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**Thermal-Hydraulic Bases for the
Safety Limits and Limiting Safety
System Settings for HFIR
Operation at 100 MW and
468 psig Primary Pressure,
Using Specially Selected
Fuel Elements**

R. B. Rothrock

MANAGED AND OPERATED BY
LOCKHEED MARTIN ENERGY RESEARCH CORPORATION
FOR THE UNITED STATES
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**THERMAL-HYDRAULIC BASES FOR THE SAFETY LIMITS AND
LIMITING SAFETY SYSTEM SETTINGS FOR HFIR OPERATION
AT 100 MW AND 468 PSIG PRIMARY PRESSURE, USING
SPECIALLY SELECTED FUEL ELEMENTS**

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CONTENTS

Abstract	1
I. Introduction	1
II. Thermal Criteria for Operation at 100 MW and 468 psig	3
III. Safety Limits and Limiting Safety System Settings	7
IV. Analysis Methods	9
V. Results and Conclusions	16
VI. References	20

TABLES

Table I: Experimental Basis for Modified Saha-Zuber Correlation	4
Table II: Safety Limit Cases	7
Table III: SSHTC "U-Factors" and Related Variables	11
Table IV: HFIR Low Primary Flow Data Since 1989	14
Table V: Minimum Values of $e_{n,min}$	18
Table VI: Calculated Thermal-Hydraulic Limiting Conditions by Track	19

FIGURES

Figure 1: FE Data from Reference 13	22
Figure 2: Flow Stability Results	23
Figure 3: Burnout Heat Flux vs. Channel Gap	24

ABSTRACT

This report summarizes thermal hydraulic analyses performed to support HFIR operation at 100 MW and 468 psig pressure using specially selected fuel elements. The analyses were performed with the HFIR steady state heat transfer code, originally developed during HFIR design. This report addresses the increased core heat removal capability which can be achieved in fuel elements having coolant channel thicknesses that exceed the minimum requirements of the HFIR fuel fabrication specifications. Specific requirements for the minimum value of effective uniform as-built coolant channel thickness are established for fuel elements to be used at 100 MW. The burnout correlation currently used in the steady-state heat transfer code was also compared with more recent experimental results for stability of high-velocity flow in narrow heated channels, and the burnout correlation was found to be conservative with respect to flow stability at typical HFIR hot channel exit conditions at full power.

I. INTRODUCTION

Purpose And Scope of This Report

This report presents the steady state thermal hydraulic analyses to support safety limits (SL) and limiting safety system settings (LSSS) for HFIR operation at 100 MW and 468 psig primary pressure, using fuel elements specially selected for adequate as-built coolant channel thickness. A selection procedure based on the coolant channel criteria presented here can therefore be used to identify those HFIR fuel elements from the current fresh fuel inventory which have the necessary power upgrade capability.

Background

The HFIR operated at its design power of 100 MW (at 650 psig initially and later at 750 psig pressure) from startup until 1986,^{1,2} when it was shut down due to pressure vessel embrittlement concerns. The reactor was restarted in 1989 with the primary operating pressure reduced to 468 psig, incorporating a program of periodic hydrostatic testing to ensure reactor vessel integrity.³ At that time the reactor operating power was also lowered to 85 MW, due to the reduced operating pressure. The steady state thermal analyses supporting the reduced operating power and pressure are documented in ref. 4, and are also reflected in the HFIR SAR⁵ and in the bases of the HFIR Technical Specifications.⁶ In order to enhance the research capabilities available to HFIR experimenters and increase the value of planned future improvements to the experimental facilities without compromising the reactor vessel life expectancy, a return to the original design power rating of 100 MW at the current operating pressure of 468 psig is under investigation.

Power Upgrade Plans

Improvements in HFIR fuel fabrication and inspection methods which have occurred since the 1989 restart have the potential of reducing the hot channel factors sufficiently to enable the reactor to return to 100 MW operation without an increase in primary system pressure (and its attendant reduction in pressure vessel life). While a new fuel specification and the associated thermal analyses to exploit these improvements are being prepared, it is desirable to evaluate the approximately 40 unirradiated fuel elements now in storage in Y-12 to identify those elements that

are acceptable for use at 100 MW by virtue of as-built core parameters that exceed the minimum specification requirements, which form the basis for the standard "worst-case" assumptions used in the baseline HFIR thermal analyses.^{2,4,5} Since all of the fresh fuel inventory will be consumed either at the current 85 MW power level or at 100 MW, timely identification of any elements capable of 100 MW operation would allow them to be saved until the technical bases for power upgrade are documented, reviewed, and approved, while consuming the remaining elements (at 85 MW) prior to the power increase.

As discussed later in detail, the approach chosen to demonstrate an enhanced power capability for selected elements is based on using the coolant channel thickness measurements made on each HFIR fuel element by the fuel supplier, to show that the coolant channels of selected elements are sufficiently wider than the minimum values assumed in the baseline analysis so that they can be operated safely at 100 MW and 468 psig. The fuel element coolant channel thickness was selected for this purpose because (1) it has a substantial effect on the heat removal capacity of the fuel elements, due to the increased hot streak flow allowed by wider channels; (2) the channel thickness is well characterized and documented in QA records for each channel in each element by the HFIR fuel channel measurement gage, hence the channel dimensional data for all HFIR elements can be conveniently reviewed in detail; and (3) the HFIR steady state heat removal code^{7,12} ("SSHTC"), to be described later, treats the effects of channel thickness explicitly and allows for direct input of the minimum as-built channel thicknesses of the inner and outer elements.

The remainder of this report presents (1) the thermal criteria to be met by the fuel elements; (2) the proposed SL's and LSSS's for 100 MW operation at 468 psig; (3) a summary of the analysis methods employed; and (4) results of the analyses for Mode 1 operation at full flow. An evaluation of the low-flow, low-power end of the Mode 1 operating band (specifically, the low-low flow scram SL and LSSS) will be published separately. As pressurization is not required for operation in Modes 2 or 3, the change of primary system pressure from 750 to 468 when pressurized has no impact on the Mode 2 and 3 analyses, and these remain valid as previously published.²

II. THERMAL CRITERIA FOR OPERATION AT 100 MW AND 468 PSIG

Thermal Criterion as Defined in the HFIR Authorization Basis

The fundamental requirement establishing SLs and LSSSs for the key process variables of inlet temperature, coolant pressure, and core power/flow ratio for steady state and quasi-steady state conditions is stated as follows in the HFIR SAR (ref. 5, Sect. 4.4.2.1, Safety Limits and Limiting Safety System Settings):

"With any given variable at its safety limit, all other variables at their LSSS, and all uncertainties in the technical knowledge of the process resolved unfavorably, no hot spot burnout can occur."

This statement is also found in refs. 2, 4 and 6. A related criterion for accident conditions⁶ is that no hot spot burnout may occur concurrent with a breach of containment. The analyses reported here address the steady state aspect only; accident transients will be evaluated and reported separately.

Historical Use of Incipient Boiling as a Thermal Criterion

While "hot spot burnout" is quoted as the basis for current safety limit analyses, the original HFIR design documentation shows that incipient boiling (IB) in the core was used as a thermal criterion on which to base maximum core power level in lieu of the "burnout" correlations available at that time, due to two concerns related to boiling effects in narrow channels:⁷

1. Flow stability in narrow channels with high bypass flow fraction, following the onset of nucleate boiling; and
2. Flow behavior within narrow channels following the onset of nucleate boiling.

In either case, it was felt by the HFIR designers that the experimental burnout data then available might not adequately reflect the consequences of diversion of flow out of a hot, narrow streak either into another (wider, cooler) region of the same channel, or into a (wider, cooler) parallel channel, at conditions beyond the onset of nucleate boiling in the narrow channel. This was of particular concern for the HFIR core due to the unusually narrow coolant channels and the additional channel distortions that could occur during operation due to deflections of the fuel plates. Because of these reservations, IB was adopted as a thermal limit for the original HFIR thermal hydraulic analyses and it was found that the goal power/flow ratio of 1.3 could be achieved, under the original core and system design conditions, using this criterion. Use of the IB criterion also made it possible to use simpler single-phase liquid models for heat transfer and fluid friction coefficients in performing the analysis, an assumption which is still present in the steady state thermal analysis code.^{7,12} Although the SLs are now based on the "burnout" criterion, the steady state thermal hydraulic analyses performed to support 85 MW operation following the 1989 restart⁴ retains IB as a basis for the trip points.

Treatment of Parallel and Narrow Channel Effects

The phenomenon of flow diversion from a heated, boiling channel into parallel nonboiling channel(s) [often termed flow excursion (FE)] has been recognized as an initiator of burnout in parallel-channel

situations, and correlations have been developed to represent this effect.^{8,9,10} Construction and operation of a thermal hydraulic test loop (THTL)¹⁵ at ORNL in support of the Advanced Neutron Source (ANS) Reactor design efforts has resulted in acquiring additional true FE data points. These data extend the FE experimental database into the high flow and narrow channel regime of the ANS design, which is also characteristic of HFIR. As a result of the ANS thermal hydraulics efforts, the "Modified Saha-Zuber" correlation was developed, which closely fits the experimental FE data evaluated in support of ANS design, including data from the ANS THTL. The Stanton Number version of this correlation, appropriate for HFIR conditions at full power/full flow, is as follows:¹³

$$St = \frac{q''}{G c_p \Delta T_{sub}} = 0.0065 (0.55 + 11.21/\Delta T_{sub})$$

where q'' , G , and c_p are the local heat flux, coolant mass flux and specific heat and St is the Stanton Number at onset of FE, defined on the basis of local subcooling, Δt_{sub} ($^{\circ}\text{C}$).

An overview of the evaluated FE database on which the correlation is based is provided in Table I.

Table I. Experimental basis for modified Saha-Zuber correlation¹³

Data source and velocity range	Nr. of data points	Experimental/predicted ratio*	
		Average	Std. dev.
THTL data	28	1.03	0.16
All data	633	1.02	0.30
V > 8 m/s	104	1.10	0.20
V < 8	529	1.00	0.31

*Here the experimental-to-predicted ratio is the ratio of Stanton Number calculated from experimental results to the Stanton Number calculated from the modified Saha-Zuber correlation as given above.

Since the SL methodology used for HFIR involves the direct combination of uncertainties, a lower bound tolerance limit for the modified Saha-Zuber correlation is appropriate for evaluation of the SSHTC calculated results. For this purpose, a limit was used such that 95% of the population would exceed the limit with 95% confidence (a "95/95" limit). Common statistical methods¹⁷ were used, in conjunction with the "all data" population with flow velocity > 8 m/s (104 data points), which is appropriate to HFIR conditions at full power.

To obtain the desired limit, the same dependence on subcooling was retained while the coefficient was reduced to achieve the desired coverage and confidence level. The resulting limit is:

$$(St)_{95/95} = 0.0047 (0.55 + 11.21/\Delta T_{sub})$$

This data population, along with the "95/95" lower bound, is plotted on Figure 1. The three data points which lie slightly below the lower bound are all at relatively low subcooling compared to HFIR hot channel conditions (40 $^{\circ}\text{C}$ or greater), where the data tend to exhibit more scatter.

To address the consequences of very narrow coolant channel gaps, FE experiments have been performed in the THTL using a rectangular test section with an 0.033-in. (0.84 mm) coolant gap to obtain experimental data in the range of worst-case HFIR coolant channel dimensions (extreme manufacturing tolerance and extreme operating deflection).²¹ The six data points from this experiment are shown on Figure 2, where they are all located above the "95/95" limit. The local flow velocities achieved in the tests were similar to calculated HFIR local hot channel velocities at full flow.

Since these test results showed no effects attributable to the narrow test section coolant gap,^{21,23} it was concluded that FE is not affected explicitly by gap thickness for dimensions of 0.033 in. or greater under these test conditions. Due to experimental limitations, the THTL FE data points have lower subcooling at the test section exit than is typical of HFIR hot channel conditions at high power. For this reason, these tests are regarded as a conservative check of the "narrow channel effect" in HFIR, since the lower subcooling in the THTL should exaggerate any effects of subcooled boiling on the channel pressure drop and flow stability.

The HFIR thermal hydraulic calculations on which the required channel dimensions for 100 MW were based were made with the HFIR SSHTC which treats burnout based on the "additive method" correlation developed by Gambill.¹¹ For the safety limit (SL) calculations, a design version of this relation is used in which parameters of the correlation are set so as to provide a conservative lower bound to experimental results. For comparison of the design burnout correlation results with the "95/95" lower bound modified Saha-Zuber FE correlation, the local Stanton numbers at the hot channel exit were obtained from local fluid conditions calculated by the SSHTC for each core location at which burnout was predicted. (These calculations are further described in Section V.) These results are also shown on Figure 2, where they can be seen to lie close to but below the "95/95" FE lower bound, and to have the same general trend with subcooling. For this reason it is concluded that thermal hydraulic evaluations using the HFIR SSHTC and based on the Gambill burnout correlation should also be conservative with respect to FE at flow and subcooling typical of HFIR hot channel conditions at full power, and that this analysis method may be used to evaluate situations with calculated local channel gaps as small as 0.033 in. at the channel exit.

Since experiments specific to HFIR hot channel conditions (flow velocity, pressure, subcooling) have not been run for gaps < 0.033 in., it is considered prudent to limit the use of this method to situations where the minimum calculated local channel thickness is 0.033 in. or greater at the core outlet, where the thermal limits occur. Smaller calculated local thicknesses at upstream points are acceptable provided IB does not occur at these nodes prior to burnout occurring at the outlet.

Summary of Thermal Hydraulic Criteria

For the reasons described above, the following criteria were employed in evaluating the safety limits and determining the required minimum coolant channel dimensions for operation at 100 MW and 468 psig with selected fuel elements:

1. "Hot spot burnout" may not occur at any point in the core. In principle, a "hot spot" consistent with FE criterion would be of sufficient size to cause the thermal-hydraulic behavior which results in flow instability. Pending further evaluation, potential hot spots in HFIR fuel will be conservatively assumed to include the combined local effects of small fuel defects (segregations and nonbonds) and fuel misalignments at the worst conditions that are permitted by the fuel specifications and the rejection thresholds of the inspection equipment.

Burnout is evaluated using the design version of the Gambill correlation,¹¹ along with local channel parameters as calculated by the SSHTC.¹²

2. Incipient boiling may not occur at any axial node above the outlet. This restriction is imposed to ensure that the hot channel conditions over its heated length can be adequately represented with the single phase liquid model used in the HFIR SSHTC. Since burnout occurs at the outlet of a channel with an assumed axial misalignment extending below the neighboring fueled regions, any small bubbles produced at this node after IB and prior to reaching burnout would be rapidly quenched in the subcooled bulk coolant stream at the unheated outlet region without significant impact on the hot channel flow.
3. The minimum calculated local coolant gap at any point that reaches IB should not be less than 0.033 in. This restriction is included, as discussed above, to ensure that the calculated worst-case core conditions remain within the range of available experimental FE data, and where the burnout correlation implemented in the SSHTC was shown to yield conservative results for FE.

III. SAFETY LIMITS AND LIMITING SAFETY SYSTEM SETTINGS

Limiting Safety System Settings (LSSS)

For convenience and to avoid further constraining primary system operation, the LSSSs for primary coolant temperature and pressure remain the same as they are for current 85 MW operation (i.e., 135°F and 343 psig). Based on protection system and instrument experience, a reduction in the power/flow LSSS from 1.30 to 1.28 should be possible without increasing the false scram frequency. The SL and LSSS for low-low flow protection will be evaluated and documented separately.

Safety Limits (SLs)

The LSSSs and SLs must be separated by a sufficient margin to accommodate instrument uncertainties.¹⁴ The actual margins used in these analyses are 3°F and 25 psi for the coolant temperature and pressure SL, and 0.06 for the power/flow SL. The margins for temperature and power/flow equal the recommended uncertainty allowances from ref. 16, while the pressure margin of 25 psi exceeds the recommended uncertainty of 20 psi. The corresponding SL and LSSS values then are:

Parameter	Coolant temperature (°F)	Coolant pressure (psig)	Power/ flow
SL	138	318	1.34
LSSS	135	343	1.28

Safety Limit Cases to be Evaluated

The criterion used to establish the SLs requires that with any one (of the three) primary variables at its SL and the other two at their LSSS, with "... all uncertainties . . . resolved unfavorably . . .," no hot spot burnout may occur. To allow for unfavorable resolution of the instrument uncertainties, they are added to or subtracted from the LSSSs as appropriate, to obtain the following set of three combinations of parameters for which the thermal criteria must be met:

Table II. Safety limit cases

Safety limit case	Values of parameters used		
	Flux/flow	Pressure* (psia)	Temperature (°F)
Pressure SL	1.34	325	138
Flux/flow SL	1.34	330	138
Temperature SL	1.34	330	138

*318 (323) psig at pressure instrument was converted to 325 (330) psia at the core inlet for use in the SSHTC, by adding 15 psi (conversion to psia) and subtracting 8 psi from the pressure drop at full flow through the inlet region above the fuel (ref. 5, Section 4.4.3.4).

Since the margin between the SLs and LSSSs for coolant temperature and flux/flow is equal to their (rounded off) instrument uncertainties, these parameters appear at the same value for each entry in the table. The margin between pressure SL and LSSS was retained at 25 psi, consistent with the spacing at 85 MW operation, while the pressure trip uncertainty is 20 psi, hence only the pressure varies among the three sets of calculations. For this reason, the first table entry (pressure safety limit) clearly entails the closest approach to thermal limits since it yields the smallest hot channel outlet subcooling among the three cases, which are otherwise identical. This set of system parameters (134 MW, 325 psia, and 138°F) was therefore used to determine the minimum as-built coolant channel dimensions which would satisfy all three of the SL and LSSS conditions above for operation at a nominal core power of 100 MW and full flow.

IV. ANALYSIS METHODS

HFIR Steady State Heat Transfer Code (SSHTC)

The HFIR SSHTC⁷ was developed in the 1960's as a means to determine the core heat removal capability within given thermal limits while accounting in detail for numerous hot channel effects related to fuel manufacturing tolerances, engineering uncertainties, and core operational behavior (e.g., oxide film growth and on-power fuel plate and channel distortions). It has been updated¹² to include modified correlations for heat transfer coefficient and critical heat flux, and was used as the principal tool for performing the two previous SL/LSSS evaluations.^{2,4} Because the SSHTC accepts as input the tolerances on as-built coolant channel dimensions and combines them to produce a worst-case on-power coolant channel profile, it is particularly suitable for this study in which the effects of as-built coolant channel dimensions on power capability are of principal interest.

The detailed treatment of hot channel (or hot "streak") flow as a function of as-built channel thickness warrants further description in view of its importance to the results presented later. The hot channel analysis model subdivides the channel into seven heated axial tracks (numbered 3 through 9) extending across the width of the channel, for each fuel element, with 26 heated axial nodes. These tracks and nodes are associated with nuclear power distribution maps with the same mesh structure found in ref. 18 for various times in an operating cycle. Additional unheated tracks and nodes represent the edge and end clad regions. It is assumed that at any radial location on a fuel plate a "hot streak" may occur, where the worst-case fuel distribution and as-built coolant channel thickness coexist for the full heated length, hence a hot streak calculation is done for each radial track. The specific characteristics assumed for the hot streak analysis are (1) there is no transverse mass, momentum, or energy mixing (i.e., the flow and coolant temperature calculations are independent of conditions in adjacent tracks); (2) the hot streak has the maximum heat flux input along its length permitted by the fuel homogeneity limits (currently a uniform 12% overload); and (3) it has the minimum allowable as-built channel thickness (termed $e_{n,min}$) over the entire core length, prior to superposition of calculated on-power channel distortions. Ordinarily, the value of $e_{n,min}$ is set to 0.040 in., which is the minimum local channel thickness allowed by the HFIR fuel fabrication specifications.¹⁹ However, for the analyses to be presented here, this input parameter was varied in order to determine the sensitivity of power margin to the channel thickness, and to establish the minimum as-built channel dimensions required on each track for operation at 100 MW.

Prior to calculating hot streak coolant flow and temperatures, the SSHTC calculates the maximum coolant channel distortions due to differences in static pressure between neighboring channels and due to differential thermal effects caused by nonuniform fuel loadings between adjacent plates and axially within individual plates. During HFIR development, various configurations of hot and cold plates separated by narrow and wide channels were evaluated to search for a worst case combination.⁷ The configuration used for the calculations to be reported here was used in the original analyses (where it was designated "Case 3") and was also used in the SL and LSSS analyses contained in the current authorization basis.⁵ In addition to the maximum channel closure due to differential expansion of the adjacent hot and cold plates, the model also assumes that the hot plate and adjacent cold plates have the maximum allowable axial fuel maldistribution between top and bottom halves, arranged such that each plate bows inward at the bottom of the narrow channel further reducing the channel thickness at the outlet. Channel distortions due to deflection of the adjacent plates are calculated for each axial node along the hot streak for use in determining the hot streak flow. The calculational model for fuel plate deflections resulting from differential thermal and pressure effects is based on out-of-pile experiments.²⁰

The hot streak flow is determined iteratively, using a channel thickness profile obtained by adding the calculated channel distortions at each axial node to the minimum as-built channel thickness, $e_{n,min}$. Starting with an estimated hot streak flow rate, the incremental pressure drop within each node is calculated using the specific channel gap computed for that node, and the increments are summed for the entire channel, adding entrance and exit losses based on a minimum local thickness of 0.040 in. at each end. The computed total hot streak pressure drop is compared with the core pressure drop specified as input, and the hot streak flow is iterated until the pressure drop is converged.

Using the converged hot streak flow and associated fluid and fuel plate surface temperatures computed along the hot streak, local channel thermal-hydraulic conditions are checked at each axial node against thermal limit criteria (either IB or burnout, as requested in the input data). For this comparison, the calculated local heat flux at each node is increased by a local peaking factor representing the effects of a fuel defect consisting of a lack of cladding-meat bond (nonbond) and a high density fuel particle ("segregation"), of the maximum size that would pass fuel plate inspection. An additional local peaking factor is included for the outlet node of each track, to account for the maximum fuel meat extension of a long fuel core (maximum length tolerance) beyond neighbor plates with short fuel cores (minimum length tolerance), an arrangement which would produce additional local peaking due to the thermal neutron flux peak in the axial reflectors. This procedure is repeated for hot streaks located on each of the heated tracks in the inner and outer elements, and the point of nearest approach to (or maximum exceedance of) the chosen thermal limit criterion is flagged for user information. If requested, the code will also perform time-dependent oxide film growth calculations and/or iterate on core total power until a specified thermal limit criterion is just reached at a single node.

Input Data Used in Analyses

The SSHTC requires as input a description of the thermal-hydraulic boundary conditions (power, temperature, pressure, core pressure drop), nuclear power distribution data, analytical mesh definition, fuel element configurations, various details of core and fuel plate tolerances, and a set of uncertainty factors ("U-factors"). These factors specify the uncertainty allowances to be used for the boundary conditions (e.g., coolant temperature), fuel fabrication variables (e.g., fuel homogeneity) and engineering data and correlations (uncertainties on nuclear power distribution, friction factor, etc.) which are used in the heat transfer analysis. The fuel element configuration (number and nominal dimensions of plates) and the core nuclear power distribution are established by the core design, and values used here are common to those of previous analyses.^{4,5} A common analytical mesh has also been used in all analyses, since it is linked to the nuclear power distribution data which remains unchanged. The operating parameters of core power, coolant inlet temperature and pressure, and core pressure drop are determined by the specific cases to be analyzed. The remaining input parameters, including the collection of 25 "U-factors," were reviewed to ensure that they were chosen appropriate to their use in the code and to the purposes of this study, and that they accurately reflect the current fuel fabrication specifications and HFIR operating experience, where applicable. As a result, some of the input values have been changed from those used in the previous analyses.^{4,5} A summary of all uncertainty factors and other key input values used in these analyses is provided in Table III, which also contains the values previously used for comparison. The basis for each change is described below.

Table III. SSHTC "U-factors" and related variables

Parameter	Value used	
	Original	Updated
U1 Global power level uncertainty	1.02	1.00
U2 Heat transfer surface uncertainty	1.045	1.00
U3 Uncertainty in power distribution	1.155	1.155
U4 "Hot plate" fuel distribution: • Upper half of plate • Lower half of plate	0.92 1.10	0.90 1.12
U5 "Cold plate" fuel distribution: • Upper half of plate • Lower half of plate	1.08 0.90	1.10 0.88
U6 Coolant inlet temperature uncertainty	1.015	1.00
U7 Friction factor uncertainty	1.05	1.15
U8 Local heat transfer correlation	0.90	0.90
U9 Oxide film growth correlation	1.25	1.25
U10 Deflection due to differential pressure	1.10	1.10
U11 Deflection due to temperature differential between hot plate and average plate	1.10	1.10
U12 Fuel plate thickness increase due to thermal expansion	2.00	2.00
U13 Fuel plate thickness increase due to radiation effects	1.00	1.00
U14 Longitudinal buckling of fuel plate due to temperature difference between fuel plate and sidewall	1.00	1.00
U15 Longitudinal buckling of fuel plate due to radiation damage	1.00	1.00
U16 Heat generation in side plates	1.00	1.00
U17 Heat generation in coolant	1.00	1.00
U18 Heat flux peaking on hot side of plate due to fuel segregation and nonbond	1.30	1.27
U19 Heat flux peaking on cold side of plate due to fuel segregation and nonbond	1.30	1.27
U20 U21 nonbond peaking factors	Calculated internally by track position.	
Burnout correlation treatment	"Design" burnout equation used.	
U23 Incipient boiling uncertainty	1.00	1.00

Table III. SSHTC "U-factors" and related variables

Parameter	Value used	
	Original	Updated
U24 Hot streak factor (maximum axially averaged fuel overload along hot streak)	1.10	1.12
U25 Local heat flux peaking factor for fuel core extending beyond nominal fuel boundary:		
• Inner track 3	1.00	1.17
• Inner track 4	1.25	1.25
• Inner track 5	1.41	1.41
• Inner track 6	1.44	1.44
• Inner track 7	1.43	1.43
• Inner track 8	1.30	1.30
• Inner track 9	1.20	1.20
• Outer track 3	1.23	1.23
• Outer track 4	1.23	1.23
• Outer track 5	1.26	1.26
• Outer track 6	1.35	1.35
• Outer track 7	1.31	1.31
• Outer track 8	1.23	1.23
• Outer track 9	1.00	1.28
Core pressure drop @ full flow	108	108 psi
e_A , average coolant channel thickness	0.049	0.050 in.
$e_{n,e}$, As-built channel thickness at narrow channel exit.	0.044	0.040 in.
$e_{n,min}$, Minimum (local) thickness of narrow coolant channel	0.040	Varied
$e_{w,min}$, Minimum (local) thickness of wide coolant channel	0.040	Varied with $e_{n,min}$

U1: Global Core Power Uncertainty

As the SL and LSSS calculations are done for a specific absolute power level specified as input, this U-factor was set to 1.00. The power measurement uncertainty is taken into account in establishing the margins between SL and LSSS, and between LSSS and actual trip instrument settings.

U2: Uncertainty in Fuel Element Heat Transfer Surface

U2 is included in the equations for calculating hot plate metal temperature, hot streak fluid temperature and hot spot local heat flux, which also contain U1, U3, and either U4, U24, or U18, as applicable, as multiplying factors on the nominal heat flux. The peak heat flux intended to be used in these calculations is proportional to the thermal neutron flux times the fissile fuel density, conservatively ignoring self-shielding effects of the higher local fuel density. The thermal neutron flux is related to the operating power level and core fissile loading, while the maximum fissile density in a "hot" fuel plate (local or averaged over a half-plate or track) is limited by specifications and

nondestructive inspection to values represented by U18, U4, and U24. Since neither the neutron flux nor the fissile density in a hypothetical hot plate is affected by the as-built total core heat transfer surface, the U2 factor is unnecessary and was set equal to 1.0.

U4/U5: Hot and Cold Plate Fuel Distribution Tolerances

U4 and U5 are specified as axially-dependent factors, selected to yield the maximum opposing thermal bowing of adjacent hot and cold plates. Their *average values over the plate* are derived from the maximum and minimum total fuel loading per plate (specified as $\pm 1.0\%$ and verified by weighing). The *maximum axial unbalance* is super-imposed on the $\pm 1\%$ total loading tolerance and is determined by the maximum and minimum averaged fuel densities accepted by the homogeneity scanner during fuel plate inspection. This value was established as $\pm 10\%$ of nominal when the original heat transfer analysis was prepared,⁷ leading to the values of (0.92, 1.10) with average 1.01 and max of 1.10 for the hot plate (U4), and (1.08, 0.90) with average 0.99 and min of 0.90 for the cold plate (U5). The homogeneity tolerance for averaged fuel density was changed (1966) to $\pm 12\%$ of nominal, and remains at that value in the present fuel specification.¹⁹ This tolerance, along with the $\pm 1\%$ limit on total fuel loading per plate, results in the updated values of (0.90, 1.12) with average of 1.01 and max of 1.12 for the hot plate (U4) and (1.10, 0.88) with average 0.99 and min 0.88 for the cold plate (U5).

U6: Coolant Inlet Temperature Uncertainty

Since specific inlet temperature values are defined for the SL and LSSS cases to be evaluated, this U-factor was set to 1.0 for convenience and the desired inlet temperature was specified explicitly as the input value. The temperature measurement uncertainty is included in the margin between the LSSS and SL.

U7: Friction Factor Uncertainty

The principle input factors controlling the calculated total core flow (friction factor, core pressure drop and average channel thickness) were reviewed to ensure that the 100 MW analyses would cover the entire range of core and hot channel flow in which Mode 1 operation at high power is desired. A review of historical primary flow and core pressure drop data shows that while most cycles exhibit relatively constant flow above the nominal full flow of 16,000 gpm with core pressure drops around 100 psi, there are occasional cycles with a decreasing flow and increasing pressure drop trend in which the flow drops below 16,000 gpm by the end of the cycle. This is attributed to increased core friction, although the mechanistic bases for the effect are not precisely known. Since the core thermal margin is least at 16,000 gpm flow and increases as the power is (automatically) reduced proportionately for flows below 16,000 gpm, the combination of 16,000 gpm primary flow and 100 MW operating power is an appropriate limit case for thermal analysis.

An examination of primary flow and core pressure drop records since the 1989 HFIR restart yielded the data shown in Table IV for times when the total primary flow rate was close to 16,000 gpm. Core flow, as inferred from pressure taps within the reactor vessel, is also shown. In order to establish an appropriate and conservative value for the friction factor uncertainty multiplier (U7) which is used in the SSHTC to compute both average channel (total core) flow and hot channel flow, the core flow and pressure drop data of Table IV were examined. These data show that a reasonable minimum core flow at 16,000 gpm primary flow would be about 12,500 gpm, and that this may be associated with a maximum core pressure drop of about 108 psi, which together determine the maximum

expected core friction factor. Using a pressure drop of 108 psi and average channel thickness of 0.050 in. (more representative of current as-built cores than the 0.049 in. previously used, and more conservative with respect to inferred friction factor), the value of U7 was adjusted until a computed core flow of 12,500 gpm was obtained at a value of U7 equal to 1.15. Because the U7 value of 1.15 in conjunction with a realistic value of average channel thickness (0.050 in.) yields a reasonable lower bound for computed core flow when compared with operating data, it is expected this combination of input parameters will also provide an appropriate minimum flow for the hot streak, where the same value of U7 is used. The resulting friction factor is somewhat conservative since it was derived using a fresh-core model, while reductions during operation typically occur later in a cycle when the coolant channels have narrowed due to oxide film growth.

Table IV. HFIR low primary flow data since 1989 restart

Cycle Nr.	Primary flow (gpm)	Core flow ¹ (gpm)	Core ΔP (psi)
302	16,000	12,800	106.5
309	16,000	12,800	108.1
310	16,000	12,780	108.1
320	16,131	12,700	104.8
328	16,038	12,869	107.2
329	15,506	12,318	109.7
341(a) ²	15,907	12,780	104
341(b) ³	15,991	12,801	104

¹As calculated by HFIR online hydraulic data system.

²Decreasing primary flow.

³Increasing primary flow.

U18/U19: Local Fuel Concentration ("Segregation") Factor

The fuel segregation factor represents the local heat flux peaking caused by a worst-case fuel defect that would be accepted by the fuel inspection equipment, and is numerically equal to the maximum relative local fuel overload allowed by the fuel homogeneity specifications (e.g., a factor of 1.30 is consistent with a maximum local overload of 30%). The value of 1.30 used previously was based on the original HFIR fuel homogeneity requirements, which were changed in 1966 to limit the local fuel overload to 27%, hence the U18/U19 value was updated to 1.27.

U24: Hot Streak Factor

U24 is used as a heat flux multiplier in obtaining the heat input to a "hot streak," which represents a narrow region of the hot channel in which the fuel plates on either side have the maximum fuel loading permitted by the homogeneity inspection equipment. This is determined by the "track averaged" fuel density limit, which since 1966 has been set at 1.12. The previous value of 1.10 was based on an earlier fuel specification.

U25: Flux Peaking for Fuel Extending Below Nominal Fuel Tip

Due to the thermal flux peaks in the upper and lower axial reflector regions, the nominal core nuclear power distribution has local power peaks at both the top and bottom of the fuel. These peaks can be further increased if, as is assumed in the SSHTC hot spot model, a plate with maximum length fuel core is located among several plates with minimum length cores so that the long core extends further up the thermal neutron flux gradient than normal. The allowance for this effect is based on flux gradient measurements reported in ref. 18, in conjunction with the HFIR fuel plate specifications relating to fuel core length and alignment, and varies with radial location (track) in the core due to the variation in axial flux gradient. The factors used in this analysis for inner element track 3 and outer track 9 were based on the thermal flux gradient data presented in ref. 18.

e_A : Average Channel Thickness

The average channel thickness directly affects the calculated total core flow, and was taken to be 0.050 in. based on manufacturing data which shows the majority of cores to be close to this nominal value. This is further discussed in conjunction with U7.

$e_{n,e}$: Narrow Channel Exit Thickness

The narrow channel exit thickness is used to calculate exit pressure loss, hence total flow, through the hot streak. The as-built channel thickness in the exit region is verified by the fuel manufacturer to be between the allowable local min and max values (0.040 and 0.060 in.) by manual pin gage, hence the minimum thickness for any track is taken as 0.040 in.

$e_{n,min}$ and $e_{w,min}$: Minimum Local Thickness of Narrow & Wide Coolant Channels

The minimum local thickness was varied in these analyses in order to determine sensitivity of thermal performance to minimum channel dimensions, and to select suitable minimum thicknesses to achieve the desired power capability. Since the selection of fuels meeting these criteria for 100 MW is made by screening all channels for the required equivalent minimum thickness, both "narrow" and "wide" channels, as used in the SSHTC, would have the same minimum thickness.

V. RESULTS AND CONCLUSIONS

Sensitivity of Core Power Capability to Minimum Coolant Channel Thickness

Since previous safety limit analyses^{2,4} had found the most limiting conditions to occur at beginning of cycle (BOC), survey calculations were made for this condition to establish the trend of burnout heat flux with hot streak thickness and to estimate the probable range of coolant channel thicknesses required to meet the thermal criteria of Part II at 100 MW. These cases were calculated using the input data shown in Table III, the "safety limit" coolant inlet temperature and pressure of 138°F and 325 psia, and various $e_{n,min}$ values between 0.040 and 0.046 in. in order to obtain the calculated "burnout" heat fluxes at the location of minimum thermal margin (the outlet nodes for each track). The design version of the Gambill additive burnout correlation¹¹ was used, which was shown in Section II to be a conservative indicator for FE at high power HFIR conditions. The results are plotted in Figure 3, which shows the computed heat flux to reach burnout as calculated from the local channel conditions at the exit of inner fuel tracks 5, 6, and 7 and outer fuel tracks 3 and 4. The peak local hot spot heat flux at the channel exit at 134 MW (in MBTU/hr/ft²) is also shown. It can be seen that for the tracks with minimum thermal margin, a minimum equivalent as-built channel thickness up to 0.045 or 0.046 in. will be required in order to provide sufficient increased heat removal capacity for 100 MW. Other tracks where there is some excess thermal margin at 85 MW or which may become limiting only at other times in a cycle when nuclear peaking factors are lower, will require a smaller increase in channel thickness, and some tracks have sufficient thermal margin at 85 MW with 0.040-in. channels that they can operate at 100 MW with no increase in the minimum as-built channel thickness.

Method of Calculating Minimum Equivalent As-Built Channel Thickness for 100 MW

Suitable values of $e_{n,min}$ for the most limiting tracks in the inner and outer fuel elements were established with the results of Figure 3 as an initial estimate and using the SSHTC in "search" mode to determine the maximum allowable power for specific input values of as-built minimum channel thickness. By varying the values of $e_{n,min}$ for inner and outer elements until a limiting power of ≥ 134 MW was calculated at BOC, minimum values of 0.0455 in. (limiting on inner track 6) and 0.046 in. (limiting at outer track 3) were determined to yield adequate heat removal capability.

Since only one value of $e_{n,min}$ can be input for each (inner or outer) element, the minimum thicknesses for the remaining 12 tracks which had greater margins were found by (1) suppressing the heat flux peak in the outlet nodes of tracks whose minimum thickness was already determined, so that they would not limit the calculated maximum power; and (2) reducing the value of $e_{n,min}$ in steps until the code determined a maximum power of 134 MW again for the next most limiting track. The outlet node power peaks were suppressed by reducing the value of U25 for the appropriate tracks sufficiently that they would not limit the core power, and this procedure was followed for all remaining tracks that required > 0.040 in. minimum as-built thickness at BOC. The minimum as-built channel thicknesses ($e_{n,min}$) determined for all tracks that were not adequately cooled with 0.040-in. thickness, were:

- Inner element: Track 5 0.0434 in.
 Track 6 0.0455
 Track 7 0.0432
- Outer element: Track 3 0.0460
 Track 4 0.0420

After the appropriate minimum channel thicknesses were determined for all heated tracks at BOC, subsequent steps in an operating cycle were analyzed using the time-dependent option of the SSHTC. This option steps through a sequence of times and nuclear power shapes from beginning through the end of a cycle, calculating fuel plate oxide film growth during each stage along with the associated changes in plate temperatures and thermal distortions of the coolant channels. At the final stage, a search is made for the limiting core power. The results of the time dependent calculations showed that the minimum track thicknesses established for BOC conditions were satisfactory for all later times in the cycle except for the end, at which track 6 of the outer element required an increase to 0.0403 in.

Subsequent calculations were made using the IB option to determine if any tracks reached incipient boiling at a node above the outlet, at power levels below the safety limit. This condition occurred on inner track 3 (BOC) and outer track 5 (EOC), and suitably increased track thicknesses were determined for these cases to ensure that subcooled boiling did not occur except at the outlet itself. In addition, the calculated minimum channel thickness at the outlet node was examined for each track, to ensure that all tracks remained at or above 0.033 in., for which THTL experimental data showed no explicit effect of test section coolant gap on the thermal hydraulic conditions causing flow instability. Results of these calculations are summarized below.

Results of Analyses with Varying Channel Thickness

The analysis procedure briefly described above with the input parameters from Table III was used to determine minimum values of $e_{n,min}$, the equivalent minimum as-built channel thickness, for which the following two thermal criteria are satisfied:

1. At the safety limit conditions (134 MW, 325 psia, and 138°F), hot spot burnout does not occur at any point in the core throughout a fuel cycle. In addition, the "burnout" criterion currently used in the steady state analysis¹¹ was compared with recent out-of-reactor experimental data on flow stability in narrow channels, and found to be a conservative lower bound for this phenomenon at typical HFIR full power/full flow conditions for channel thicknesses ≥ 0.033 in.
2. Incipient boiling (IB) does not occur at any point above the outlet of the channels, at any time in a fuel cycle, at power levels below the safety limit.

These requirements were discussed earlier, and ensure that normal heat transfer conditions would be maintained at all power levels up to the safety limit conditions without hot spot burnout or flow instability, and that the hot streak conditions are consistent with the single phase hydraulics model used in the SSHTC. The resulting minimum values of $e_{n,min}$ by track are shown in Table V.

Table V. Minimum values of " $e_{n,min}$ " by track

Track	Minimum value of " $e_{n,min}$ "		
	BOC	EOC	Overall (in.)
Inner: 3	0.0418	0.040	0.0418*
4	0.040	0.040	0.040
5	0.0434	≤ 0.042	0.0434
6	0.0455	≤ 0.042	0.0455
7	0.0432	≤ 0.042	0.0432
8	0.040	0.040	0.040
9	0.040	0.040	0.040
Outer: 3	0.0460	≤ 0.041	0.0460
4	0.0420	≤ 0.042	0.0420
5	0.040	0.0406	0.0406*
6	0.040	0.0403	0.0403
7	0.040	0.040	0.040
8	0.040	0.040	0.040
9	0.040	0.040	0.040

*To suppress IB at upstream nodes.

In addition to satisfying the minimum values of $e_{n,min}$ tabulated above, it is also desired to select fuel elements with sufficient channel thickness that the minimum calculated gap at the outlet is no smaller than the 0.033-in. test section used in developing flow stability experimental data for use in HFIR analysis. A review of the calculated channel thickness assuming worst-case differential pressure and temperature effects²² showed that two of the 14 heated tracks could have minimum on-power gaps < 0.033 in. at EOC when the as-built minimum local thickness is specified consistent with Table V. These tracks, and the minimum local as-built gap necessary to ensure an on-power gap ≥ 0.033 in. are:

- Outer track 5: 0.0414 in. at outlet
- Outer track 6: 0.0415 in. at outlet

It is not necessary to have a track thickness greater than or equal these values for their entire length, or averaged over their entire length, since values of $e_{n,min}$ of 0.0406 and 0.0403 in. provide enough hot streak flow to satisfy the basic thermal criteria at all points along the track. This requirement is included only to ensure that the burnout correlation used to verify safety limits is applied within the range of channel parameters for which it is supported by experimental data typical of HFIR hot channel conditions, and it applies only to the location where IB would first occur (i.e., the core outlet).

Summary of Hot Streak Conditions at Limiting Tracks

For the six tracks whose minimum equivalent as-built thickness $e_{n,min}$ is limited by "burnout" (inner tracks 5, 6, and 7 and outer tracks 3, 4, and 6), the calculated thermal hydraulic conditions at the channel outlet are presented in Table VI for information, along with the corresponding values of $e_{n,min}$ assumed and the time during a cycle when the track becomes limiting. The local Stanton Number and subcooling are also plotted on Figure 2 as the open data points. Details of the calculations can be found in ref. 22.

Table VI. Calculated thermal-hydraulic limiting conditions by track

Track	Inner 5	Inner 6	Inner 7	Outer 3	Outer 4	Outer 6
Limiting time in cycle	BOC	BOC	BOC	BOC	BOC	EOC
$E_{n,min}$ (in.)	0.0434	0.0455	0.0432	0.0460	0.0420	0.0403
Coolant temp (°F)	280.0	267.3	272.2	280.8	300.3	312.2
Pressure (psia)	215.0	214.8	215.5	215.2	215.2	210.8
Burnout heat flux ($\times 10^6$) [*]	3.20	3.42	3.35	3.18	2.83	2.86
Coolant velocity (ft/s)	48.0	50.1	49.8	49.1	47.4	51.4
Local coolant channel gap at outlet (in.)	0.0400	0.0430	0.0424	0.0451	0.0399	0.0318
Stanton Nr. ^{**}	0.0029	0.0026	0.0027	0.0028	0.0032	0.0035
Subcooling (°C) ^{**}	59.9	66.9	64.2	59.6	48.7	41.4

^{*}In BTU/hr/ft². In all cases, the calculated local hot spot heat flux at the track outlet is $\leq$ the stated "burnout heat flux."

^{**}Data for Stanton Nr. and subcooling (°C) are coordinates of the points shown as "Gambill Burnout Correlation" on Figure 2.

Conclusions

HFIR fuel elements with sufficient coolant channel thickness to meet the minimum values of Table V, with a minimum channel thickness of 0.0414 and 0.0415 in. on outer tracks 5 and 6 respectively *at the core outlet* and which otherwise meet the requirements of the current HFIR fuel specification¹⁹ can be safely used at a normal operating power of 100 MW and pressure of 468 psig. The SLs and LSSs assumed to apply for 100 MW operation at full flow are as summarized in Section III. Under these conditions, the core will have safety margins against burnout consistent with those documented in the current authorization basis for 85 MW operation.

Methods for evaluating the equivalent minimum channel thickness for as-built HFIR fuel elements against the minimum values for $e_{n,min}$ of Table V using the printed fuel coolant channel gage reports, and the results of this evaluation for specific fuel elements, will be documented separately.

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FE DATA FROM REFERENCE 13

Vel. > 8 m/s, $Pe > 70,000$

Figure 1. FE data from Reference 13.

Flow Stability Results

Comparison With "95/95" Lower Bound

Figure 2. Flow stability results.

Local Heat Flux Limit

At Beginning-Of-Cycle Conditions

Figure 3. Local heat flux limit.

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