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High Flux Isotope Reactor Uncertainty Factors

Emilian Popov
Belgacem Hizoum

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OAK RIDGE National Laboratory

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OAK RIDGE NATIONAL LABORATORY
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ABBREVIATIONS

CHF	critical heat flux
DOE	US Department of Energy
HEU	highly enriched fuel
HFIR	High Flux Isotope Reactor
HSSHTC	HFIR steady-state heat transfer code
LEU	low-enriched uranium
IFE	inner fuel element
OFE	outer fuel element
ORNL	Oak Ridge National Laboratory
U_3Si_2-Al	uranium silicide dispersion fuel

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ABSTRACT

This report provides a brief summary of the uncertainty factors used for High Flux Isotope Reactor (HFIR) steady-state heat transfer analyses. These factors are mainly used in the HFIR Steady-State Heat Transfer Code (HSSHTC) to perform core thermal margin evaluations that determine safe reactor operation. The attempt to classify these factors stems from the assumption that the current approach is characterized by an excess of conservatism, thereby restricting reactor performance. The work documented herein was of a limited scope and pertained mainly to factors' description and initial grouping based on their functional use. Suggestions are provided for further evaluation for the low-enriched uranium (LEU) to the uranium silicide dispersion fuel (U_3Si_2-Al).

1. INTRODUCTION

The steady-state heat transfer analysis used to determine and validate HFIR's safe operation considers 26 uncertainty factors, named $U_1 - U_{26}$ [1]. These factors capture the uncertainties in reactor process conditions, tolerances, uncertainties due to fuel manufacturing, and analytical model/correlation uncertainties. The uncertainty factors are computer code parameters that are used in a cumulative, deterministic manner to resolve conditions that could lead to adverse outcomes for reactor safety. Although the distinction between those uncertainties may not always be clear, these factors may be classified into the following three major categories.

1. **Modeling related**: This category includes topology parameters—both nominal values and tolerances—specified by the fuel element fabrication drawings. They influence the local heat transfer conditions, either in their effects on heat flux, coolant flow rates, or temperatures. This category also includes hot spot uncertainties, defined as those that affect only a sufficiently small area of the fuel plate as to preclude any effects other than those on local coolant velocity or local heat flux. (That is, these factors are assumed to have no effect on the bulk water temperatures or total channel flow rate or on fuel plate buckling.)
2. **Reactor operating conditions**: This category includes parameters that influence the heat flux or coolant condition, such as inlet temperature, pressure, flow rate, power level, the calculated and/or experimental geometrical power distribution factors, and the operating cycle history of the fuel element.
3. **Correlations and constants**: This group involves uncertainties in the calculations, methods, and correlations employed in predicting the actual fuel element heat transfer conditions. Additionally, the category includes varying constants in some of the data correlations, which are related to the local heat transfer coefficient, fuel plate oxide film buildup, and fuel plate deflection. This allows for incorporation of additional experimental data as well as for changing the form of the correlations.

2. CATEGORY 1 (U_2, U_4, U_5, U_{12}, U_{13}, U_{14}, U_{15}, U_{16}, U_{17}, U_{18}, U_{19}, U_{20}, U_{21}, U_{24}, U_{25}, U_{26})

The U_2 factor quantifies the uncertainty in fissile loading. The factor acts in altering the local heat flux, thereby influencing the determination of the coolant temperature. It is specified by the fuel element fabrication, with typical tolerances specified for the HFIR highly enriched fuel (HEU) fuel of 1.01. *For the LEU fuel, this factor will be revised by the LEU fuel fabrication process*.

The U_4 and U_5 factors designate uncertainty in the average fuel concentration in the hot and cold plate. A hot plate is defined as a fuel plate that has the maximum average fuel concentration permitted in the specifications associated with the HEU fuel [2]. These specifications require that the average amount of uranium within any given area measuring 1/2 in. or more along the length and across the full width of the plate must be within 12% of the nominal design value. These factors are applied to the heat balance relation for calculating the bulk water temperatures in the hot and cold channels. The numerical values of these factors are a function of their location on the fuel plate surface, and they must align with the specifications mentioned above. According to [1], a value of 0.90 for the upper half of the plate and 1.12 for the lower half of the plate were assumed for U_4. The U_5 values were assumed to be 1.10 for the upper half of the plate and 0.88 for the lower half of the plate [1]. *The value of the LEU fuel will be determined by the fuel fabrication tolerances standard, once established.*

The U_{12} factor denotes uncertainty in the increase in the fuel plate thickness due to thermal expansion of the aluminum cladding. Consequently, the coolant channel thickness will decrease slightly and, therefore, affect the flow area and in turn the flow rate. In addition to this effect, there is also an increase of fuel plate thickness due to the partially restrained thermal expansion along the plate width and length (Poisson's effect). According to McLain [2], this results in an additional increase of 1.3 in the thickness of the fuel plate. For the HEU fuel, both effects were combined to a total uncertainty, which was estimated to be $U_{12} = 2$. *Note that it is not expected that this uncertainty factor will be affected by the LEU conversion since the material of the fuel cladding is maintained the same for the LEU fuel.*

The factor U_{13} represents uncertainty for the increase in the fuel plate thickness due to radiation swelling. The radiation swelling of the fuel plates reduces the coolant channel thicknesses in two ways. First, it increases the thicknesses of the fuel plates. The second effect of the radiation swelling of the fuel plates may increase their longitudinal deflection. According to McLain [2], the existing experimental data were insufficient to determine the uncertainty associated with this phenomenon. The safety analysis for HFIR has used a value of 1.0. *To determine the value of this factor for LEU, it is necessary to produce fuel radiation swelling experimental data.*

U_{14} denotes the uncertainty factor for fuel plate deflection due to longitudinal buckling induced by thermal expansion of the fuel plate, which is caused by a temperature difference between fuel plates and side plates. According to Chapman [3] and Appendix D of McLain [2], the developed correlation for the longitudinal deflection of the fuel plates is conservative, and, therefore, a value of 1.0 is used for the HEU fuel. *Regarding the LEU fuel, the uncertainty factor and correlation will remain applicable if the fuel plate and side plate temperature differential is less than 100 MW HEU conditions. The potential impact to the fuel plate thermal expansion coefficient as a result of displacing aluminum with silicide should also be considered.*

U_{15} represents uncertainty in the longitudinal fuel plate deflection due to the radiation growth (or radiation swelling) of the fuel plate material. As stated in McLain's study [2], the correlation for the deflection calculation is conservative, so an uncertainty factor of 1.0 was applied. *Verification of the correlation and determination of the uncertainty from experimental data are necessary for the LEU fuel.*

U_{16} represents uncertainty in the side plate heat generation, and a value of 1.00 is used.

U_{17} represents uncertainty in the coolant heat generation rate, and a value of 1.00 is used.

Factors U_{18} and U_{19} denote the local fuel segregation flux peaking factors for the hot and cold side, respectively. The term *hot side* is defined as the side facing the concave clad surface, which is situated close to the fuel zone, and the *cold side* is the side farther away from the fuel zone that faces the convex side of the cladding surface. The fuel plates may have localized pockets of segregated uranium within circular portions of the plate surface having diameters of 5/64 in., which corresponds to the diameter of the x-ray beam of the fuel inspection device. According to the original HFIR HEU fuel specification, the concentration of fuel within this circular area must not be greater than 30% above the nominal amount. Based on this, the value of the HEU fuel segregation factors for both hot and cold sides were assumed to be 1.3; see McLain et al. [2] and Hilvety et al. [4] for further details. This value was changed to 1.27, see

[1] and the current fuel specification [5]. For the LEU fuel, the specification has not been finalized at the time of this writing. However, in a study conducted by Primm et al. [6] with U-Mo alloy fuel, a value of 1.27 was used. Chandler [7] employed a consistent value of 1.27 during the update of the legacy method with higher-fidelity representation of the current HEU fuel core, which corresponds to a maximum allowable fuel concentration of 27% over the nominal amount. The examination of the LEU HSSHTC input file corresponding to this study revealed that although the input file shows a fixed value of 1.27, this value is not being used since the defect factor is being provided as a combined correlation function of fuel thickness between segregation and nonbond defect [8]. The study undertaken by Hizoum et al. in 2023 [9] attempted to determine the peaking factors of low-enriched uranium (LEU) fuel for each defect individually. The results showed that both U18 and U19 had a value of 1.12. The decrease in this factor is a function of silicide overpacking possible assuming the current inspection size. In thermal safety analyses, this factor serves to increase the local hot spot heat flux, which can be used either to calculate an incipient boiling power level or to determine the heat flux peaking factor necessary to reach burnout at a given power level. *These factors must be reevaluated for LEU fuel.*

The variables U_{20} and U_{21} denote the factors associated with the nonbond defect flux peaking that is applied to the hot and cold sides of the inner and outer fuel elements (IFE/OFE). The occurrence of nonbonds or blisters is a direct result of the fabrication rolling process, wherein voids might form due to inadequate bonding between the cladding material and the fuel cermet. This anomaly is characterized by a much higher thermal resistance compared with that of a good bond, leading to adverse effects on the heat transfer characteristics and therefore limit the maximum power level. These factors are derived with the aid of two-dimensional heat transfer software tools like COMSOL, HEATING, or HotSpot using prototype geometry model based on Hilvety 1967 approach described in [4]. For the HEU fuel, the results of simulation were correlated by Hilvety et al. [4] as a function of the arc fuel plate length (s). For the inner fuel element, the correlation for the hot and cold side is given as:

$$U_{20,hotSide} = 1.33687 - 0.35423s + 0.14503s^2 - 0.01669s^3$$
$$U_{21,coldSide} = 0.863686 - 0.016507s - 0.010950s^2 + 0.0047976s^3 \tag{1}$$

and for the outer fuel element, the correlation for the hot and cold side is expressed as:

$$U_{20,hotside} = 1.180171 - 0.278079s + 0.151756s^2 - 0.014261s^3$$
$$U_{21,coldside} = 0.881393 - 0.249204s + 0.181639s^2 - 0.033932s^3 \tag{2}$$

The nonbond factor correlation and its calculation details for the LEU silicide fuel are presented in the study performed by Hizoum et al. 2023, [9]. The correlations are given for the IFE fuel element (5.3 gU/cc silicide with 27% overloading at beginning of cycle conditions) as:

$$U_{20} = 1.16519 - 0.05977s + 0.00410s^2 + 0.003413s^3$$
$$U_{21} = 0.89599 - 0.0038s + 0.01772s^2 - 0.00521s^3 \tag{3}$$

and for the OFE as:

$$U_{20} = 1.10795 - 0.02770s + 0.00711s^2 + 0.00083s^3$$
$$U_{21} = 0.90578 + 0.01973s - 0.00517s^2 - 0.000542s^3 \tag{4}$$

In the HotSpot study [16], the peaking factors for both segregation and nonbond defects are combined into a single function of 5.3 gU/cc silicide fuel thickness (t), see eq. (5). Note that according to Appendix A of Reference [9], this approach is valid only for symmetric fuel.

$$UBar = -4.4003\text{E-}7t^4 + 3.8877\text{E-}5t^3 - 1.2422\text{E-}3t^2 + 1.1398\text{E-}2t + 1.2861 \quad (5)$$

The hot streak factor uncertainty U_{24} is applied to increase the bulk coolant temperature to account for the effects of maximum allowable axially averaged fuel density loading (i.e., fuel homogeneity tolerance) [10]. The current value for the HEU core is 1.12. *The LEU value will be a function of the maximum overloading allowed by the fuel specification.*

The factor U_{25} represents the flux peaking for fuel extending beyond normal boundaries. It is known that the thermal safety margin is typically limiting at the bottom of the core because the coolant temperature increases, and the pressure decreases with increasing axial distance down the fuel elements. A radially dependent uncertainty factor, U_{25}, is applied in the safety basis thermal hydraulic calculations to include the power peaking effects impacting fuel zones that may be axially lower than those in neighboring fuel plates. Uncertainty factor U_{25} is used to capture the uncertainty associated with the bottom axial location of the fuel zone. Current fuel specifications allow for (1) a ± 0.635 cm variation in the end location of the fuel meat on either end of the nominally 50.80 cm long active region and (2) the fuel plate to be axially misaligned within the fuel element up to 0.0381 cm. To account for this effect, MCNP-calculated axial power peaking factors are applied to the last row of axial fuel nodes to provide additional exit power peaking:

$$U_{25}(r,d,t) = \frac{\phi_{thermal}(r,d,t)}{\phi_{thermal}} \phi_{endFuel}(r,t) \;, \quad (6)$$

where $\phi^{endFuel}_{thermal}(r,t)$ is the thermal flux (energy < 0.625 eV) at an axial location of −25.4 cm with respect to the core horizontal midplane, radial location r with respect to the core axial centerline, and at time t during the reactor cycle; $\phi_{thermal}(r,d,t)$ is the thermal flux at radial location r, axial location d relative to the end of fuel, and at time t during the cycle. It was assumed that the value of this factor is 1.0 at every location except at the bottom end of the fuel bearing material. *For the LEU fuel, this factor will be determined by the fuel design and neutronics calculation.*

Uncertainty in the radial fuel edge peaking U_{26} is equal to 1.0. It is not currently used for HEU or LEU calculations.

3. CATEGORY 2 (U_1, U_3, U_6)

The U_1 factor represents the uncertainty in the reactor power level. This is determined from the primary coolant flow rate and the temperatures of the coolant entering and leaving the reactor vessel. In HSSHTC, the factor is applied in modifying the calculation of the local heat flux at any local surface area within the fuel element, thereby impacting the determination of the coolant temperature at any position within the fuel element. A typical value for the magnitude of this uncertainty is 1.0, which is determined from the ratio of the actual to the measured power level. *This uncertainty is accounted for in the reactor safety limit conditions and will not be affected by the LEU fuel conversion.*

The U_3 factor serves as a characterization of the uncertainty present in the calculated power density distributions in comparison to experimental data. For the HEU fuel ($U_3O_8 - Al$) neutronics analysis, an uncertainty factor of 1.10 has been factored into these power densities to account for the uncertainties associated with the flux distributions and fuel burnup during the fuel cycle [2]. According to Chandler [7], a power distribution uncertainty factor of 1.19 is taken into account for the LEU fuel thermal analysis. This factor comprises two components: 10% of the total represents the uncertainty associated with neutron transport calculations, whereas the remaining 9% of the factor is allocated to account for experimental variations that could affect the local power density. The factor acts in modifying the local heat flux, which subsequently affects the magnitude of the coolant temperature. *For LEU cores, this factor will be reevaluated with relevant neutronics analyses.*

The U_6 factor denotes uncertainty in the inlet temperature applied to bulk water temperature. The typical value used in HFIR HEU heat transfer analysis is 1.0 [1], [4]. Also, a factor of 1.015 was used in a study by Ilas and Primm [11], and a value of 1.0 was used recently by Chandler in his study for updating the performance and safety basis assessments of the HFIR HEU fuel [7]. The factor is applied to alter the inlet temperature and update the inlet water density and the average coolant conditions. *This uncertainty is accounted for in the reactor safety limit conditions and will not be affected by the LEU fuel conversion.*

4. CATEGORY 3 (U_7, U_8, U_9, U_{10}, U_{11}, U_{22}, U_{23})

The U_7 factor represents uncertainty related to the frictional pressure drop correlation. In HSSHTC, the calculation of the frictional pressure drop is performed using the Darcy–Weisbach equation. This model incorporates the Darcy frictional factor, which is derived from the Blasius equation in the form of $0.235/Re^{0.2}$. This Blasius equation is a fit to the Colebrook model friction factor for a channel roughness over a hydraulic diameter of 12×10^{-4}. According to McLain et al. [2], the uncertainty for this correlation is set to a value of 1.05. The report does not provide an explanation for how this number is derived. However, it is thought that it is acquired by comparing the HSSHTC correlation with the Moody diagram, as shown in Figure 6 of the same reference. In another study, Gambill et al. [12] performed experimental determinations of friction factors on thin rectangular channels. The results were compared to the conventional Moody diagram and were found to be accurate within 15%, which is higher than the uncertainty currently used for the HEU fuel. Additionally, the current correlation should also be replaced with a correlation that combines the Reynolds number (*Re*) and the surface roughness parameters to better capture the change in the friction factor with changes in the surface roughness during the fuel cycle. *Note that it is not expected that this uncertainty factor will be affected by the LEU fuel conversion because the material of the fuel cladding is the same.*

The U_8 factor indicates the uncertainty in the local heat transfer correlation. The factor is used to modify the heat transfer coefficient to account for this uncertainty. The correlation used in HSSHTC for predicting local heat transfer coefficients in the HFIR fuel elements is a modified version of the Hausen equation. Gambill and Bundy [12] assessed the correlation and estimated its accuracy to be within 10%. Thus, this uncertainty factor is set to 0.90. *It is expected that the LEU fuel conversion will have no impact on this uncertainty factor.*

The U_9 factor represents uncertainty in the aluminum oxide film thickness correlation [13] and has a value of 1.25. The formation of the fuel plate oxide film buildup is a consequence of fuel plate corrosion that occurs during the operation of the HFIR. The reduction in the thickness of the coolant channels and poor thermal conductivity of this oxide layer leads to an increase in the metal temperatures of the fuel plate. *It is expected to change for the LEU fuel due to possibly longer fuel cycle.*

U_{10} denotes uncertainty associated with the deflection of the fuel plate due to differential pressures between a narrow and a wide channel. This differential pressure is due to the coolant velocity in the wide channel being higher than that in the narrow channel, resulting in lower operating pressures in the wide channel. It is assumed that the differential pressure is uniform over the entire plate surface and is based on an average of core entrance and exit differential pressures. Deflections of HFIR fuel plates that have fixed (pinned) edges due to these pressure differences have been analyzed by Chapman [3]. The data were correlated, and the estimated analysis with these correlations were deemed to be accurate to within 10%. Therefore, an uncertainty factor of 1.10 has been used for the HEU fuel. *For the LEU fuel, although the cladding material remains unchanged compared to that of the HEU fuel, it is not apparent whether the same correlation can be applied. McLain et al. [2] notes that the differential pressure averaging assumptions are conservative if the limiting heat flux occurs below the core midplane, which may not be the case for LEU fuel designs. Thus, further investigation will be required to define this factor.*

The U_{11} factor represents the uncertainty of the calculated deflection due to the difference in the temperature between an individual fuel plate and that of an average fuel plate. The deflections of HFIR fuel plates have been analyzed in [3]. The data were correlated, and the estimated uncertainty factor of 1.10 has been factored into these correlations for the HEU fuel. *Regarding the LEU fuel, although the cladding material is the same, it is not clear whether the LEU fuel conversion will impact the form of the deflection correlations. Therefore, further investigation will be required.*

The U_{22} factor represents the uncertainty in the burnout heat flux correlation. This factor serves as a multiplier on the burnout heat flux. The term burnout is associated with the phenomenon that occurs when the heat flux becomes sufficiently large such that vapor bubbles formed from boiling coalesce into a vapor film that covers the surface, dramatically dropping the heat transfer efficiency and causing a large increase in the wall temperature [14]. Gambill [12] employed a superposition correlation to calculate burnout heat fluxes in subcooled water systems. In this method, the burnout heat flux is the sum of a term representing forced convection in the absence of boiling and a term that characterizes nucleate boiling contribution in the absence of forced convection. The correlation uncertainty is 0.8. *This factor will not be affected by the LEU fuel conversion.*

The U_{23} factor denotes the uncertainty in the incipient boiling correlation. It is applied as a multiplier to the incipient boiling criteria. The correlation is a measure of the heat flux at which the first significant effect of the nucleate boiling bubbles can be observed. A number below 1 for uncertainty results in a conservative thermal margin because it requires lower reactor power level to induce boiling. Conversely, a factor higher than 1 will lead to a non-conservative thermal margin due to the higher power level required to cause nucleate boiling. In HSSHTC, the incipient boiling criteria is that of Bergles and Rohsenow [15]. According to [2], qualification of the correlation against experimental data showed that it is conservative. Thus, it was recommended to assign a value of 1.0 to the uncertainty factor U_{23}. *This factor will not be affected by the LEU fuel conversion.*

5. SUMMARY OF FINDINGS

5.1 CONCLUSIONS

This review designates the factors and their basic meaning. It does not provide a full explanation of how the factors were derived and used, nor how they were coded in HSSHTC. Another aspect of proper factor usage is the verification of their performance. Steps must be taken as part of a more comprehensive analysis that should form the basis of possible statistical treatment to reduce the factors' overall impact on the HFIR thermal limits. The following are some suggestions regarding how to proceed with this broad task in the future:

1. Determine the uncertainty factors' ranges and their statistical distribution.
2. Classify which factors treat the same physical phenomenon and reduce redundancy.
3. Employ modern computational tools to reevaluate each factor's consistency.
4. Verify that the factors are properly coded in HSSHTC.

5. Perform ranking and determine which factors are more or less important for a specific safety limit.
6. Examine the HSSHTC modeling paradigm and document for further reference.

The grouping provided here indicates a reasonable rating in terms of the level of confidence in the factors' determination. Group 1 seems to be the group of factors that require a higher level of attention, followed by groups 2 and 3. Group 1 also contains the highest number of factors and may require a sub-classification to better distinguish between the driving physics behind them.

5.2 FACTORS REQUIRING FURTHER INVESTIGATION

Some factors' formulation is more difficult to comprehend, and it was not studied in sufficient detail within this work. The attempt was to sort the factors and determine which are self-explanatory and which require more work to be understood properly. The factors that should receive additional investigation are presented in what follows.

U_4 and U_5, which deal with varying fuel concentration. They are applied to the hot (more fuel) and cold plates (less fuel) to correct the heat input. The actual usage in the HSSHTC code must be assessed for interference with other similar factors, such as U_{24}.

U_{13} to U_{17} and U_{26} are assumed equal to 1.0 for HEU fuel according to [10] and [7]; that is, they do not, in fact, have any effect. Further LEU evaluation is needed based on more recent research in this area. If those phenomena were determined to be unimportant, these factors could simply be eliminated.

Non-bond uncertainties expressed by factors U_{20} and U_{21} and their application to a single-channel model with radial sub-channel discretization should be further investigated.

The U_{25} factor for longer than nominal fuel lengths should be investigated. Currently determined based on 'nominal' neutronics fuel dimension, the factor prediction could be improved with more detailed reactor physics simulations.

U_{10} and U_{11} are factors dealing with pressure and temperature deflection. The analyses carried out for a recent event revealed that a loose plate may severely aggravate the channel topology. These factors should be reevaluated to account for the probability of such an occurrence. The implementation of these factors has not been fully understood.

Except for the final two, the remainder of factors belongs to Group 1, and as indicated above, this is the most significant group for further investigation.

5.3 PHENOMENA-BASED CLASSIFICATION

Several factors address the same physical process or the prediction thereof. A question about redundancy can be posed. This section identifies factors that should be further studied to prevent superposition of uncertainties. This classification is merely for exploratory purposes and is by no means comprehensive.

U_4 and U_5 against U_{18} and U_{19}. These factors are used to account for fuel concentration distribution due to manufacturing tolerances. They all affect the power generation and distribution. The first group relates to hot and cold plates, whereas the second group relates to hot and cold *sides* of the hot plate. The HSSHTC code models a single channel, and the probability of combining these factors into one plate is a potential subject for investigation.

U_1 and U_3 against all other factors dealing with power distribution. These factors imply uncertainties in the calculation of power based on operation parameters. They should interfere with the power factors due to fuel concentration abnormalities. Further evaluation may be needed.

An illustration of factor superposition is depicted in Figure 1 when all applicable factors are simultaneously applied to a fuel plate modeled in COMSOL. Though in COMSOL the factors act on the power deposition in the fuel section, in HSSHTC they are directly applied to the heat flux to fluid without any option for heat dissipation in the plate. Moreover, HSSHTC is one-dimensional—meaning no turbulence mixing, radial heat transfer, or mass transport can be modeled, resulting in likely worse heat transfer conditions.

Note that the hot streak factor, U_{24}, is derived solely based on the accuracy of plate scanner. Recently developed direct numerical simulation models, used to predict HFIR channel turbulence quantities [16], allow for accurate computation of the flow mixing and streak dissipation due to true, and very high, flow turbulence. This is just an example of how newly developed predictive capabilities can be used to verify and fine-tune the factors to proper values.

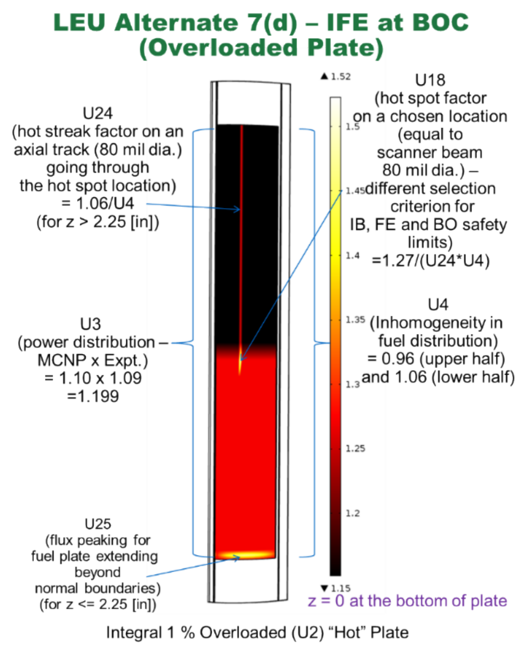

Figure 1. Incorporation of factors into the COMSOL model of 'hot' plate showing the simultaneous interference [10].

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