General Electric Advanced Technology Manual

Chapter 3.2

Thermal Limits

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3.2 THERMAL LIMITS

Learning Objectives:

1. State the requirements for Technical Specifications and explain the significance of Limiting Condition for Operation as applied to Safety Limits and Power Distribution Limits.

2. When given an initial set of operating conditions, the student will be able to use the format and content of the Technical Specifications to identify the applicable plant/or operator response.

3.2.1 Introduction

Limits on plant operation are established to assure the plant can be safely operated and not pose any undue risk to the health and safety of the public. This is accomplished by demonstrating that radioactive releases from the plants during normal operation, abnormal operation, and postulated accidents meet applicable regulations within conservative limits. These limits are specified by the Technical Specifications to prevent fuel damage from occurring.

The objective for establishing thermal limits for normal operation and transient events is to maintain the integrity of the fuel cladding. This is done by limiting fuel rod power density to avoid over stressing the fuel cladding due to pellet-clad differential expansion, and to avoid centerline melting. Transition boiling must also be prevented to avoid cladding damage due to overheating.

The objective for establishing a thermal limit for postulated accidents is to maintain core geometry by minimizing gross cladding failures. This failure could occur during a Design Basis Accident Loss-of-Coolant Accident (DBA LOCA) where the loss of coolant causes a severe heatup of the cladding. Under worst case conditions, the fuel could suffer gross fragmentation failure due to the quenching action of the Emergency Core Cooling System (ECCS) when the core is reflooded. This is prevented by limiting the stored heat in the fuel, thereby limiting cladding heatup during a LOCA.

The thermal limits established for these purposes are the ECCS/LOCA limit, the thermal-mechanical limit, and the minimum critical power ratio (MCPR) limit (Figure 3.2-1).

3.2.2 Thermal-Mechanical Limit

The thermal expansion rates of the UO_2 pellets and zircalloy cladding are different. The relative expansion arises from several sources:

- UO_2 fuel thermal expansion coefficient is approximately twice that of zircalloy.
- Fuel pellets operate at higher temperature than the cladding.
- Fuel pellets undergo irradiation growth as they are exposed.
- Fuel pellets crack and redistribute toward the cladding when under thermal stress.

This contact places stress on the cladding. If the stress exceeds the yield stress of the cladding material, the cladding will crack. Cladding cracking due to differential expansion of the pellet and clad is prevented by placing a limit on the peak fuel pin power level which would result in 1% plastic strain on the clad. The 1% plastic strain limit itself is conservative. It has been shown that even at the design end of life exposure on the fuel cladding (most brittle condition), greater than 1% plastic strain on the clad is required for cladding failure. This limit is called the *mechanical* limit.

Another limit on peak fuel pin power prevents centerline melting. During transient conditions, fuel pellet overpower occurs which must be limited to prevent centerline melting. This limit is called the fuel pellet *thermal* limit.

These two peak kw/ft limits are usually grouped together and called the *thermal-mechanical* limit.

Technical Specifications do not directly limit peaking factors; therefore it is possible to operate the core at low power with a high TPF. If power is then increased by flow it is possible to exceed the thermal-mechanical (LHGR) limit. To prevent this problem from occurring, Technical Specifications requires the APRM scram and rod block settings to be adjusted whenever the fraction of rated power (FRP) is greater than the core maximum fraction of limiting power density (CMFLPD). Where the fractional limiting power density is the actual LHGR divided by the design value. The process computer automatically calculates the CMFLPD along with the periodic core performance log.

3.2.2.1 Steady State Thermal-Mechanical Limit

The peak kw/ft limit is exposure dependent. The combined steady state limit is determined by the most limiting thermal or mechanical limit and is set by the manufacturer for each fuel type. The limit at zero exposure is 11.8 kw/ft for GE12 fuel and 13.4 kw/ft limit for the newer GE14 fuel design. This increase in kw/ft was made to improve the capability for longer cycles, extended power uprate, and reduce fuel cycle cost through more aggressive spectral shift operation via axial power shape control. These limits start to decrease after approximately 15,000MWd/st. The zero exposure limit is called Linear Heat Generation Rate (LHGR) limit, by most Technical Specifications.

3.2.3 APLHGR Limit

In the event of a DBA LOCA, the heat stored in the fuel at the time of the event could significantly damage the fuel cladding. The criteria that must be satisfied during this event are given in 10 CFR 50.46. During the DBA LOCA, the core region is voided of liquid in a relatively short time (less than 30 seconds). With no coolant, the only mechanism for heat removal from the cladding is radiative heat loss. The elevated fuel cladding temperatures cause an increase in the rate of oxidation of the zircalloy by the high temperature steam. Formation of zirconium oxide causes the cladding to become brittle. If the cladding temperature increases sufficiently (greater than 2200 ^{o}F) for extended length of time, the hot brittle fuel cladding could fragment by the quenching action when the ECCSs reflood the core. The chemical reaction becomes self-sustaining at approximately 2800 ^{o}F.

Because the LHGR is used to determine APLHGR the ECCS/LOCA limit and the thermal -mechanical limit can be combined into one number. The result is an exposure dependent curve of Maximum Average Planar Linear Heat Generation Rate limit ($MAPLHGR_{limit}$).

Current GE BWR MAPLHGR limits (as a function of exposure) are based on the most limiting value of either the ECCS/LOCA limits or the thermal-mechanical design limits. Since the thermal-mechanical design limit is included in the determination of the $MAPLHGR_{limit}$, it cannot be exceeded if the $MAPLHGR_{limit}$ is met. General Electric has proposed and the NRC has agreed that the separate specification of the steady state thermal-mechanical limit in the Technical Specifications is redundant and can be eliminated. The $MAPLHGR_{limit}$ will continue to provide assurance that the limits in 10 CFR 50.46 will not be exceeded, and that the fuel design analysis limits defined in NEDE 24011-P-A (GESTAR-II) will be met. The steady state thermal-mechanical limits are incorporated by reference into GESTAR-II.

Figure 3.2-2 is an example of a typical $MAPLHGR_{limit}$ curve for General Electric fuel. The general shape of the curve is produced by using the most limiting kw/ft value calculated for each of the previous criteria. A number of different factors contribute to the change in the curve:

- Changes in local peaking factor with exposure.
- Buildup of fission product gases inside the fuel rod increase the internal gas pressure and decrease the thermal conductivity of the gas pressure.
- Fuel pellet densification
- Response of the plant ECCSs during the DBA LOCA.

The last concern requires plant specific analysis. Therefore, the curves may be slightly different for different plants even though the fuel type is the same.

PCT following a LOCA is primarily a function of the average heat generation rate of all the rods in a fuel assembly at any axial location and is dependent secondarily on the rod-to-rod power distribution within an assembly. The peak cladding temperature is calculated assuming an LHGR for the highest powered rod less than or equal to the design LHGR corrected for fuel densification.

The calculational procedure used to establish the APLHGR limits for Technical Specification is based on a loss-of-coolant accident analysis. The analysis was performed using General Electric calculational models which are consistent with the requirements in Appendix K to 10 CFR 50. The LOCA analysis was performed utilizing the new improved calculational model, SAFER/GESTR-LOCA. The analysis demonstrated that LOCAs do not limit the operation of the fuel. Therefore, the APLHGR limits for the fuel types shown in the Core Operating Limits Report are based on the fuel thermal-mechanical design criteria.

3.2.3.1 Modifications Associated with the APLHGR Limit

A flow dependent correction factor is applied to rated conditions APLHGR to assure that the 2200 ^{o}F PCT limit is complied with during a LOCA initiated from less than rated core flow. In addition, other power and flow dependent corrections are applied to rated conditions APLHGR limit to assure that fuel thermal-mechanical design criteria are preserved during abnormal transients initiated from off-rated conditions. The MAPFACs are defined separately as a function of power and flow.

$$MAPLHGR \times MAPFAC_p = MAPLHGR_p$$
$$MAPLHGR \times MAPFAC_f = MAPLHGR_f$$

The MAPLHGR is taken from a figure similar to Figure 3.2-2 for each fuel type, and the MAPFACs are taken from Figures 3.2-3 and 3.2-4. $MAPFAC_p$ is usually determined from feedwater controller failure event results. $MAPFAC_f$ is usually determined by the recirculation pump runout event results. Below P_{bypass}, there is significant sensitivity to core flow during transients. P_{bypass} is defined as the power level which a reactor scram on turbine stop valve position/turbine control valve fast closure is bypassed. For this reason the $MAPFAC_p$ is further defined separately for a high flow (> 50% core flow) and a low flow condition (≤ 50% core flow). Below 25% rated power, surveillance of thermal limits are not required, due to the very large operating margins. Therefore, the $MAPFAC_p$ graph is not addressed below 25% power.

For single loop operation, a multiplication factor is applied to the rated conditions

APLHGR power and flow dependent correction factors and the limiting values for APLHGR for each fuel type used in a particular cycle.

After the correction factors have been applied, the lowest MAPLHGR value is the $MAPLHGR_{limit}$ for that power and flow. These calculations are performed by the process computer.

3.2.3.2 MAPLHGR Determination

The process computer calculates the total power produced in every node in the core. A portion of the power produced in a node is produced outside the fuel pins by gamma heating and neutron moderation. This power is divided into two parts: The fraction of the total nodal power that is produced outside the fuel channel in the leakage flow (FLK) and the fraction of the total nodal power produced in the channel that is not conducted through the cladding (FCH). Therefore, for comparison to the $MAPLHGR_{limit}$, the average power density in a node is calculated as follows:

$$MAPLHGR = \frac{Pnode \times (1\text{-}FLK\text{-}FCH) \times 1000 \times PTOPF}{NRB \times DZSEG}$$

where:

FLK	=	Fraction of core power deposited in leakage flow
FCH	=	Fraction of core power deposited in active channel flow by methods other than convection.
PTOPF	=	Fraction of core thermal power generated in the bottom 144 inches of fuel.
NRB	=	Number of fuel rods per bundle.
DZSEG	=	Fuel segment length (ft) = 0.5
Pnode	=	Power produced in the node (MW)

3.2.3.3 Peak kw/ft Determination

The process computer calculates the peak kw/ft value for each fuel bundle node in the core. The full core power distribution program (also known as the Perodic Core Performance Calculation) edits these values as MRPD (Maximum Rod Power Density).

MRPD = MAPLHGR x FLOP

FLOP = Maximum rod power/average rod power in across section of fuel segment (local peaking factor).

Once these peak nodal kw/ft values are calculated, the computer compares these to the zero exposure steady state thermal-mechanical limit of 13.4 kw/ft (or 14.4 kw/ft for GE8B, GE9B, GE10B, and GE11B). The process computer calls the steady state thermal-mechanical limit RPDLIM. The ratio of MRPD to RPDLIM is called Fraction of

Limiting Power Density (FLPD). As long as the largest value of FLPD is less than one, we are assured that we have not exceeded the thermal limit.

3.2.4 CPR Safety Limit

Critical power is the fuel bundle power required to cause transition boiling somewhere in the bundle. The critical power ratio (CPR) of a fuel bundle is the ratio of its critical power to its actual operating bundle power. The minimum value of CPR for all fuel bundles in the core is the Minimum critical power ratio (MCPR) and represents the bundle which is the closest to transition boiling. MCPR limits are imposed to avoid fuel damage due to severe overheating of the cladding.

The required Operating Limit MCPRs (OLMCPRs) at steady state operating conditions are derived from the established fuel cladding integrity Safety Limit MCPR of 1.06 for two-loop operation and 1.07 for single-loop operation, and an analysis of abnormal operational transients. For any abnormal operating transient analysis evaluation with the initial condition of the reactor being at the steady state operating limit, it is required that the resulting MCPR does not decrease below the Safety Limit MCPR at any time during the transient assuming instrument trip setting as given in Technical Specifications. The steady state MCPR thermal limit is derived from the single design basis requirement:

> *Transients caused by single operator error or equipment malfunction shall be limited so that, considering uncertainties in monitoring the core operating state, at least 99.9% of the fuel rods are expected to avoid boiling transition.*

3.2.4.1 Modifications Associated with the MCPR Limit

The current licensing basis approved with the GENESIS/ODYN models for calculating the OLMCPR for pressurization events is performed in accordance with either or both of two methods known as Option A and Option B. These currently used options are summarized below:

Option A

This approach is comprised of the two-step calculation which follows:

1. The pressurization transient is analyzed using the GENESIS/ODYN models to obtain the change in the critical power ratio (ΔCPR) for the core. Conservative input parameters are used in the analysis, (e.g. scram speed per Technical Specifications).

2. The licensing basis OLMCPR is given as OLMCPR = 1.044 (Safety Limit CPR + ΔCPR).

Option B

This procedure provides for statistical determination of the pressurization transient ΔCPR/(Safety Limit + ΔCPR) such that there is a 95% probability with 95% confidence (95/95) that the event will not cause the critical power ratio to fall below the MCPR Safety Limit. This approach can be satisfied in one of two ways:

1. A *plant-specific* statistical analysis can be performed per the approved statistical methodology procedures to determine the 95/95 ΔCPR/(Safety Limit + ΔCPR); or

2. Generic ΔCPR/(Safety Limit + ΔCPR) Statistical Adjustment Factors (SAF) for grouping of similar type plants can be applied to plant-specific calculations to derive the 95/95 ΔCPR/(Safety Limit + ΔCPR) value.

Utilities using Option B must demonstrate that their plant's scram speed distribution (t_{ave}) is consistent with that used in the statistical analysis (t_B). This is accomplished through an approved Technical Specification which requires testing and allows adjustment of the operating limit MCPR if the scram speed is outside the assumed distribution.

The GEMINI/ODYN set of methods has been compared against actual test data. The results of the comparison indicate an improvement in prediction accuracy with GEMINI/ ODYN models. The true 95/95 ΔCPR/(Safety Limit + ΔCPR) will be determined using the same fundamental approach established for the current GENESIS/ ODYN Option B and accounting for the improvement in prediction accuracy. The resulting procedure, which will be used with the GEMINI/ODYN models, simplifies the current two option approach into one.

Licensing analyses accomplished with GEMINI/ODYN models will permit plants to operate under a single set of MCPR limits if scram speed compliance procedures identical to those in current plant Technical Specifications are followed. If scram speed compliance is not demonstrated, more conservative MCPR operating limits must be met. The statistical determination of the transient ΔCPR/(Safety Limit + ΔCPR) factor for the pressurization event will continue to assure 95% probability with 95% confidence that the critical power will not fall below the MCPR Safety Limit.

The Technical Specification limit will be determined from the following general equation:

$$OLMCPR_{TechSpec} = OLMCPR_{95/95} + \frac{t_{avg} - t_s}{t_A - t_B} (\Delta OLMCPR)$$

where:

ΔOLMCPR = factors derived by the new methodology

$OLMCPR_{95/95} = \Delta CPR_{95/95}$ + MCPR Safety Limit

For plants that demonstrate scram speed compliance (i.e. $t_{ave} \leq t_B$) using the NRC-approved procedures, the specification limit becomes:

$OLMCPR_{TechSpec} = OLMCPR_{95/95}$ (for $t_{ave} \leq t_B$)

If scram speed compliance is not demonstrated by a plant or if a plant chooses not to perform the scram speed compliance procedures (i.e. $t_{ave} \leq t_B$), then a more conservative limit must be used.

The actual operating limit will be a straight-line interpolation between these two values dependent on the results of scram speed testing, Figure 3.2-5.

At less than rated power conditions, transients such as rod withdrawal errors, feedwater controller failures, or recirculation pump runouts become limiting. For this reason, the OLMCPR is raised to compensate for such transients. These operating limits are:

$MCPR_f$ = a flow biased MCPR operating limit
$MCPR_p$ = a power biased MCPR operating limit (K_p power adjustment factor)

A flow adjusted factor (K_f) increases the CPR operating limit at core flows less than rated (Figure 3.2-6). The upper curve is used when operating in the automatic flow control mode to prevent violation of the OLMCPR if flow increases to the maximum flow rate allowed by the recirculation system. The lower curves are used when operating in the manual flow control mode to prevent violation of the safety limit MCPR if flow increases to the maximum flow rate allowed by the recirculation system.

When operating below P_{bypass} the severity of a limiting event becomes significantly sensitive to the initial flow at which the transient begins. A high initial flow is more limiting. Therefore, to prevent application of the more conservative high flow limits to a typical low flow startup condition, the $MCPR_p$ is further defined for high flow (> 50% core flow) and low flow conditions ($\leq$ 50% core flow). The 50% cutoff for flow is a conservative value.

Since the initial core flow below P_{Bypass} affects the severity of the transient, the value taken from Figure 3.2-7 is the $MCPR_p$ and not the correction factor K_p. Below P_{Bypass}, the severity of events such as Load Reject without bypass of Turbine Trip without bypass can exceed that of a feedwater controller failure.

When operating at rated power and flow conditions, the OLMCPR is the limiting value for MCPR. However, at less than rated power and flow conditions, the $MCPR_f$ and $MCPR_p$ are determined and the largest value of the two becomes the OLMCPR for that power and flow condition.

The process computer calculates $MCPR_{limit}$

where:

$MCPR_{limit} = max[(K_p \times OLMCPR), MCPR_f]$.
OLMCPR = 1.32

3.2.5 Exercise

A concerned nuclear engineer trainee at a facility expresses his concerns that the facility may not be operating within the thermal limits as defined by Technical Specifications.

The data available to you consists of the following:

- 2500 MW_{th} core operating at 90% CTP
- A GE9B (62 fuel rods, 150in. active fuel length) bundle producing 4.5 MW_{th}
- Node 16 producing 0.38MW_{th} (Uncontrolled)
- Critical power for the GE9B bundle is 6.5 MW_{th}
- Core Flow = 80%; NBUN = 560 bundles
- PTOPF = 0.995
- FLK + FCH = 0.04
- Attachment 1 (Last Core Operating Limits Report for the plant)
- Bundle exposure of 25 GWd/st
- Operating limit MCPR = 1.32

Assuming that all of the information given to you is accurate, make the appropriate calculations and determine if the thermal limits have been exceeded.

3.2.6 Thermal Limits Assessment with Power Uprate

The proposed Constant Pressure Power Uprate (CPPU) increases the average power density proportional to the power increase and has some effects on operating flexibility, reactivity characteristics and energy requirements. The maximum allowable peak bundle power is not increased by power uprate. The additional energy requirements for power uprate are met by an increase in bundle enrichment, and increase in reload fuel batch size, and/or changes in fuel loading pattern to maintain the desired plant operating cycle length. The power distribution in the core is changed to achieve increased core power, while limiting the MCPR, LHGR, and MAPLHGR in any individual fuel bundle to be within its allowable value as defined in the COLR.

No new fuel product line designs are introduced and there are no changes to fuel design limits required due to CPPU. However, the power level above which fuel thermal margin monitoring is required may change with CPPU. The original plant operating licenses set this monitoring threshold at a typical value or 25% of rate thermal power. Because the fuel thermal margin monitoring is a fuel bundle requirement, it is more appropriate to consider the monitoring threshold in terms of average bundle power. The average bundle power for the highest power density plant with the plant operating at original licensed thermal power is 4.8 MW_{th}. At a power level of 25% of original rated thermal power, the average bundle power for this plant is 1.2 MW_{th}. Consequently, below an average bundle power of 1.2 MW_{th}, the bundle powers are low enough such that thermal margin monitoring is not required.

For CPPU, the fuel thermal margin monioting threshold is scaled down, if necessary, to ensure that the monitoring is initiated by the time the average bundle power reaches 1.2 MW_{th}. Specifically, if the average bundle power at 25%
uprate power (P_{25})increases above 1.2 MW_{th}, then the existing power threshold value is lowered by a factor of 1.2/P_{25}.

A change in the fuel thermal monitoring threshold also requires a corresponding change to Technical Specificaion reactor core safety limit for reduced pressure or low core flow. Thus, a Thermal Power limit of 25%RTP for reactor pressure <785 psig or flow <10% would be reduced.

As of June 2011, the BWR power uprates are listed in Figure 3.2-9.

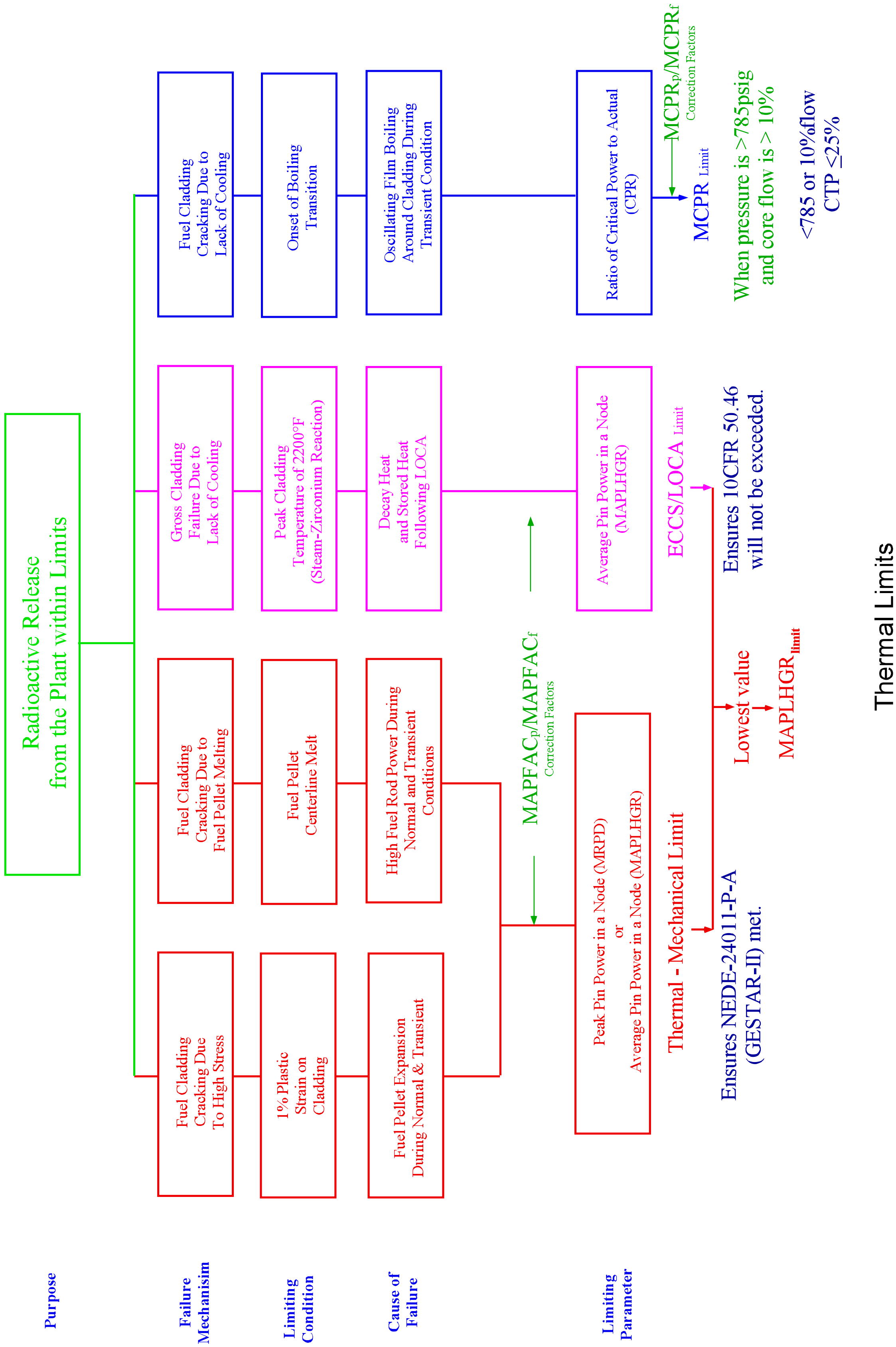

Figure 3.2-1 Thermal Limits

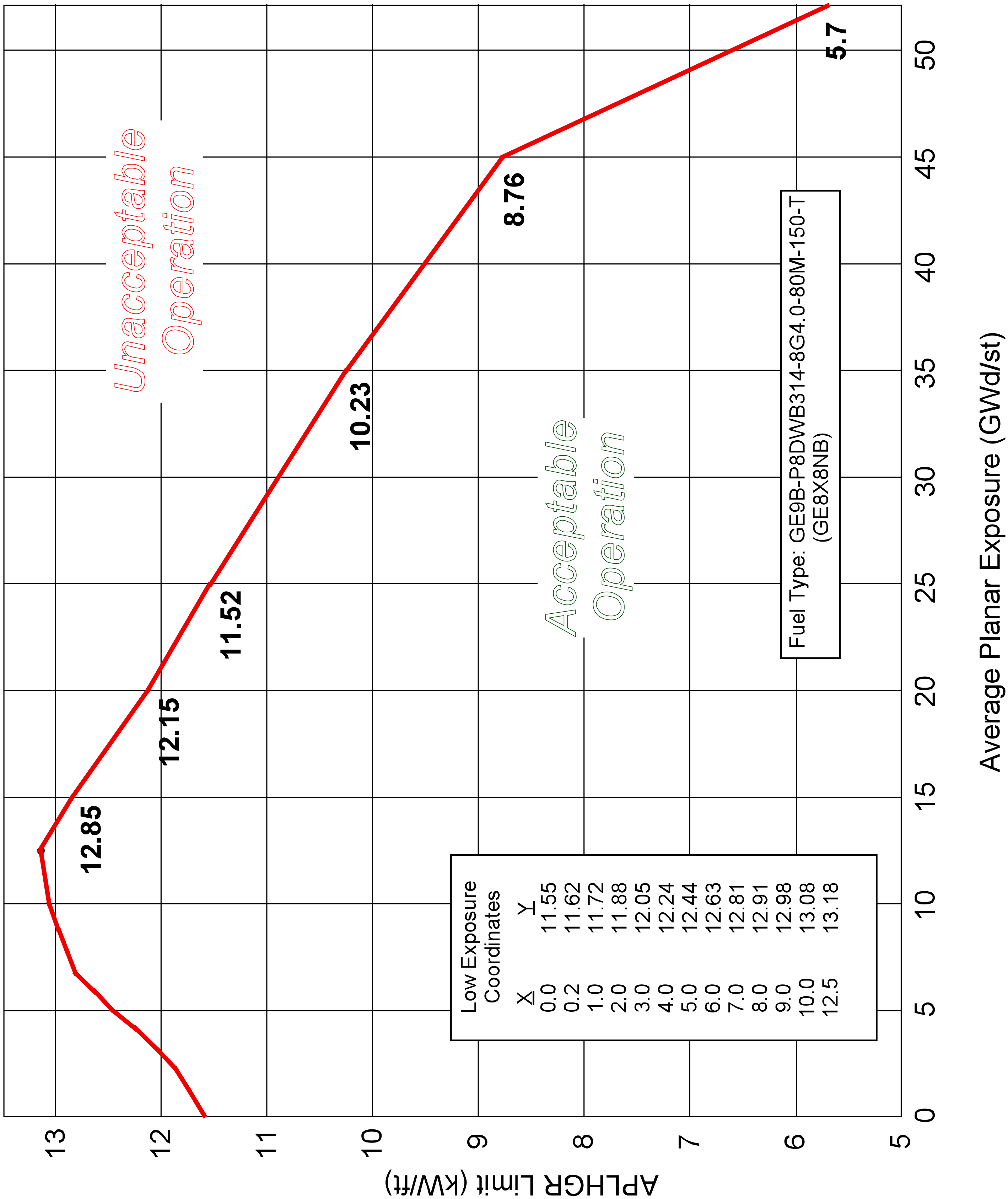

Figure 3.2-2 Average Planar Linear Heat Generation Rate Limit vs. Average Planar Exposure

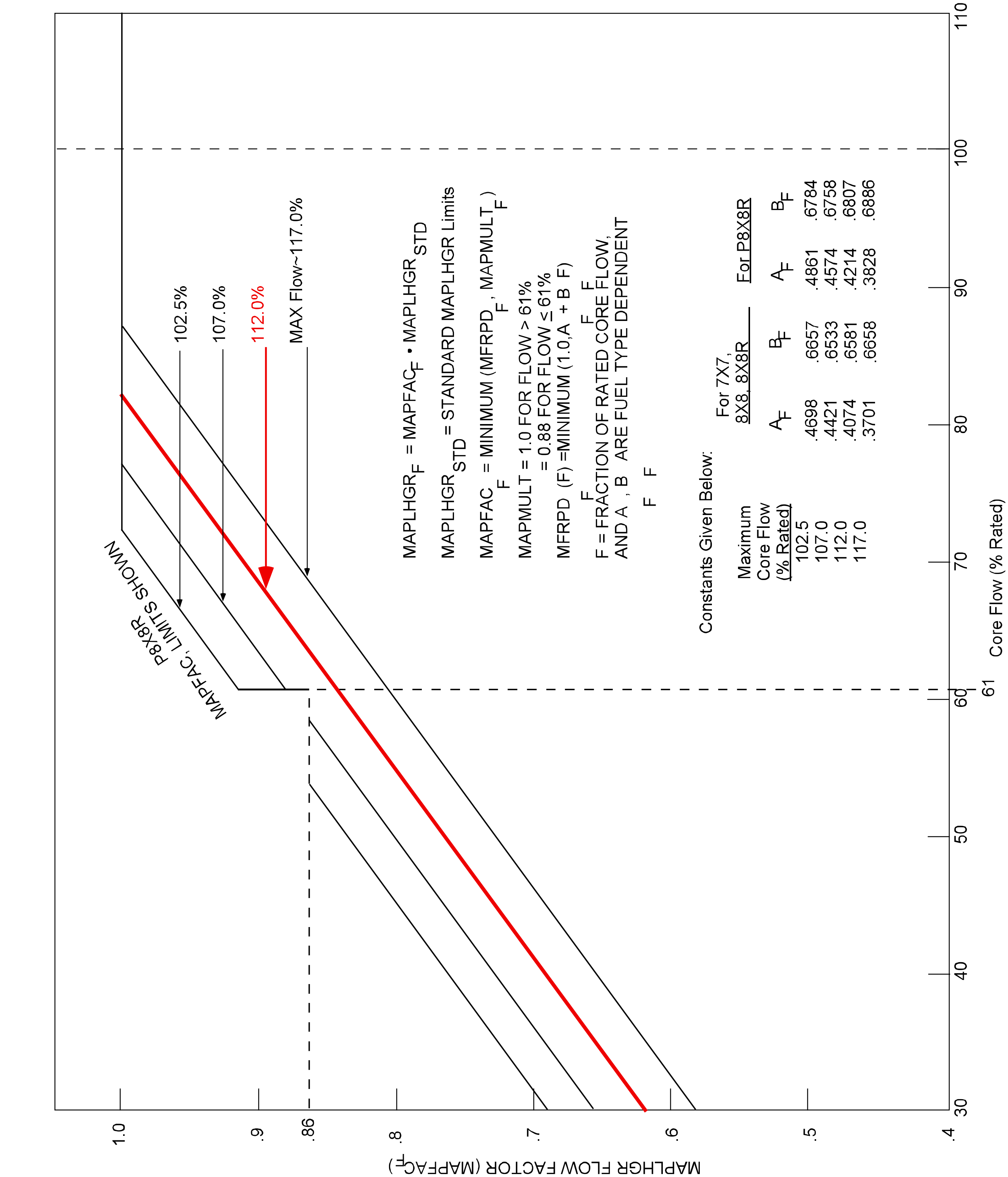

Figure 3.2-3 $MAPFAC_F$

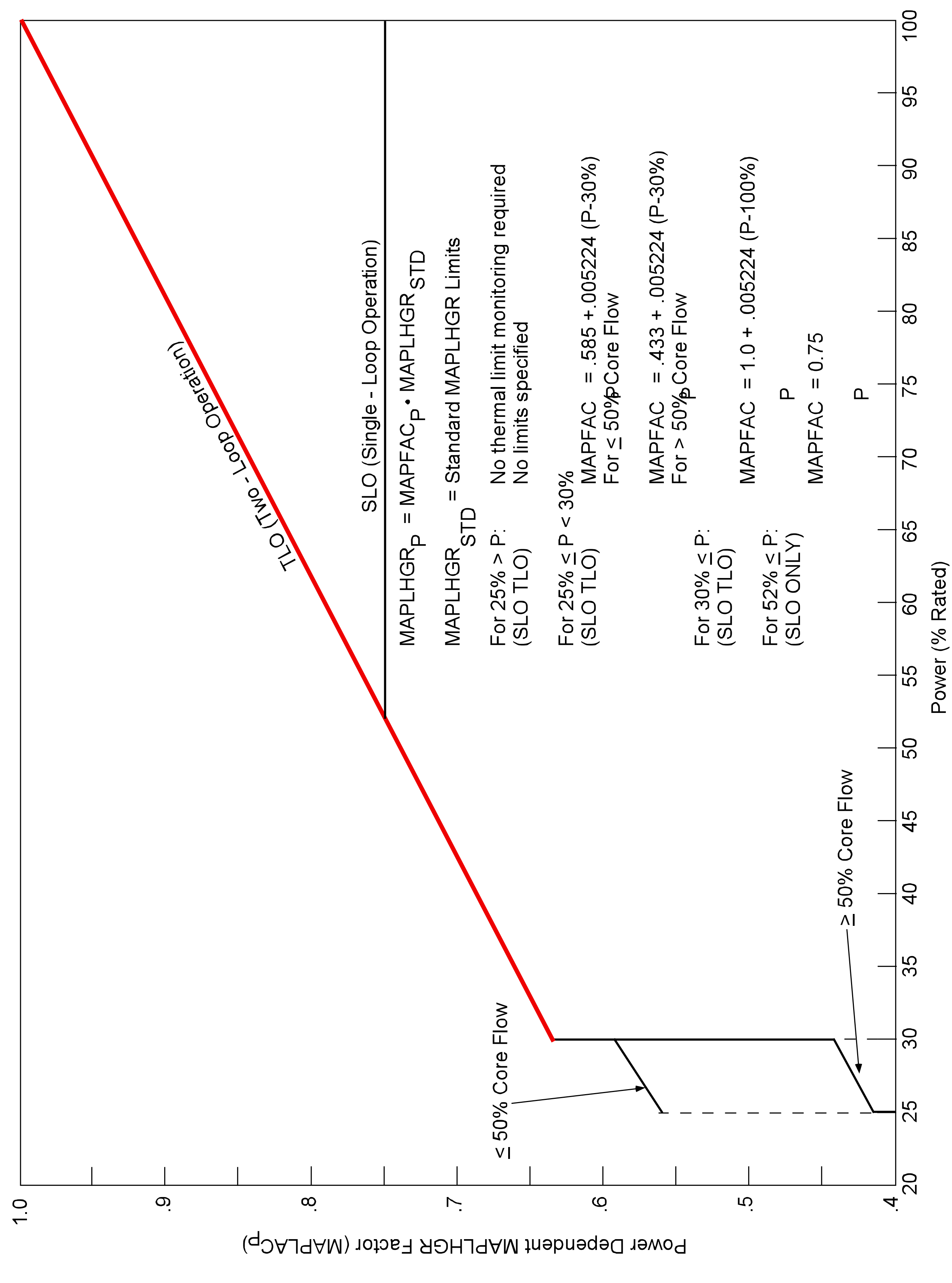

Figure 3.2-4 $MAPFAC_P$

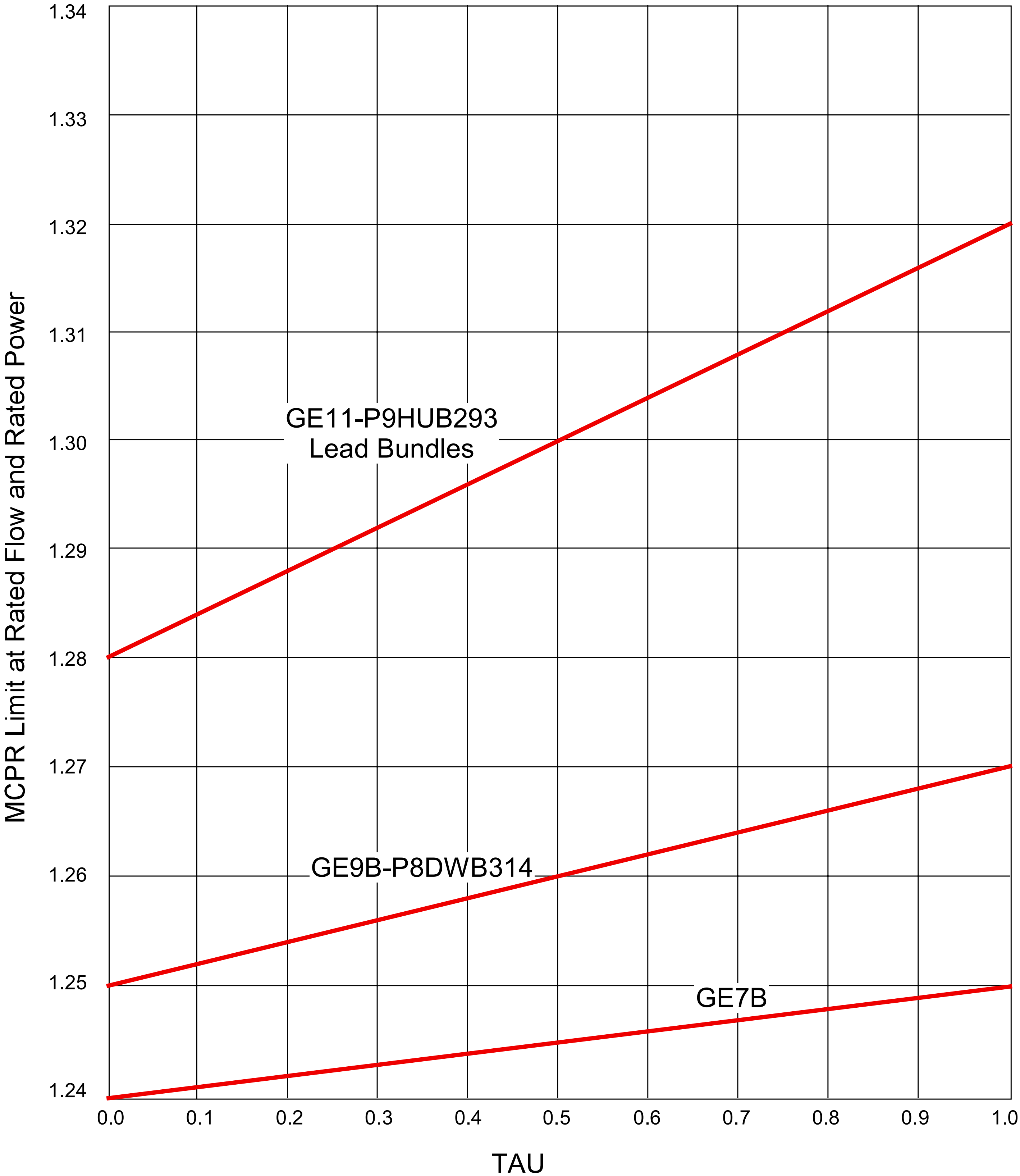

Figure 3.2-5 MCPR Limit as Function of Average Scram Time

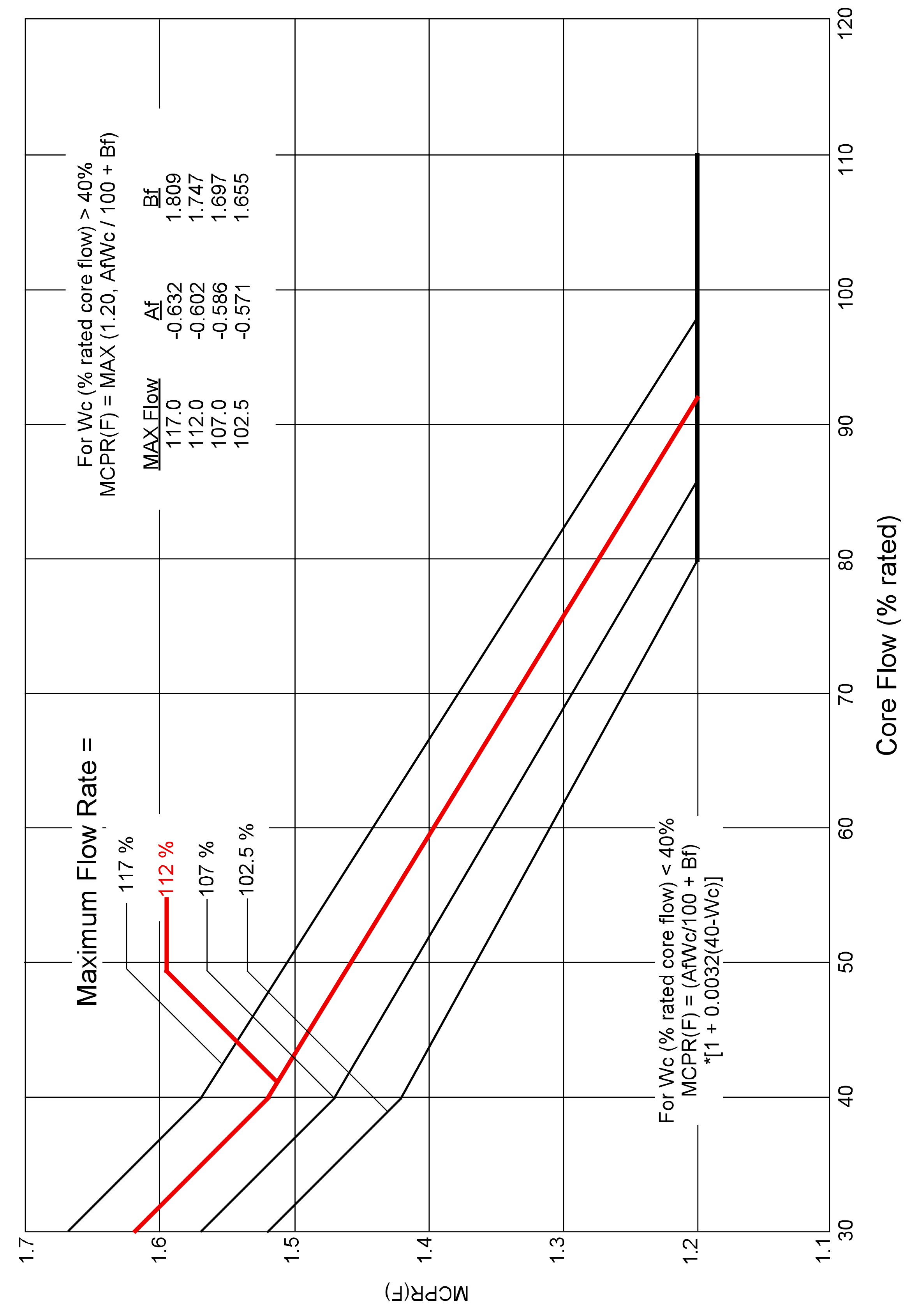

Figure 3.2-6 Flow - Dependent MCPR Limits, MCPR(F)

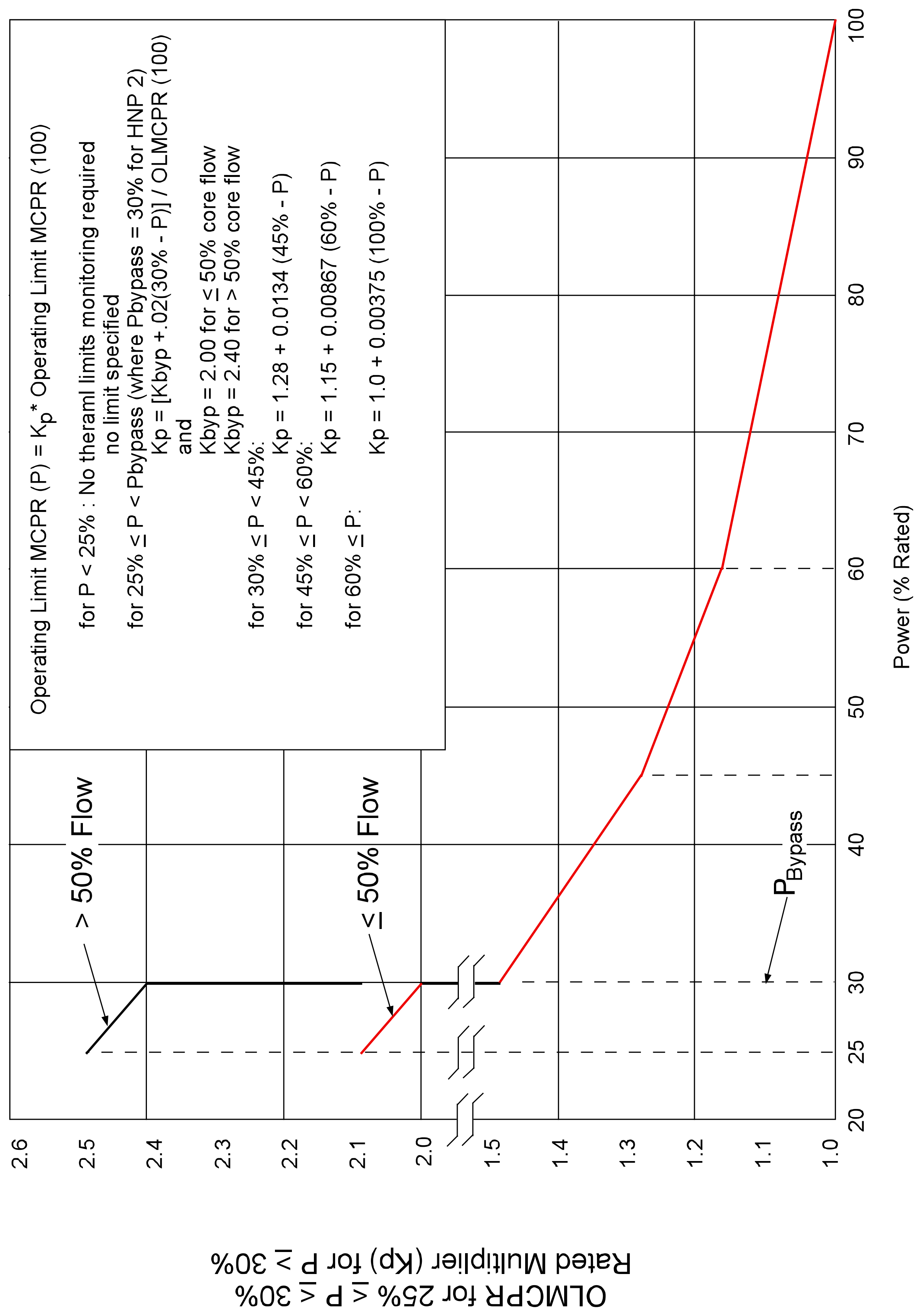

Figure 3.2-7 Power-Dependent MCPR Multiplier (Kp)

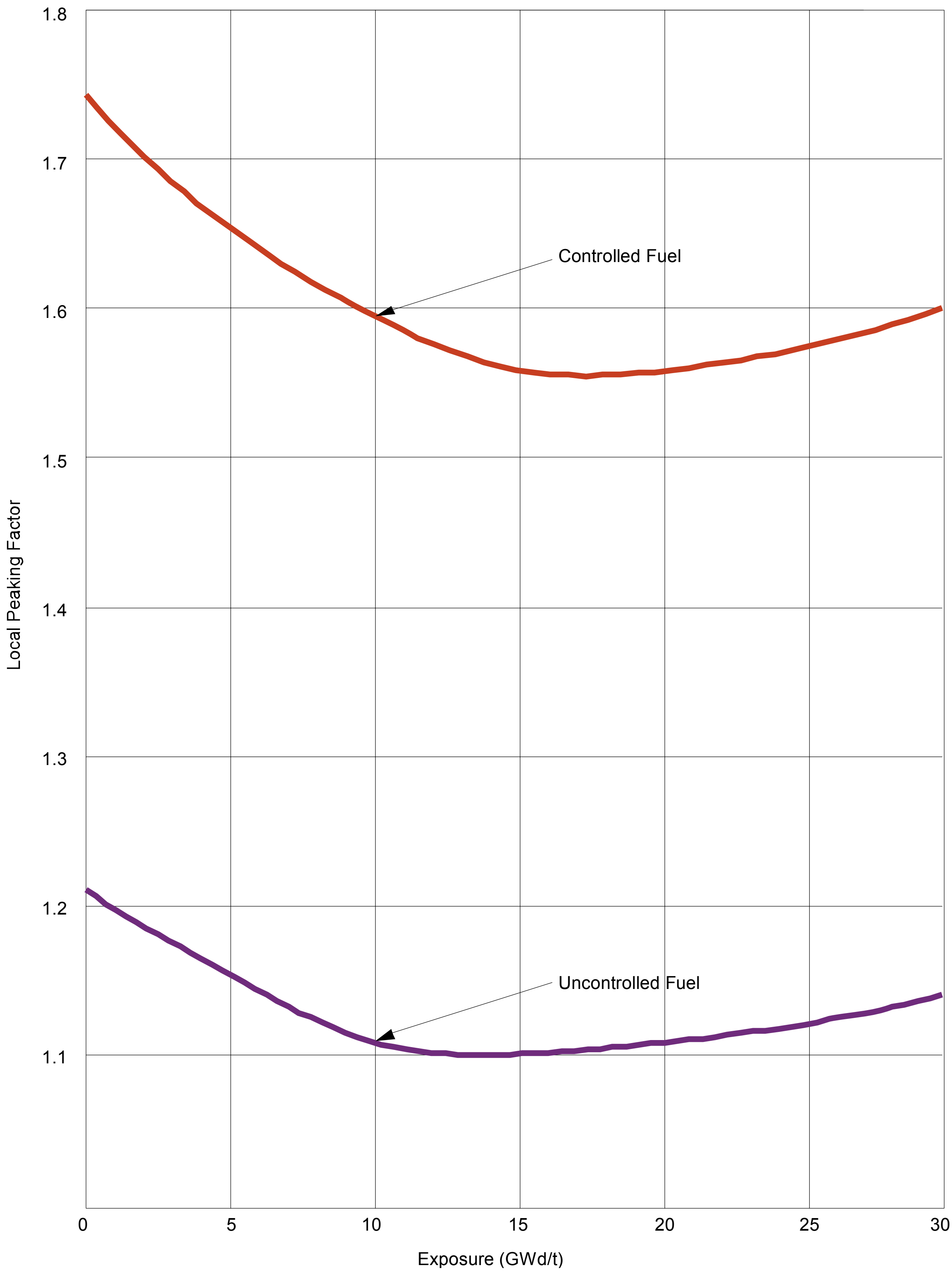

Figure 3.2-8 Typical Values for Local Peaking Factor

BWR Power Uprates☼

Plant	Total Uprate Power (~% OLTP)	MWth
Clinton	120	3473
Brunswick - 1, 2	120	2923
Vermont Yankee	120	1912
Duane Arnold	119.4	1912
Susquehanna - 1, 2	118.9	3952
Quad Cities -1, 2	117.8	2957
Dresden - 2, 3	117	2957
Hope Creek	116.4	3840
Hatch - 1, 2	114.5	2804
River Bend	106.7	3091
Limerick - 1, 2	106.6	3515
Peach Bottom – 2, 3	106.6	3514
LaSalle - 1, 2	106.6	3546
Monticello	106.3	1775
Browns Ferry -1, 2, 3	105	3458
Perry	105	3758
Columbia (WNP-2)	104.9	3486
Nine Mile Point - 2	104.3	3467
Fermi 2	104	3430
FitzPatrick	104	2536
Grand Gulf	101.7	3898
Cooper	101.6	2419

Pending Approval

Browns Ferry 1, 2, 3	119.3	3952
Monticello	119.2	2004
Nine Mile Point 2	119.3	3988
Grand Gulf	114.8	4408

☼Data is current as of 06/13/2011

Figure 3.2-9 BWR Power Uprates