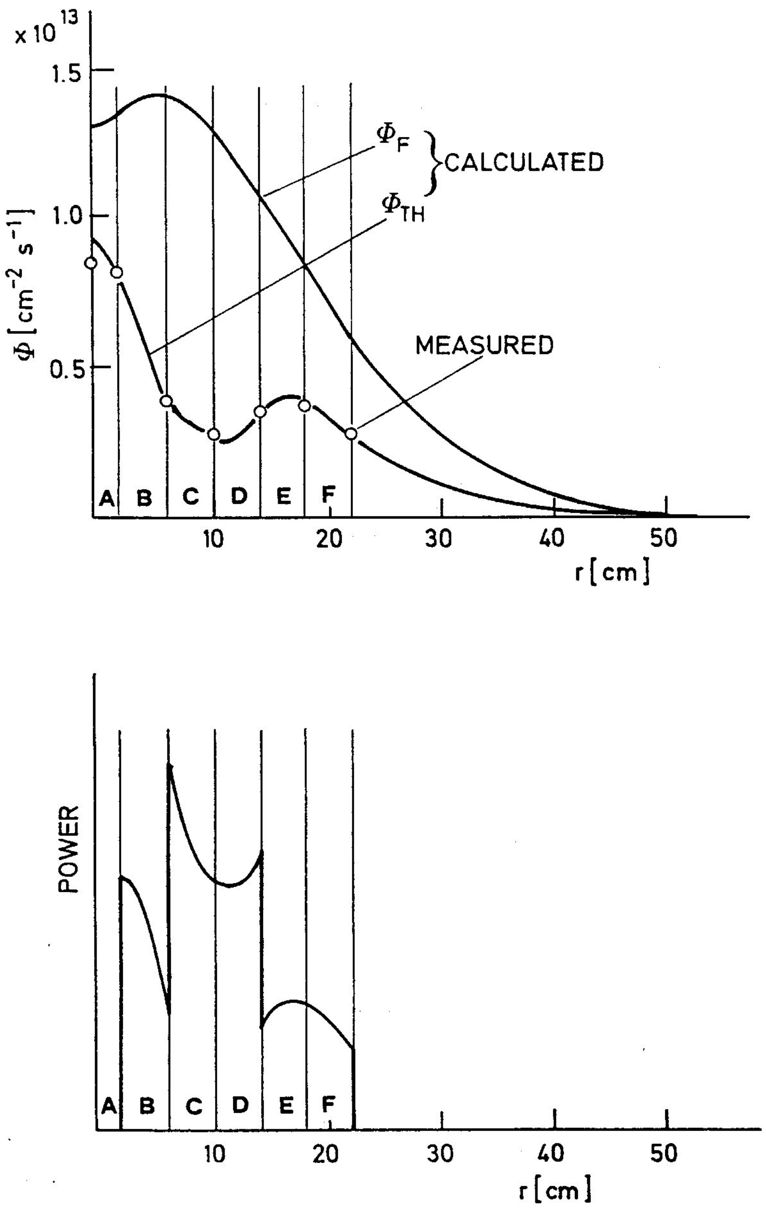

Fig. 1. Flux and power radial distribution in mixed TRIGA core

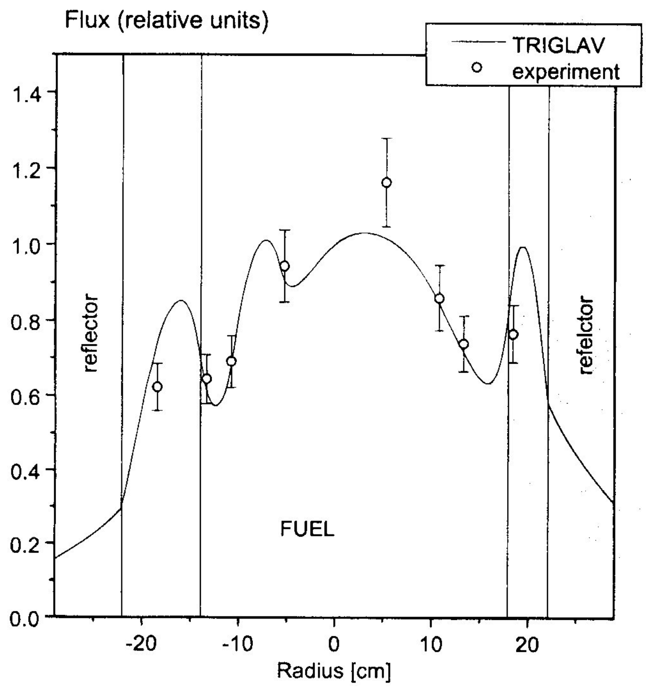

Fig. 2. Radial flux distribution in uniform TRIGA core

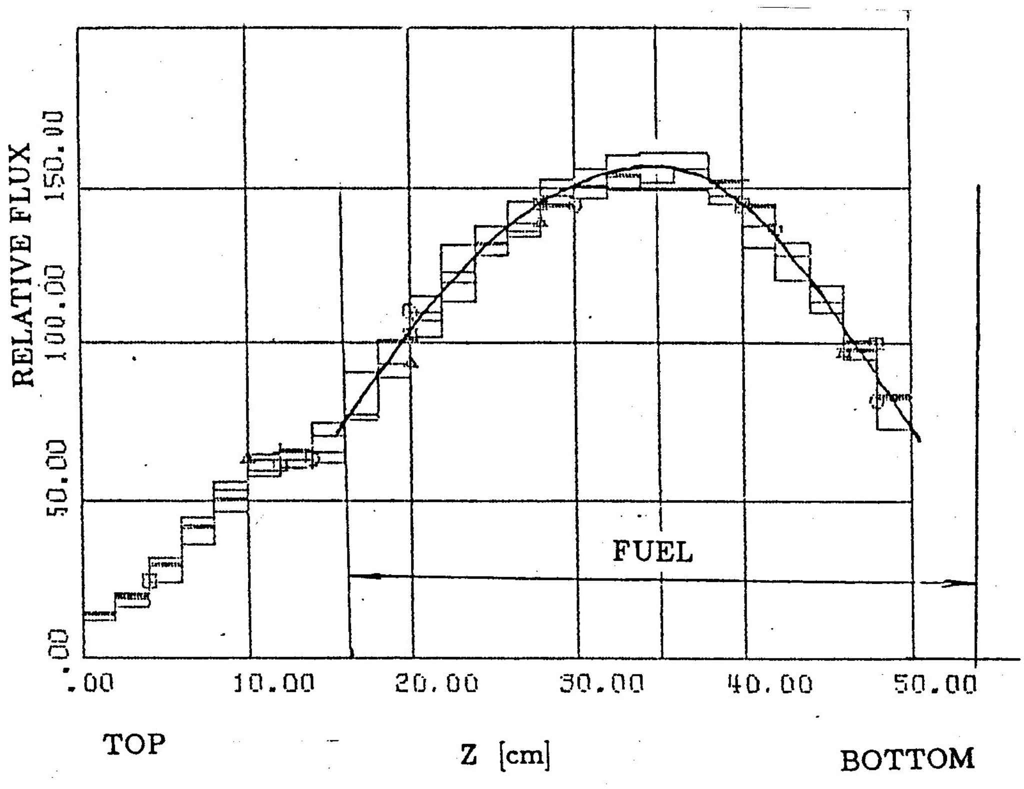

Fig. 3. Axial flux distribution in uniform TRIGA core

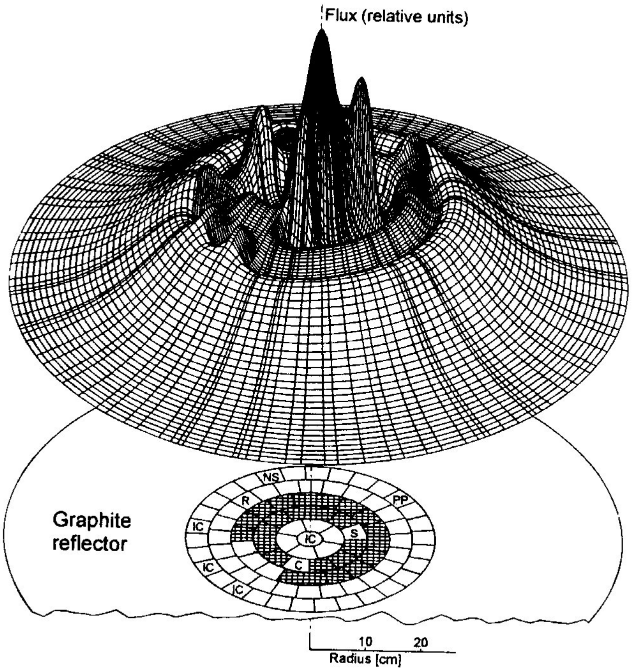

Fig. 4. Thermal flux distribution in mixed TRIGA core (70% enriched FLIP fuel mixed with 20% enriched Standard fuel).

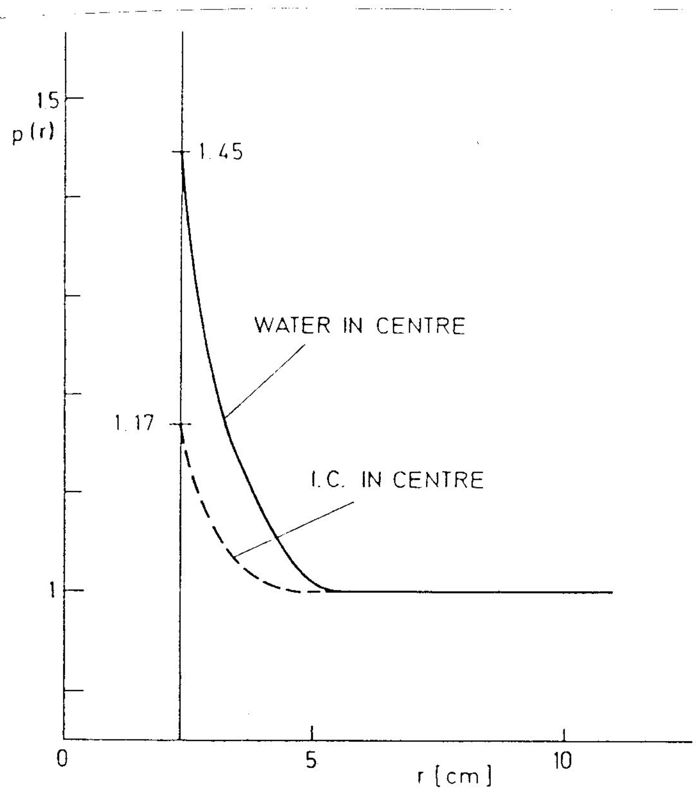

Fig. 5. Radial power density distribution around a core position not containing fuel rod

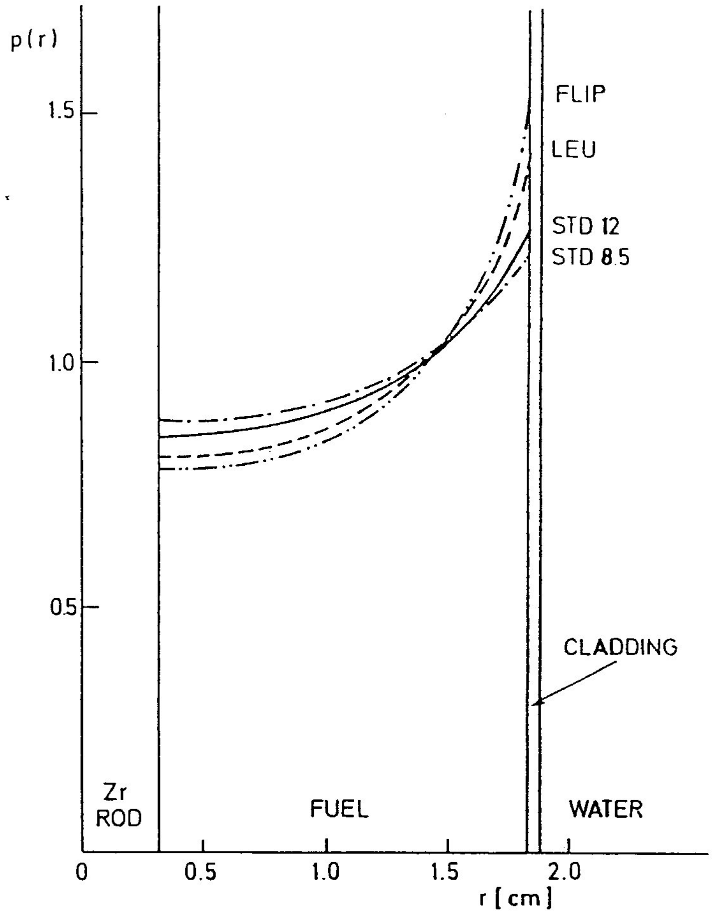

Fig. 6. Relative radial power density distribution in fuel rod for different types of TRIGA fuel

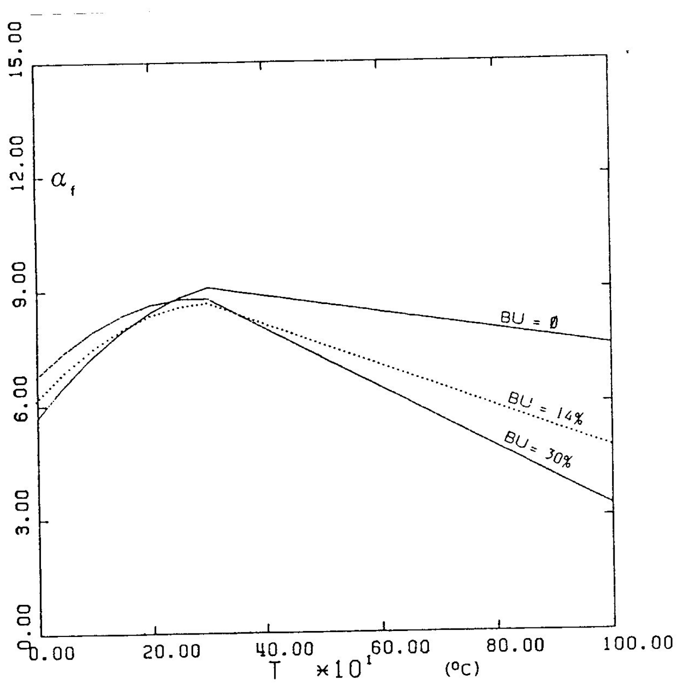

Fig. 7. Fuel temperature reactivity coefficient in pcm/^{0}C as a function of fuel temperature and burn up for standard, 20% enriched TRIGA fuel containing 12wt% uranium

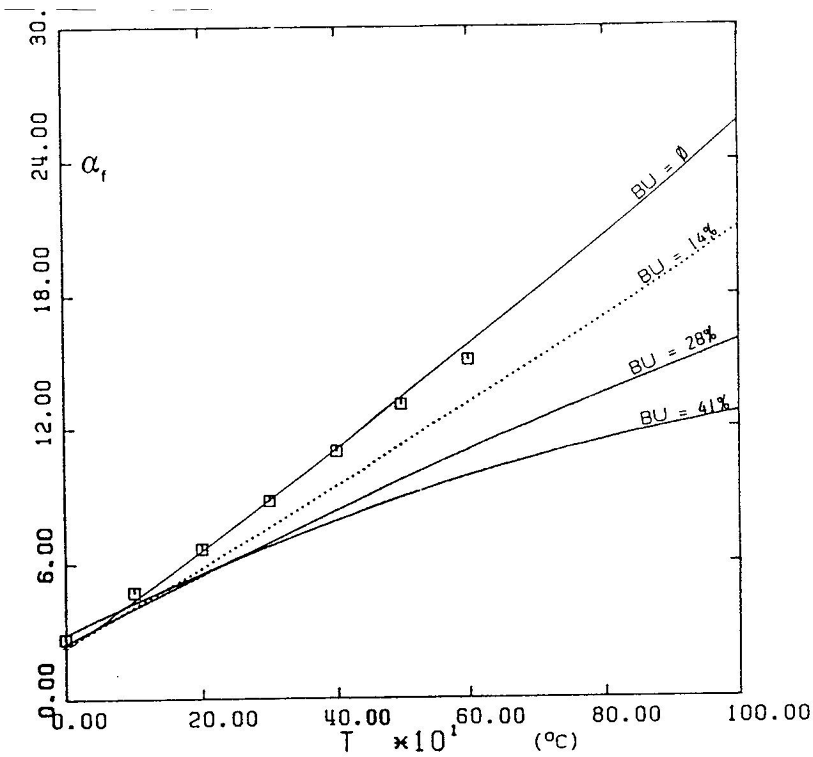

Fig. 8. Fuel temperature reactivity coefficient in pcm/^{0}C as a function of fuel temperature and burn up for FLIP, 70% enriched TRIGA fuel containing 8.5wt% uranium