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Statistical Fuel Assembly Hold Down Methodology

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ABSTRACT

Typical fuel assembly designs for PWR reactors contain a fuel assembly hold down spring system that provides sufficient net downward force to counteract the vertical hydraulic lift force created by the core flow rate so that the fuel assembly designs remain in a seated position during Condition I and II events for compliance to the design bases of the Standard Review Plan.

The net force on the fuel assembly consists of the downward force of the spring, the downward force of the weight of the fuel assembly, the upward buoyancy of the water, and the upward forces imposed on the fuel assembly by the coolant flow. This topical report describes the Statistical Fuel Assembly Hold Down (SHD) Methodology that utilizes probabilistic methods for some of the uncertainties of the analysis variables.

Included in the report are the general equations, description of the analysis process, and multiple examples for clarity of the applications. The purpose of the examples is to illustrate the dependence of the net downward force on the core configuration, operating condition, and time in life of the fuel and to highlight the process an analyst would use to arrive at the limiting case.

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1.0 Introduction

Typical fuel assembly designs for PWR reactors contain a fuel assembly spring holddown system that provides sufficient net downward force to counteract the vertical hydraulic lift force created by the core flow rate so that the fuel assembly designs remain in a seated position during normal operation and anticipated transients to satisfy the design bases criteria for Standard Review Plan Section 4.2. Fuel assemblies possess components, known as end fittings, tie plates, or nozzles, that engage with the lower and upper core plates to maintain the lateral positioning of the fuel assembly within the core volume during operation. The components typically contain a hold down spring system that provides an additional downward force to prevent the fuel assembly from lifting off the lower core support grid during normal operation and anticipated transients.

The net force on the fuel assembly consists of the downward force of the fuel assembly hold down spring, the downward force of the weight of the fuel assembly, the upward buoyancy force of the water, and the upward force imposed on the fuel assembly by the coolant flow. If the net downward force is negative the fuel assembly lifts vertically off the lower core support grid. This could cause potential damage to the fuel assembly from vibration or mechanical interaction with neighboring fuel assemblies. On the other hand, if the net downward force is too positive, or high, excessive fuel assembly compressive forces could occur within the fuel assembly and potentially result in greater fuel assembly distortion (bow and/or twist) with consequences as severe as restrictive downward control rod movement. Therefore, it is prudent from the design perspective to achieve the design bases criterion without including an overly conservative hold down force requirement.

Fuel assembly design analyses have typically focused on assuring the fuel assemblies remain seated and have been highly conservative by treating most uncertainties deterministically. As a result, the actual fuel assembly compressive forces during plant operation have been much greater than the calculated forces and, in some cases, may have contributed to observed fuel assembly distortion. Because of the potential damaging consequences of fuel assembly distortion, Framatome ANP has developed an analysis methodology that reduces this excess conservatism in the calculation of the required fuel assembly downward spring force. This methodology, known as Statistical Fuel Assembly Holddown Methodology, utilizes the application of probabilistic methods much like used in the statistical core design methodology (Reference 1).

This topical report describes the Statistical Fuel Assembly Hold Down (SHD) Methodology that utilizes probabilistic methods for some of the uncertainties of the analysis variables.

Included in the report are the general equations, description of the analysis process, and multiple examples for clarity of the applications. The purpose of the examples is to illustrate the dependence of the net downward force on the core configuration, operating condition, and time in life of the fuel and to highlight the process an analyst would use to arrive at the limiting case.

Framatome ANP has prepared this report in a format that describes a logical method for the calculation of net fuel assembly hold down. The method has been illustrated with specific examples. In applications to different cores some of the variables, their uncertainties and the methods of determining the values will change. During the course of applying this methodology variables and uncertainties may be added or deleted on a case by case basis. For each new or different application (indeed for any change in a core configuration that has been previously analyzed) each variable and uncertainty must be examined and qualified on a case by case basis. If a variable that has an uncertainty is not qualified or selected for probabilistic treatment, it must be compounded (held at its worst level within its uncertainty).

2.0 Methodology

The statistical design methodology being applied to fuel assembly hold down calculations was originally developed for Framatome ANP critical heat flux (CHF) applications in Reference 1. The methodology is composed of five basic steps.

- Identify the independent variables affecting the dependent variable (in this case, the net fuel assembly hold down force).
- Develop a model with which to calculate the dependent variable while varying each of the independent variables simultaneously.
- Quantify the uncertainties about each of the independent variables to be treated (variables not treated probabilistically must continue to be treated deterministically).
- Perform a probabilistic (Monte-Carlo) propagation of these uncertainties through the model to obtain an overall uncertainty on the dependent variable.
- Establish a tolerance limit on the value of the dependent variable that results in the required protection level and confidence.

The generalized statistical design method is illustrated in Figure 2-1.

3.0 Classes of Variables

There are two classes of variables used in calculating the net fuel assembly hold down force:

Mechanical – variables which affect the hold down spring force

Examples include: hold down spring constant, fuel assembly irradiation growth, fuel assembly thermal growth, hold down spring set after cool down, fuel assembly weight, fuel assembly length, and the distance between the core plate.

Hydraulic - variables which affect the upward hydraulic force on the fuel assembly

Examples include: core coolant temperature, core inlet maldistribution flow factor, component form loss coefficients, buoyancy, and reactor coolant system flow (which is in turn dependant on the reactor coolant pump head capacity curve and the system hydraulic resistance).

Each of these variables has uncertainties about their nominal values for a given core configuration, operating condition and time in life condition. Such a condition is referred to as a statepoint throughout this report. Previously, most uncertainties considered in the fuel assembly hold down analyses have been treated deterministically (the exception being that some of the mechanical uncertainties used in determining the spring compression may have been combined using a simple square root sum of the squares method). In the deterministic treatment of uncertainties (compounding of the uncertainties) each variable is assumed to be at its worst level within its uncertainty simultaneously. Therefore, the effect of the uncertainties is directly additive and results in excessive conservatism. A probabilistic combination of the uncertainties, on the other hand, provides a much more realistic prediction of the actual effect of these uncertainties and reduces some of the excessive conservatism.

4.0 Physical Model for Propagation

The Statistical Fuel Assembly Hold Down (SHD) model calculates an overall fuel assembly hold down force for a specific operating core statepoint. The net fuel assembly hold down force is equal to the force due to the hold down spring depression, increased by the fuel assembly dry weight, decreased by the fuel assembly buoyancy force and the hydraulic resistance of the fuel assembly.

Net Fuel Assembly Hold Down Force = (Spring Depression)(Spring Constant)
+ Dry Weight of the Fuel Assembly
- Fuel Assembly Bouyancy Force
- Hydraulic Resistance Force of the Fuel Assembly

or

$$NHD = (SD)(SC) + (DW) - (VOL)(DEN) - [\,LDP\,(BP^2)\,] \qquad [1]$$

where

NHD:	Net hold down force, lbf
SD:	Spring depression, in
SC:	Spring constant, lbf/in
DW:	Dry weight of the assembly, lbm
VOL:	Displacement volume of the assembly, ft^3
DEN:	Average density of the water, lbm/ft^3
LDP:	Hydraulic lift pressure drop, lbf/in^2
BP:	Fuel assembly bundle pitch, in

Several of the above terms are further described in more detail. The fuel assembly hold down spring depression, water density, and hydraulic lift pressure drop are functions of additional parameters.

$$SD = \text{Spring Depression} = FAH + TG + IG + FSH - CPD - SS - IR \qquad [2]$$

$$DEN = \text{Average density of the water} = f(P,T) \qquad [3]$$

LDP = Hydraulic lift pressure drop

$$= f\,(P, T, Q, FF, BPF, SR, K) \quad [4]$$

where

CPD:	Distance between the upper and lower core plate, in
FAH:	Fuel assembly height, in
TG:	Fuel assembly thermal growth, in
IG:	Fuel assembly irradiation growth, in
FSH:	Free spring height, in
SS:	Spring set, in
IR:	Spring relaxation, in
P:	Reactor coolant system pressure, psia
T:	Inlet temperature, F
Q:	Reactor coolant system volumetric flow rate, gpm
FF:	Core Inlet flow fraction
BPF:	Core bypass flow fraction
SR:	Fuel rod surface roughness, in
K:	Fuel assembly shock and frictional hydraulic resistances

The core volumetric flow rate Q_c, contributing to the fuel assembly hydraulic lift pressure drop, is a function of the reactor coolant system volumetric flow rate and the core bypass fraction.

$$Q_c = Q\,(1 - BPF)$$

The fuel assembly height, FAH, for this calculation is the distance from the lower core plate engagement surface on the fuel assembly to the upper plate engagement surface, typically the top of the hold down spring system.

The sub-functions are SD (spring depression), DEN (density) and LDP (hydraulic lift pressure drop). The spring depression sub-function can be broken into separate means and variances on FAH, CPD, TG, IG, SS and FSH as described in section 7.0. The coolant density sub-function DEN is a deterministic function of P and T and is described in section 8.0. The hydraulic lift pressure drop sub-function will vary depending on the core operating statepoint as described in section 6.0 and the propagated hydraulic uncertainties (see section 7.0).

The hydraulic lift pressure drop, LDP, is further developed with a functional relationship for later propagation.

Hydraulic Lift Pressure Drop, $LDP = K\,(\rho)\,(V^2 / 2g_c)$

where

V : Fuel assembly coolant velocity, ft/sec
ρ : Coolant density, lbm/ft^3
g_c : Gravitational constant, 32.174 $ft\text{-}lbm/lbf\text{-}sec^2$

The fuel assembly coolant velocity, V, is equal to the core volumetric flow rate divided by the fuel assembly flow area.

$$V = Q_c / A$$

where

Q_c: Core Volumetric flow rate, gpm
A : Fuel assembly flow area, in^2

Substitution yields the hydraulic lift pressure drop as

$$\begin{aligned} LDP &= K\,(\rho)\,[\,Q_c^2 / (2g_c\,A^2)\,] \\ &= [\,K\,(\rho) / (2g_c\,A^2)\,]\,(Q_c^2) \\ &= (LR)(Q_c^2) \end{aligned} \qquad [5]$$

where

LR: Hydraulic lift resistance, psi/gpm^2

Here K represents the shock and frictional losses, ρ is the effective core density and A the fuel assembly flow area. Note that ρ is not necessarily the same as DEN in the buoyancy term. The hydraulic lift resistance, LR, is determined from the base design case knowing the core volumetric flow, Q_c. Using Equations 1, 2 and 5 the final propagation equation becomes

$$NHD = (SD)(SC) + (DW) - (VOL)(DEN) - LR(Q_c^2)(BP^2) \quad [6]$$

Summarizing, when using Equation 6 with Equation 2, there are 14 primitive variables that determine the net hold down force (NHD). They are: SC, CPD, FAH, TG, IG, FSH, SS, IR, VOL, DEN, DW, LR, Q_c and BP.

The determination of net hold down is then accomplished with Monte Carlo propagation of the probability distributions of these variables about their means for various statepoints (P, T, time in life, power or adiabatic, etc.) through the main NHD model (Equation 6). Note that these statepoints must represent the limiting operating conditions (for lift) throughout life. The limiting statepoint is not known a priori and thus several must be examined (see Section 6.0).

Note that some of these 14 primitives may not have probabilistic distributions, may already be treated as nominal or may be required to be compounded. In those instances, these variables will exhibit a constant contribution to the governing equation (NHD) and will not contribute to the overall NHD variance.

Once the overall NHD variance is established, a 95/95 statistical tolerance limit is established (Reference 3, normality assumed) by adjustment of the nominal statepoint NHD calculations (see Section 9.0).

5.0 Mathematical Models for Propagation

Monte Carlo propagation of random normal and/or uniform distributions requires a compact mathematical model. The random normal distribution with a mean of zero and a variance of one is designated as N[0,1]. The uniform distribution with a mean of zero and half range of one is designated as U[-1,1]

Microsoft Basic incorporates the RND function which generates random numbers between positive and negative unity as well as a RANDOMIZE function. The RANDOMIZE function provides an arbitrary (user set) seed number so that the same series of numbers from the RND function will not repeat (unless the seed number is the same as the previous case).

The random normal distribution is generated as

$$N[0,1] = \sum_{i=1}^{12} [RND_i] - 6. \qquad [7]$$

Figure 5-1 shows the results of a random normal simulation of 10,000 trials with this model. Table 5-1 shows the detailed statistics for this simulation. Table 5-2 shows the statistical results of four such simulations. All simulations pass the D prime test for normality (Reference 2).

The uniform distribution, if needed, is generated as

$$U[-1,1] = 2(RND) - 1 \qquad [8]$$

simply to zero the mean. Note that if the normal distribution cannot be verified for a given uncertainty, the uniform distribution can be conservatively substituted for propagation.

Both of these models have been incorporated into the coding shown in Appendix A.

6.0 Statepoints for Evaluation

In order to assure an analysis considers the limiting condition for the fuel assembly hold down system, a series of statepoints are examined that cover various plant operating conditions. Generally, the more limiting condition for the fuel assembly hold down system is during isothermal operation at low coolant temperatures where the coolant density and reactor coolant system flow rate are high. This condition generally occurs during plant startup when the reactor coolant pumps are activated and during plant shutdown when the pumps are deactivated. The more limiting condition when the reactor is at power is during a steady-state overpower condition.

The statepoint condition is defined by the

- reactor coolant system volumetric flow rate (Q),
- core bypass flow fraction (BPF),
- core coolant temperature (T),
- core pressure (P),
- core power level,
- core configuration (fuel design distribution within the core), and
- fuel burnup

For any analysis determining the adequacy of the hold down spring system, it is necessary to examine the more limiting statepoints for the plant and to identify which statepoint is the most limiting statepoint. The results of the most limiting statepoint define the minimum net hold down margin for the core. A typical series of statepoints that would be initially examined include:

- isothermal reactor coolant pump startup statepoint
- steady-state design overpower condition statepoint

When the core is composed of one fuel design, the distinguishing differences between the various fuel assemblies would be their respective pressure drops and burnup. The fuel assembly burnup influences the hold down spring force (the product of the hold down spring constant SC and the spring depression SD) discussed in Section 7.0. When the core is composed of different fuel designs, the limiting fuel assembly for each fuel design is determined for each of the statepoints.

7.0 Uncertainties for Propagation

The uncertainties that are propagated would generally include:

- Core Volumetric Flow Rate (Q_c)
- Hold Down Spring Constant (SC)
- Hydraulic Lift Resistance (LR)
- Fuel Assembly Wet Weight (DW, VOL, DEN)
- Bundle Pitch (BP)
- Mechanical Analysis (Spring Depression, SD)

Again, if the uncertainties associated with these terms are not probabilistically propagated, then the uncertainties would be addressed deterministically.

7.1 Core Volumetric Flow Rate (Q_c)

The nominal core volumetric flow rate for the analysis would be equal to or greater than the measured flow rate for a plant decreased by the core bypass flow fraction. The core volumetric flow rate uncertainty would be equal to or greater than the RCS flow rate measurement uncertainty.

7.2 Hold Down Spring Constant (SC)

The hold down spring constant is dependent on the spring system design for the respective fuel design. Although most fuel designs contain a hold down spring system, it is possible that the hydraulic environment for some fuel designs may not require the additional hold down force associated with a spring system in order to satisfy the design bases of the Standard Review Plan Section 4.2. In such cases, the analysis does not include a hold down spring constant.

The nominal hold down spring force (SF) and uncertainty (SFU) can be obtained from hardware tests that quantify the spring forces versus deflection characteristics. The spring force uncertainty is based on the variability of the spring force during the measurements.

7.3 Hydraulic Lift Resistance (LR)

The lift resistance (LR) variable, developed in Section 5.0, is a composite variable. It will vary from statepoint to statepoint and be dependent on the core operating power level, the core flow rate, and core inlet conditions for any given core. The lift resistance variable contains the unit-less resistance term, K, that represents the shock losses and frictional losses attributed to the fuel assembly hardware. The uncertainty of the lift resistance variable is dependent on the uncertainty attributed to the shock losses. The uncertainty can be calculated on a measured to predicted basis and corrected for the number of degrees of freedom.

7.4 Fuel Assembly Wet Weight (DW, VOL, DEN)

The wet weight of the fuel assembly is dependent on the fuel assembly dry weight and displaced volume as well as the density of the displaced coolant. The dry weight of the fuel assembly can be based on measurements or calculated using individual component dimensions and densities. The density of the displaced coolant can be determined based on the operating condition. The variability of the wet weight is extremely small, therefore, the fuel assembly wet weight value is a nominal value with no uncertainty.

7.5 Bundle Pitch (BP)

The bundle pitch for the fuel assembly is a dimension that is used in the formulation of the shock losses for hardware components based on pressure drop tests. Therefore, it is important for the value to be used in the determination of the net hold down force to be the same as the value used in derivation of the shock losses. Consequently, the nominal dimension of the bundle pitch is used with no uncertainty.

7.6 Spring Depression (SD)

In equation 2, the spring depression is found to be dependent on six basic dimensions.

- Distance between the upper and lower core plate (CPD), in
- Fuel assembly height (FAH), in
- Thermal growth (TG), in
- Irradiation growth (IG), in
- Free spring height (FSH), in
- Spring set (SS), in

As noted in Section 4.0 the fuel assembly height, FAH, for this calculation is the distance from the lower core plate engagement surface on the fuel assembly to the upper plate engagement surface, typically the top of the hold down spring. The nominal and uncertainty values for each of the above six terms are either derived from calculations or based on measurements.

8.0 Net Hold Down Force Determination

Once the statepoints are defined and the variables and uncertainties are identified and quantified, a base design case is examined for a plant. The base case represents the hydraulic evaluation of the core using a NRC-approved code, such as LYNXT (Reference 5) or XCOBRA-IIIC (Reference 6), to obtain a fuel assembly pressure drop for each assembly in the core. The plant operating conditions of the statepoint typically define the base design case. The exception is when the base design case evaluation of the statepoint using a volumetric flow rate falls within ~10% of the statepoint nominal flow rate. This flexibility is deemed acceptable because the pressure drop prediction (based on the base design case conditions) can confidently be adjusted for different flow rates by the square of the flow rate ratio within the propagation model.

Although each individual fuel assembly within the core could be evaluated with its respective pressure drop and burnup condition using the SHD methodology, the minimum fuel assembly hold down requirement must be met by the limiting fuel assembly in the core. The limiting fuel assembly for a specific fuel design type will have the highest pressure drop for a given burnup condition (e.g., beginning-of-life, end-of-life). In most situations, the fuel design and spring system will have a hold down capability that will be known as a function of burnup. The analyst may elect to conservatively analyze all the fuel in the core assuming the burnup associated with the lowest hold down capability for the fuel. This action can reduce the amount of analysis and still assure the limiting fuel assembly condition is adequately protected.

Upon the completion of the hydraulic evaluation at the statepoint conditions, the thermal-hydraulic code predicted pressure drop is known for the base design case:

$$\text{Code Predicted } \Delta P_{\text{Base Design Case}}$$

based on a RCS Volumetric Flow Rate (Q), Core Bypass Fraction (BPF), core configuration, core power level, system pressure (P), and inlet coolant temperature (T). The coolant density sub-function DEN can be defined by the density of the average core coolant temperature extracted from the thermal-hydraulic code predictions.

The code predicted pressure drop for the base design case as well as the variables and their respective uncertainties are used as input to the propagation model (Appendix A). The propagation model is currently coded using Microsoft Compiled Basic (Reference 4). An example of the input file for the propagation model is available at the end of Appendix B for the calculational example.

The propagation model determines the dependent variable (net hold down force) the required number of times (10,000 for the calculational examples shown in Appendix B). The mean net hold down (NHD) and its variance are then calculated. The net hold down for the statepoint with the statistical protection at the 95 percent level with 95 percent protection is calculated as

$$NHD_{95/95} = NHD_{mean} - k_{95/95/n}\,(\sigma_{NHD})$$

For n = 10,000

$$NHD_{95/95} = NHD_{mean} - k_{95/95/10,000}\,(\sigma_{NHD})$$

where $k_{95/95/10,000}$ = 1.670 (Reference 3, page 51)

After computing the $NHD_{95/95}$ *for each statepoint, the minimum* $NHD_{95/95}$ value of the statepoints defines the limiting condition. The fuel assembly has adequate hold down when the limiting condition net hold down is positive.

When examining a mixed core, or transition core, when multiple fuel designs reside in the core, the net hold down force determination is performed for each specific fuel design. Since the hydraulic behavior and hold down capability of different fuel designs will likely be different, it is necessary to examine each specific fuel design individually to assure each fuel design experiences adequate fuel assembly hold down.

9.0 Analysis Process

In determining the net fuel assembly hold down force (NHD) using the probabilistic methods, the following process is followed.

- Define the statepoints for analysis (Section 6.0)

- Determine the nominal values and uncertainties for the primitive variables (Section 7.0)

- Determine the design base case by calculating the pressure drop for all the fuel assemblies in the core for a flow rate condition equal to or similar to the statepoint using a NRC-approved computer code.

- Using the propagation model, determine the net hold down force for each fuel assembly. If the net hold down force for each fuel assembly is demonstrated to be positive, adequate hold down force has been demonstrated. The minimum hold down margin for the core would be the minimum net hold down force determined for any fuel assembly.

The process can be further simplified by introducing conservative actions such as:

- by using the highest pressure drop of a group of fuel assemblies (same fuel design) as being representative of the entire group,

- by using the lowest hold down force of a group of fuel assemblies (same fuel design) as being representative of the entire group, and/or

- by using conservatisms in defining other nominal values and uncertainties.

10.0 Summary

The Statistical Fuel Assembly Hold Down (SHD) Methodology provides the means to account for the probabilistic occurrence of uncertainties of parameters that contribute to the determination of the hold down force. The methodology provides 95 percent protection at the 95 percent level that each fuel assembly has adequate fuel assembly hold down protection when the net hold down force is predicted to be zero. This analysis technique is applicable to full cores (containing the same fuel design) as well as for transition cores (where multiple fuel designs co-reside).

Framatome ANP has prepared this report in a format that describes a logical method for the calculation of net fuel assembly hold down. The method is illustrated with specific examples in Appendix B. In applications to different cores, some of the variables, their uncertainties and the methods of determining the values will change. Variables and uncertainties may be added or deleted on a case by case basis. For each new or different application (indeed for any change in a core configuration that has been previously analyzed) each variable and uncertainty must be examined and qualified on a case by case basis. If a variable that has an uncertainty is not qualified or selected for probabilistic treatment, it must be compounded (held at its worst level within its uncertainty).

11.0 References

1) BAW-10170P-A, "Statistical Core Design for Mixing Vane Cores," D. A. Farnsworth and G. A. Meyer, Babcock & Wilcox, December 1988.

2) "American National Standard Assessment of the Assumption of Normality," ANSI N15.15, American National Standards Institute, 1974.

3) D. B. Owen, "Factors for One-Sided Tolerance Limits and for Variables Sampling Plans," Sandia Corporation Monograph, March 1963.

4) "Microsoft BASIC(PDS), BASIC Language Reference," Version 7.0, Microsoft Corporation, 1989.

5) BAW-10156-A, Rev.1, "LYNXT – Core Transient Thermal-Hydraulic Program," J. H. Jones, et. al., B&W Fuel Company, August 1993.

6) XN-75-21(P)(A) Revision 2, "XCOBRA-IIIC: A Computer Code to Determine the Distribution of Coolant During Steady-State and Transient Core Operation," Exxon Nuclear Company, January 1986.

Table 5-1

Statistics and D Prime Test for Simulation RNDTEST3

```
DATA FILE  :      RNDTEST3    # OF DATA    :          10000
MAX VALUE  : 0.457447D+01     MIN VALUE    : -.371901D+01
RANGE      : 0.829348D+01     MEDIAN       : 0.628090D-02
MEAN       : 0.768456D-02     STD DEV      : 0.100121D+01
SKEWEDNESS : 0.365873D-02     KURTOSIS     : -.628678D-01
UPPER D'   : 0.282672D+06     LOWER D'     : 0.281496D+06
DPRIME VAL : 0.282589D+06   ACCEPT NORMALITY (5% LEVEL)
```

Table 5-2

Random Normal Generations with SHD Model

File	Mean	Standard Deviation	D prime Value
RNDTEST1	-.0082	1.0012	282398
RNDTEST2	-.0008	0.9986	282375
RNDTEST3	0.0077	1.0012	282589
RNDTEST4	0.0132	0.9873	282641
ALL	0.0030	0.9971	

Note that the upper and lower D prime values are 282762 and 281496 respectively. Each file contained 10000 values and each passed the normality test.

Figure 2-1

Statistical Determination of Uncertainties

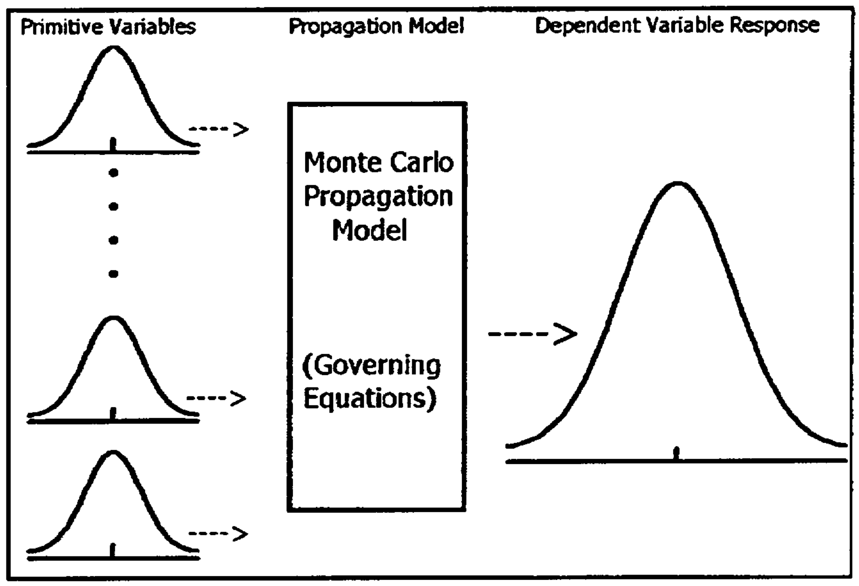
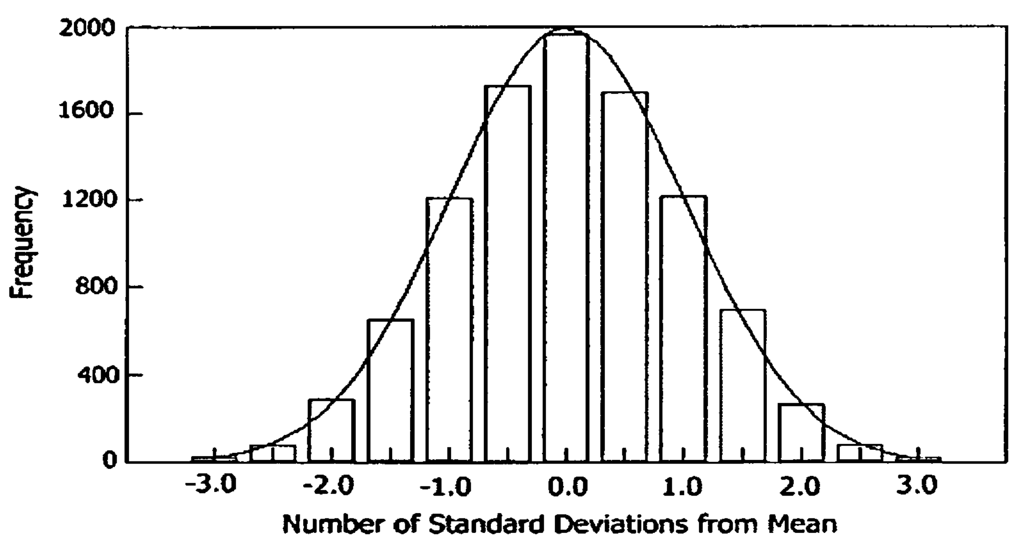


Figure 5-1

Typical Results of SHD Normal Distribution Model



Appendix A Propagation Model Code Listing

In this appendix the statistical method has been applied via a scientific program for propagation and calculation of hold down and its uncertainty on a case by case basis. The methods are clearly indicated here with comments. The Microsoft Compiled Basic programming language was chosen because it illustrates program flow and technique in a clear and understandable manner. In future analyses, however, the programming language, models, and techniques may change, however, the statistical methodology discussed in this topical report would still be utilized. Any scientific programming language would suffice, but as stated in the above, the variables, models and techniques must be separately qualified on a case to case basis.

Propagation Model Code Listing (continued)

Propagation Model Code Listing (continued)

Propagation Model Code Listing (continued)

Propagation Model Code Listing (continued)

Propagation Model Code Listing (continued)

Appendix B Calculational Example

An analysis example is provided to demonstrate the process for identifying the limiting condition for the net fuel assembly hold down force for a particular fuel design. The situation being evaluated is the introduction of a new fuel design, designated Type A, into a core composed of a Type B fuel design. Previous pressure drop testing has shown the hydraulic resistance for Type A is greater than the hydraulic resistance for Type B. Therefore, it is expected that the highest pressure drop for Type A will occur when the core is composed exclusively of Type A fuel. This will be demonstrated later in the example.

The core configurations to be examined are:

- 4 Type A Fuel Assemblies in a Core of Type B Fuel, End-of-Cycle, First Cycle
- 40% Type A Fuel Assemblies in a Core of Type B Fuel, End-of-Cycle, First Cycle
- Full Core of Type A Fuel

The full core of Type A fuel will be examined first and in detail. Analysis results for all three core configurations will be provided.

- Define the statepoints for analysis (Section 6.0)

  Since it has not already been established in this example which operating condition yields the limiting net fuel assembly hold down force, it is necessary to examine the "isothermal" condition and the "at power" condition.

  The reactor coolant pump startup condition for this plant is a minimum of 85°F. This will become the "isothermal" case. The plant has a steady-state overpower condition of 125% full power. This will become the "at power" case.

  For this example, the hold down spring system for the Type A fuel design has been previously demonstrated to have the minimum hold down force at end-of-life conditions. Since the fuel assembly wet weight and predicted pressure drop are independent of the fuel assembly burnup, it is conservative to apply the end-of-life hold down force for the Type A fuel design for all the fuel in the core. The statepoints then become:

Statepoint 1: 85°F, isothermal, full flow, end-of-life

Statepoint 2: 125% full power, full flow, end-of-life

- Define the nominal values and uncertainties for the variables (Section 7.0)

The nominal values and uncertainties for Statepoint 1 are as follows.

Q_c, Core Volumetric Flow Rate

The RCS Volumetric Flow Rate (Q_{RCS}) Nominal Value is [

]

The nominal bypass flow factor (BPF) is [

] The core flow fraction (CFF) is the RCS flow fraction reaching the core.

CFF = 1 – BPF

[ ]

The RCS volumetric flow rate uncertainty is [

]

The core volumetric flow, Q_c for each case is calculated as

[ ]

where

[ ]

Finally, because of the increased primary system resistance at the low coolant temperature for Statepoint 1, the RCS volumetric flow rate is further reduced by [ ] This reduction accounts for the difference in the RCS flow rate at a low coolant temperature condition and the hot system condition when the RCS flow rate is measured (to confirm the RCS flow rate is less than or equal to the nominal value used in the analysis).

SF, Hold Down Spring Force

For this example, the nominal spring force for the Type A hold down spring system is defined as a function of the spring constant and spring depression.

$$SF = SC\,(SD)$$

The spring system for the Type A fuel design is composed of 4 springs with individual spring forces defined as

$$SF = \sum_{i=0}^{5} C_i\,(SD^i)$$

where

SF:	Spring Force, lbf
C_i :	Spring constant coefficients, lbf/in
SD :	Spring compression, in
C_0 through C_5 :	Spring constant equation coefficients.

For the hold down spring in Type A fuel, the coefficients are

The uncertainty for the spring force is calculated on a measured to calculated basis from the polynomial fit and it's uncertainty ($\sigma_{m/c}$) is corrected for the number of degrees of freedom (96-1-6 coefficients) of the fit. The spring force uncertainty (SFU) is a standard deviation based on the calculated value of the spring force (SF).

The spring force is reduced due to the decrease in elasticity modulus for the material by a factor. For this example at 85°F, the reduction is [ ] Therefore, the total spring force becomes:

$$SFT = 4\ (MF)\ N(SF,\ SFU^2)$$

where

MF = [ ] for Statepoint 1
4 = number of springs in the example spring system

The nominal total spring force and uncertainty are calculated in the propagation model based on the spring depression.

LR, Lift Resistance

The standard deviation of the spacer grid shock losses for Type A fuel is [

]

The lift resistance uncertainty for the spacer grid shock losses is
[ ]

The lift resistance uncertainty for the remaining shock losses is
[ ]

Therefore, the total lift resistance for each propagation (LR) is calculated as

[ ]

The lift resistance and its uncertainty are calculated within the propagation model routine.

CPD, Distance between low and upper core plates
[ ]

FAH, Fuel Assembly Height

[ ]

TG, Fuel Assembly Thermal Growth

[ ]

FSH, Free Spring Height

[ ]

IG, Fuel Assembly Irradiation Growth

[ ]

LDP, Hydraulic Lift Pressure Drop

[ ]

SS, Spring Set

[ ]

IR, Spring Relaxation

[ ]

- Determine the design base case by calculating the pressure drop for all the fuel assemblies in the core for a flow rate condition similar to the statepoint using a NRC-approved computer code.

For this example, the LYNXT code (Reference 5) is used to compute the highest pressure drop across any fuel assembly. Instead of evaluating the Statepoint 1 specific RCS volumetric flow rate (Q) of [ ] gpm and a core bypass flow fraction of [ ], the base design case values of [ ] gpm, for the RCS volumetric flow rate, and [ ], for the core bypass flow fraction, were used.

Code Predicted $\Delta P_{\text{Base Design Case}}$ = [ ] psi
Average Coolant Density (DEN) = 62.59 lbm/ft^3

- Using the propagation model, determine the net hold down force for each fuel assembly. If the net hold down force for each fuel assembly is demonstrated to be positive, adequate hold down force has been demonstrated.

  Note, the Statepoint 1 conditions for the RCS flow rate of [ ] gpm and a core bypass flow fraction of [ ] are input as well as the LYNXT base design case values of [ ] gpm and [ ], respectively. Afterwards, the variables, CPD distance between the upper and lower core plate, FAH fuel assembly height, TG thermal growth, IG irradiation growth, FSH free spring height, and SS spring set are input with their respective uncertainties.

  The input data to the propagation model for Statepoint 1 is shown in Table B-1. The output for Statepoint 1 is shown in Table B-2.

The evaluation of Statepoint 2 is performed in the same manner using spring characteristics and pressure drop predictions associated with operation at 125% full power. The input data to the propagation model for Statepoint 2 is shown in Table B-3 and the output for Statepoint 2 is shown in Table B-4.

The results for the two statepoints are:

	Description	Minimum Net Fuel Assembly Hold Down (lbf)	Nominal Net Fuel Assembly Hold Down (lbf)
Statepoint 1	85°F, full flow, end-of-life, full core Type A	[ ]	[ ]
Statepoint 2	125% full power, full flow, end-of-life, full core Type A	[ ]	[ ]

The calculational example minimum net fuel assembly hold down for the core configuration with a core composed exclusively of Type A fuel would be [ ] lbf based on (95/95) confidence and protection.

The remaining two core configurations,

- 4 Type A Fuel Assemblies in a Core of Type B Fuel, End-of-Cycle, First Cycle
- 40% Type A Fuel in a Core of Type B Fuel, End-of-Cycle, First Cycle

are also examined for both statepoints to determine which core configuration defines the limiting condition or minimum net fuel assembly hold down force. The major differences in the above two configurations, relative to the full core configuration, are: 1) the burnup basis for the spring hold down force and 2) the highest fuel assembly hydraulic lift pressure drop. The input data to the two core configurations (for both statepoints) are shown in Tables B-5, B-7, B-9, and B-11. The respective output files are shown in Tables B-6, B-8, B-10, and B-12. The hydraulic lift pressure drop results and coolant densities for all of the configurations (for both statepoints) are provided in Table B-13. The results of the evaluation of all three configurations are provided in Table B-14. Examination of Table B-14 shows that the Type A fuel design will have the least net hold down force when the core is composed completely of Type A fuel. Since the net hold down force is positive, the calculational example shows the Type A fuel design will be adequately restrained against the lower core plate to satisfy the design bases criterion.

Table B-1

Calculational Example Input File for Statepoint 1, Full Core Type A

Table B-2

Calculational Example Output File for Statepoint 1, Full Core Type A

Table B-3

Calculational Example Input File for Statepoint 2, Full Core Type A

Table B-4

Calculational Example Output File for Statepoint 2, Full Core Type A

Table B-5

Calculational Example Input File for Statepoint 1, 4 Type A Fuel Assemblies in a Core of Type B

Table B-6

Calculational Example Output File for Statepoint 1, 4 Type A Fuel Assemblies in a Core of Type B

Table B-7

Calculational Example Input File for Statepoint 2, 4 Type A Fuel Assemblies in a Core of Type B

Table B-8

Calculational Example Output File for Statepoint 2, 4 Type A Fuel Assemblies in a Core of Type B

Table B-9

Calculational Example Input File for Statepoint 1, 40% Type A Fuel in a Core of Type B

Table B-10

Calculational Example Output File for Statepoint 1, 40% Type A Fuel in a Core of Type B

Table B-11

Calculational Example Input File for Statepoint 2, 40% Type A Fuel in a Core of Type B

Table B-12

Calculational Example Output File for Statepoint 2, 40% Type A Fuel in a Core of Type B

Table B-13

Varying Hydraulic Information for the Calculational Example

[1] : End-of-cycle, first cycle of irradiation
[2] : 125% full power

Table B-14

Net Fuel Assembly Hold Down Force for the Most Limiting Type A Fuel Assembly

[1] : For this example the most restrictive, or limiting, condition for the Type A fuel assembly design occurs at end-of-life under the full core situation.