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Investigation of a Process for Estimating Conditional LOOP Probability

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PRODUCT DESCRIPTION

As part of an effort to support the BWR Owners Group (BWROG) on issues related to the so-called “Option 3 LOOP-LOCA Separation” initiative, EPRI has prepared a methodology to evaluate the conditional Loss Of Offsite Power (LOOP) following a nuclear unit trip.

Results & Findings

The report concluded that failure of the fast transfer (LOOP) in response to a transient (main-generator trip) is the proper surrogate for a Loss-Of-Coolant Accident (LOCA)/LOOP for a nuclear power plant (NPP) that supplies all house loads from the main generator.

Challenges & Objectives

Due to the rarity of LOCA events and the availability of a substantial database of other events that have challenged the availability of offsite power, it was necessary to determine which other initiating events can serve as surrogates for the LOCA event. Nuclear Regulatory Commission (NRC) document ADAMS ML022120660, Appendix G, tries to relate the effect of an NPP main-generator trip with the effect of an emergency core cooling system (ECCS) actuation.

Applications, Values & Use

The probability of losing all offsite power is an important input to many nuclear power plant safety assessments. Reliable offsite power is one key to minimizing the probability of severe accidents. This report provides a new approach to assessing the probability of loss-of-offsite power as a result of transients and accidents that trip the main generator. The method is useful in estimating initiating-event frequency for probable risk assessments (PRAs).

EPRI Perspective

NRC Report NUREG/CR-6890 determines a conditional LOOP probability following a trip. For uncomplicated reactor trips, the NUREG advocates using a 0.009 (~0.01) conditional probability value for the “high season” (May, June, July, August, and September) while noting the nominal mean value following de-regulation is 0.0053. The higher value is based on a sparse data set of 2 LOOP events resulting from 275 reactor trips.

In this report, using the existing data to Bayesian update the pre-deregulation prior results in a posterior mean 0.0032. The plant-specific response to a reactor trip will depend on plant design and siting as well as the transmission grid condition. This recognition is particularly important when interpreting the NUREG/CR-6890 value of 0.01 for the “high season.”

Approach

The project team’s goal was to provide an updated approach to estimating conditional loss of offsite power given a hypothetical loss-of-coolant accident at a nuclear plant. A Bayesian

approach was used to evaluate the data and determine an approach that handles the sparse data available for making such an estimate.

Keywords
Offsite power
Losses
LWR
Risk analysis
Safety analysis

ABSTRACT

The probability of losing all offsite power is an important input to many nuclear power plant safety assessments. Reliable offsite power is one key to minimizing the probability of severe accidents. This report provides a new approach to assessing the probability of loss-of-offsite power as a result of transients and accidents that trip the main generator.

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INTRODUCTION

As part of an effort to support the BWR Owners Group (BWROG) on issues related to the so-called "Option 3 LOOP-LOCA Separation" initiative, EPRI has prepared a methodology to evaluate the conditional Loss of Offsite Power (LOOP) following a nuclear unit trip. The original initiative was begun in 2004, when the BWROG submitted report NEDO 33148 to NRC. This report, entitled "Separation of Loss of Offsite Power from Large Break LOCA," provided a risk-informed justification for the separation of LOOP events from Large Break Loss of Coolant Accident (LBLOCA) events for regulatory purposes.

In the course of events, NRC has issued a series of requests for additional information (RAI) to help resolve the technical questions surrounding the BRWOG's application. One of these requests has led to this report, which develop an improved approach to the estimating the probability of a LOOP following a LOCA. In particular, NRC's RAI 8 was worded as follows:

> Section 4.2 states that "Section G.4.2 of Reference 15 provides the basis for concluding that the probability of grid-centered events is less than the plant-centered events." The NRC staff notes that the basis for that conclusion may not be valid. …
>
> Please describe the information that a particular licensee would have to provide to justify that the probability of LOOP due to transient factors is less than the probability of LOOP due to plant-centered factors for a given nuclear power plant requesting the subject exemption. Alternately, provide a methodology and justification for calculating a plant-specific probability of consequential LOOP from transient (grid-centered) factors.

2
RAI RESPONSE

The methodology of estimating the conditional probability of LOOP given a LOCA contained in the LTR is based on the one developed by BNL. Because of concerns expressed in the RAI, the BWROG is proposing an alternate methodology developed by EPRI which is presented below. The EPRI methodology is based on a Bayesian treatment of operating data. This response offers a methodology and justification for calculating a plant specific probability of consequential LOOP.

LOOP means loss of the Class 1E 4160V buses Any NPP transients that have induced a dual safety-bus LOOP have been exceedingly rare indeed. Although this is a good thing, it makes accurately estimating the probability of such an occurrence difficult.

An approach to estimating conditional LOOP probability with recent operating data is presented below. This approach has two tenets.

1. Pre Trip house load is much larger than the post trip load even when considering SI actuation.

   One, the pre-trip house load on the power grid is much larger than the post-trip, post ECCS actuation load on the power grid. At many NPPs, AC power for ECCS surveillance tests (e.g., IWP of ASME Section XI) comes from the main-generator. Failure to fast transfer the source for ECCS loads from the main-generator to the off-site supply in response to a transient (i.e., main-generator trip) is the proper surrogate for a LOCA/LOOP. For NPPs that always serve ECCS loads from the off-site source, then “main-generator trip/undervoltage relay actuation” or “main-generator trip/diesel generator start” is the proper surrogate for LOCA/LOOP.

2. Plant trip data can be pooled and a Bayesian approach applied.

   Tenet two is that a Bayesian approach can provide a good estimate of the probability that a dual-safety-bus LOOP will follow any main generator trip. Table 2-3 captures several hundred events where large NPP main generators tripped off-line in response to a system problem inside the NPP (excluding the site switchyard) thereby challenging the availability of off-site power.

As will be demonstrated, the empirical evidence would have to change substantially to create a situation where the condition LOOP probability becomes large enough to challenge the 1×10^{-6} review limit discussed in the LTR.

Determining a Proper Surrogate for the LOCA Initiator

Due to the rarity of LOCA events and the availability of substantial data base of other events which have challenged the availability of off-site power, it is necessary to determine which other initiating event(s) can serve as surrogates for the LOCA event. The notion has been raised that loss of load due to LOCA is more challenging to grid stability than loss of load due to other causes. The citation in Figure 2-1, from NRC document ADAMS ML022120660, Appendix G (also see ADAMS ML022120667) is an example. It tries to relate the effect of an NPP main-generator trip with the effect of an ECCS actuation.

> The first event results in a sudden loss of a large amount of electric-power generation to the offsite transmission-system grid, and the last two events demand electric power from this grid to feed safety and non-safety loads. Starting these loads requires a motor-starting (inrush) current which, in turn, can cause undervoltage at the Class 1E buses. Thus, a LOCA can cause voltage instability in the offsite transmission-system grid due to the combined effect of losing electric-power generation and demanding electric power for safety and non-safety loads. This instability can degrade voltage at the unit's switchyard, thereby actuating degraded voltage protection (relays) which then disconnect the Class 1E buses from the offsite grid. These buses subsequently are powered by the onsite emergency AC power sources, usually the EDGs.
>
> [1]The term "Class 1E buses" is used to represent the safety buses that provide AC power to ECCS loads. These buses can be fed by offsite power and the emergency diesel generators (EDGs).
>
> July 2002 G-2 Risk-Informing 10 CFR 50.46/GDC 35, Rev. 1

Figure 2-1
Presumed Relationship Between Main Generator and ECCS Loads On the Grid

The notion raised in Figure 2-1 fails to recognize the facts that the ECCS loads are very small compared to the loss of power from the main-generator, and the ECCS loads are more than compensated for by the tripping of the reactor coolant pump motors. This paragraph equates the effect of a NPP main-generator trip with the effect of an ECCS actuation. Likening main-generator trip with the effect of an ECCS actuation does not seem supported in practice. The power-grid takes 800MWe to 1100MWe from a typical NPP main-generator. The sum of all ECCS loads is less than 10MWe. The loss of load event is accompanied by a loss of demand on the order of 20MWe, i.e., the reactor coolant pump motors. Therefore, the power-grid instability is likely only related to the loss of the 800MWe to 1100MWe supply. The power-grid routinely operates successfully while users change the demand for power in an amount equivalent to ECCS pump starts and loading. Because at most NPPs, the same NPP on-site switchyard supplies the reactor coolant pump motors and the ECCS pump motors, it is unlikely that the initiation of ECCS will cause a fault in the NPP switchyard. The pre-trip house load on the power grid is much larger than the post-trip, post ECCS actuation load on the power grid. Therefore, main-generator trip should be the surrogate for the LOCA initiator, rather than the main-generator trip/ECCS actuation suggested by the NRC documents. The pre-trip house load on the power grid is much larger than the post-trip, post ECCS actuation load on the power grid.

For some NPPs house-loads are shifted (i.e., fast transferred) from the main-generator to the start-up transformers. The fast-transfer occurs any time the main-generator trips. The consequential LOOP probability (as a result of a LOCA) is almost purely a function of the reliability of the fast-transfer sub-system built for each bus. Note that there are typically two Class 1E 4160V buses providing power for ECCS equipment. LOOP means both buses are lost. Thus, the probability of LOOP (aside from common cause factors) is the square of the reliability assigned to the fast transfer sub-system. Therefore, failure of the fast transfer (i.e., LOOP) in response to a transient (i.e., main-generator trip) is the proper surrogate for a LOCA/LOOP for a NPP that supplies all house loads from the main generator.

Conditional LOOP Probability Following a Trip

NUREG/CR-6890 (see page 51) determines a conditional LOOP probability following a trip. For uncomplicated reactor trips, the NUREG advocates using a 0.009 (~0.01) conditional probability value for the “high season” (May, June, July, August, and September) while noting the nominal mean value following de-regulation is 0.0053. The higher value is based on a sparse data set of 2 LOOP events resulting from 275 reactor trips. That analysis sought to find a distinction between regulated and deregulated electricity markets. In that analysis, prior to de-regulation the conditional value was 0.003. Using the existing data to Bayesian update the pre-deregulation prior results in a posterior mean 0.0032. The plant specific response to a reactor trip will depend on plant design and siting as well as the grid condition. This recognition is particularly important when interpreting the NUREG/CR-6890 value of 0.01 for the “high season” is entirely based on trips at all NPPs from 1997 to 2004, two of which occurred in the months from June to September. As a result of the sparse data set, all plants and all trips were considered to be the same, and thus pooled together in the statistical analysis. The relatively low consequential LOOP probability reflects the robustness of the grid to accommodate loss of generation capability, even during the high stress months. The relative sparseness of the LOOP data given a large number of trips over the past indicates that a coincidental combination of plant trip and marginal grid capabilities is rare. The plant specific calculations should consider switchyard equipment, bus arrangement and relay deployment. In practice, these details should be important in determining the consequential LOOP probability.

Plant-Centered vs Grid-Centered LOOP Events

It is misleading to compare the number of plant-centered LOOP events to a count of grid-centered LOOP events as a basis for consequential LOOPs as is inferred in Figure 2-2 (also from ADAMS ML022120667). In fact, the type of LOOP is irrelevant to figuring out whether or not a LOCA will induce a LOOP on both Class 1E buses.

2. The data on LOOP events in NUREG/CR-5496 [Ref. G.14] indicates that there are more LOOP events due to plant-centered failures than due to grid-related failures. NUREG/CR-5496 evaluates LOOP events at nuclear power plants during the period 1980 to 1996, and classifies the events in three categories:
   "Plant-centered events are those in which the design and operational characteristics of the plant itself play the major role in the cause and duration of the loss of offsite power.
   Grid-related events are those in which problems in the offsite power grid cause the [LOOP] and impact its duration."
   Severe-weather events are those resulting from "weather with forceful and non-localized effects."
   The data on LOOP events gathered by NUREG/CR-5496 indicate that there are 65 LOOP events due to plant-centered failures and 6 events due to grid-related failures. In other words, the number of LOOP events due to plant-centered failures is about one order of magnitude

July 2002 G-20 Risk-Informing 10 CFR 50.46/GDC 35, Rev. 1

Figure 2-2
Presumed Relationship Between LOOP Events and Consequential LOOP Events

One of the first NPP responses to a LOCA will be a main-generator trip. It is the main-generator trip (loss of 800MWe to 1000MWe supply into the power-grid) that may or may not induce a LOOP on the Class 1E buses. The probability of main-generator trip following LOCA is 100%. However, there are many other events that will cause a main-generator trip. Thus, a fair estimate of consequential LOOP in response to LOCA is to ratio the number of LOOPs subsequent to main-generator trip over the number of main-generator trips. That procedure excludes LOOPs that induce a main-generator trip. In other words, the numerator should count each real sequence having an in-plant initiator followed by a main-generator trip, which is then followed by a LOOP. Note that a LOOP will be a symptom of either a fast-transfer failure, or the cause of an undervoltage sub-system actuation (leading to a diesel generator start). The denominator should count each real event starting with an in-plant initiator followed by a main-generator trip in the sequence. Given the small effect of ECCS loads on the power-grid, it is unreasonable to limit the denominator to main-generator trip/ECCS actuation events.

An NPP transient that trips the main-generator and results in a power-grid transient can be considered significant when, as part of the event, the power-grid cannot connect to the Class 1E 4160V buses. The empirical evidence (events are listed on Table 2-3) is that NPP main-generator-trip transients rarely cause at-large power-grid outages in the post-deregulation era, much less a more limited effect like LOOP of all safety buses. As shown in Table 2-1 and discussed below, only two out of the 232 NPP main-generator trips in Table 2-3 were associated with a LOOP. Of those two, each licensee would have to evaluate whether or not the cause of the LOOP in Table 2-1 is applicable to itself. Similarly, the licensee will have to review a complete list of events to see which events could potentially occur in their plant, maybe more than 232, maybe less. As time goes on, there will be new main generator trips and a few new consequential LOOP events. Note that the plants are expected to screen out events caused by SSCs not present in their plant. On net, however, the list of 232 will grow larger over time. For illustration purposes, this analysis assumes 2 LOOP events occurred following 232 NPP main-generator trips on Table 2-3 are good surrogates for LBLOCA/LOOP experiments. Using a Bayesian process, a plant-specific LOOP probability given a generator trip event can be calculated for the plant which will represent the LOOP probability given a LOCA.

The following discussion provides an upper bound estimate of LOOP probability given a LOCA and an upper bound estimate of LOCA/LOOP frequency. It assumes that each plant is similar enough to assume the conditional LOOP as a result of an endogenous main generator trip arises from the same population. Switchyard arrangement, fast transfer applicability, and proximity to other large sources of VARs on the grid will temper this assumption.

Depending on whether or not both events on Table 2-1 are considered valid transient/LOOP events and other factors listed on Table 2-1, the conditional LOOP generic-prior probability will fall between 0.4% and 1.3%. The number varies because the generic-prior excludes events at the plant being studied. A Bayesian update would be needed to estimate the plant specific value. The following describes the Bayesian approach to creating a plant specific LBLOCA conditional LOOP frequency.

Table 2-3 captures several hundred events where large NPP main generators tripped off-line in response to a system problem inside the NPP (excluding the site switchyard). Of the events listed, 232 are considered surrogates for LBLOCA events that could cause LOOP. Events considered to be a surrogates where main generator trips were a result of an on-site induced transient (e.g., feedwater failures, steam generator low level, and turbine-generator failures). Events traced to offsite causes (e.g., grid-disturbances, storms) were excluded from the list of 232 events counted as surrogates for LBLOCA in the context of consequential LOOP**.** The events are assumed to result in either a consequential LOOP or not. A review of events listed in Table 2-3 indicated that only 2 resulted in consequential LOOPs (see Table 2-1). Note that the number 232 is subject to interpretation; as the number decreases holding other facts constant, the consequential LOOP probability increases. As will be demonstrated, the empirical evidence would have to change substantially to create a situation where the condition LOOP probability becomes large enough to challenge the 1×10^{-6} review limit discussed in the LTR.

Table 2-1
NPP Trip Events with LOOP

NPP Trip Events with LOOP		
Site	**Date**	**Reference**
Indian Point	31Aug1999	OE 10273 dated 09/22/99 LER (247) 99-015 dated 09/30/99
Diablo Canyon	15May2000	LER (275) 00-004 dated 06/13/2000 Rev 1, 08/30/2000

Indian Point Spurious Reactor Scram

During full power operation, with planned instrument and control maintenance in progress, a spurious reactor scram signal shut down Unit 2. The feed for the emergency buses properly transferred from the unit auxiliary transformer to off-site power from the station auxiliary transformer. This transformer is fed by a 138 kV line from Buchanan substation. When Unit 2 trips and this transfer takes place, it is not unusual for voltage on the line from Buchanan to dip. A tap changer in the station auxiliary transformer is supposed to restore the voltage to an acceptable level before the emergency buses relay out on low voltage. However, at the time of this unit trip the tap changer was on manual because of a previous failure in its control circuit. With the off-site power voltage dip uncorrected, the emergency buses automatically disconnected from off-site power because of low voltage and the EDGs started and loaded. However, one EDG output breaker had an incorrect over current relay setting and the breaker opened when pump motors attempted to start. This second loss of power on this emergency bus activated the station blackout logic. In the presence of the Unit trip signal, the blackout logic would not allow the emergency buses to be transferred back to off-site power, even though such power was at all times available. With the reasons for the various automatic actions unclear, it was deemed imprudent to override the blackout logic until there was adequate analysis and testing. Off-site power was restored to the emergency buses about 12 hours after the event began.

Diablo Canyon

On 05/15/00 Diablo Canyon I tripped from 100% power and lost all off-site power to its 4 kV vital (safety) buses and its 4 kV non-vital buses when a 12 kV bus connection failed. The failure and resulting fire occurred in a non-safety related switchgear room. A fast transfer of 12 kV buses was successful and maintained off-site power to reactor coolant pumps and various other non-vital loads. The unit's three EDGs started and powered the 4 kV vital buses. At Diablo Canyon I, non-vital 12 kV loads are normally fed from the generator 25 kV output via 25/12 kV unit auxiliary transformer 1-1. The bus connection failure occurred in the bus duct leaving this transformer. The fault caused the main turbine generator to trip, which deenergized the 25 kV feed to this transformer. The generator 25 kV output also was powering vital and nonvital 4 kV loads through 25/4 kV unit auxiliary transformer 1-2, hence these loads were also deenergized. There is a backup off-site source of power for 4 kV vital buses via a 230/12 kV transformer and then 12/4 kV startup transformer 1-2. Unfortunately the 4 kV startup bus is located immediately above where the 12 kV fault occurred. The fault and fire spread to this bus and caused startup transformer 1-2 to trip and lock out. Hence the vital buses were without any source of off-site power. Off-site power was restored to the 4 kV vital and non-vital buses and the EDGs secured 33:34 (33 hours and 34 minutes) after the event began. Diablo Canyon Unit 2 remained at 100% power and was unaffected by the event.

The data is assumed to be distributed as a binomial distribution with a mean of 2/232=0.009. This mean represents an estimate of the probability of the LOOP occurring given a main generator trip has occurred. The estimate of the distribution of the mean is taken as a Beta distribution with mean, Θ =0.009, and variance, σ^2= np(1-p). Using the Equation 2-1 and

Equation 2-2 below and matching moments with the Beta distribution allows one to define the distribution parameters α and β

$$\Theta = \alpha/(\alpha+\beta) \quad \text{and} \quad \sigma^2 = \alpha\beta/((\alpha+\beta)^2(\alpha+\beta+1)) \qquad \textbf{Equation 2-1}$$

A comparison of these distributions employing consistent means and variances is presented in Figure 2-4.

Using Bayesian inference techniques (see for example Reference 1 and Reference 2) and taking the Beta distribution as the prior distribution for Θ and assuming an event space with n trials and x successes (representing plant specific experience not involved in the prior, endogenous events), the Bayesian point estimate of the mean of the plant specific data can be shown to be represented as Equation 2-2.

$$P(LOOP|\, LBLOCA) = \Theta = \frac{\alpha+x}{\alpha+\beta+n} = \frac{n}{\alpha+\beta+n}\left(\frac{x}{n}\right) + \frac{\alpha+\beta}{\alpha+\beta+n}\left(\frac{\alpha}{\alpha+\beta}\right) \qquad \textbf{Equation 2-2}$$

Here n is the number of endogenous main generator trips, and x is the number of conditional LOOP events endogenous to the NPP being studied. The α and β are Beta parameters. (A derivation of these parameters is provided in Appendix A. The final presentation in Equation 2-2 shows that the posterior is a weighted average of the endogenous and exogenous data respectively.

Table 2-2 provides some feel for the size of the conditional LOOP probability determined from this method. It seems that no matter the approach, an NPP with a LOCA/LOOP annual frequency close to 1E-06 would be very unusual. Even if one considers main-generator trip a surrogate for LOCA, the LOCA/LOOP probability is small. Of the 232 endogenous main-generator trip events selected (see Table 2-3), one NPP *site* had 8 endogenously caused main-generator trip events, another 5, with the rest being 4 or less. Many NPPs did not have even one event that qualified in the group of 232. Note that the value of 232 is quite subjective.

The model is a strong function of the number of exogenous LOOP events. The plant specific values will be higher (all things being equal) as the exogenous consequential LOOP events increase. The key to understanding Table 2-2 is to see how much the plant specific consequential LOOP changes as compared to the prior. In this model, the plant specific value (posterior) cannot fall below the industry value (prior). Plants with a consequential LOOP (all else equal) will have significantly higher posterior estimates relative to the prior, as compared to those with no consequential LOOPs.

Table 2-2
Bayesian Update Results for Hypothetical NPPs

NPP	Industry	Industry	Endogenous	Endogenous	Beta Distribution	Beta Distribution	Posterior	Increase Factor over Prior
	Main Gen. Trips	Consequential LOOPs exogenous to the NPP, i.e.,	Main Generator Trips	Consequential LOOPs	Alpha Parameter (Eq. 2-9)	Beta Parameter (Eq 2-10)	Plant Specific Conseq. LOOP Prob. (Eq 2-2)	
1	228	1	1	1	0.498	225.502	0.66%	1.50
2	228	2	5	0	1.991	220.009	0.88%	1.00
3	228	1	5	1	0.498	221.502	0.66%	1.50
4	228	1	10	1	0.498	216.502	0.66%	1.50
5	150	1	1	1	0.497	147.503	1.00%	1.51
6	150	2	5	0	1.986	142.014	1.33%	1.00
7	150	1	5	1	0.497	143.503	1.00%	1.51
8	150	1	10	1	0.496	138.504	1.00%	1.51
9	300	1	1	1	0.498	297.502	0.50%	1.50
10	300	2	5	0	1.993	292.007	0.67%	1.00
11	300	1	5	1	0.498	293.502	0.50%	1.50
12	300	1	10	1	0.498	288.502	0.50%	1.50

Combining the high-end of the conditional LOOP probability estimate with the high estimate of 7.6E-06/year for Large LOCA (see page 4-7 of NEDO-33148), yields a LOCA/LOOP frequency of 1.01×10^{-7}/year, well below the 1×10^{-6} threshold proposed. Note that 1.01×10^{-7}/year assumes LOCA/LOOP leads directly to core damage—no mitigating systems, no mitigating human actions. Regulatory Guide 1.174 considers a 1×10^{-6} increase in CDF to be small.

Once a LOOP event occurs at a plant extreme care must be taken in the use of Equation 2-2 to ensure the plant design is such that the event is really a random occurrence. If the event were traced to a specific cause, then risks may be found to have changed based on deterministic factors.

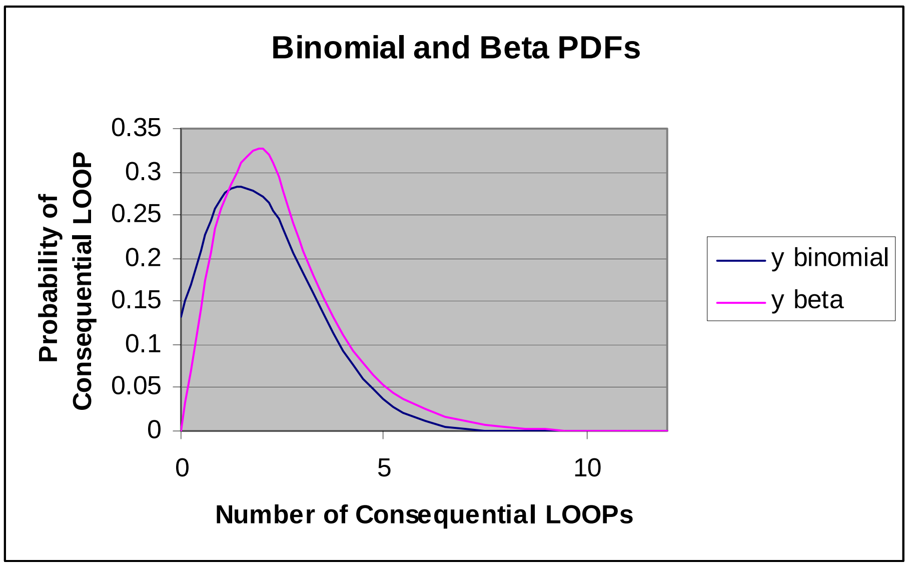

Figure 2-3
Comparison of Binomial and Beta Distributions

References

1. Wassermann, L., *All of Statistics: A Concise Course In Statistical Inference*, Springer, New York, 2003.
2. Hogg, R., et al., *Introduction to Mathematical Statistics*, Sixth Edition, Pearson Education, Inc., 2005.

Table 2-3
Recent Events of Main Generator Tripping In Response To An Event Within An NPP

Recent Events of Main Generator Tripping In Response To An Event Within An NPP		
Reactor Unit	**Date**	**Reference**[1]
Beaver Valley 1	13-Nov-03	40320
Beaver Valley 1	07-Sep-06	42834
Beaver Valley 1	05-Jul-00	37145
Beaver Valley 2	17-Mar-01	37845
Beaver Valley 2	02-Apr-06	42467
Braidwood 2	14-Apr-99	35592
Braidwood 2	03-Dec-03	40370
Braidwood 2	28-Mar-05	41535
Browns Ferry 2	17-Sep-99	36194
Browns Ferry 2	13-Apr-05	41595
Browns Ferry 2	15-May-99	35720
Browns Ferry 2	05-Aug-05	41896
Browns Ferry 2	27-Jul-02	39100
Browns Ferry 2	25-Jul-01	38171
Browns Ferry 3	24-May-00	37027
Browns Ferry 3	11-Feb-05	41404
Browns Ferry 3	23-Nov-04	41219
Browns Ferry 3	17-Sep-05	41997
Brunswick 1	13-Jul-05	41837
Brunswick 2	29-Mar-99	35522
Brunswick 2	22-Sep-00	37364
Brunswick 2	09-Apr-05	41582
Brunswick 2	04-Nov-03	40297
Brunswick 2	22-Sep-00	37365
Brunswick 2	28-Jun-99	35878
Brunswick 2	04-Nov-03	40297
Byron 1	13-May-99	35710
Byron 1	15-Oct-02	39286
Byron 1	07-Nov-02	39353
Byron 2	13-Jan-00	ML003685744
Byron 2	19-Oct-05	42063
Callaway	03-Feb-04	40500
Callaway	27-Jan-04	40484
Callaway	13-Feb-00	36685
Callaway	15-Feb-04	40522

Table 2-3 (continued)
Recent Events of Main Generator Tripping In Response To An Event Within An NPP

Recent Events of Main Generator Tripping In Response To An Event Within An NPP		
Reactor Unit	**Date**	**Reference[1]**
Callaway	19-Jan-05	41347
Catawba 1	13-Feb-00	36686
Catawba 1	04-Feb-03	39559
Catawba 1	17-Jan-01	37667
Catawba 2	30-Dec-99	36551
Catawba 2	05-Jun-00	37059
Clinton	22-Mar-04	LER 2004-001-00
Clinton	24-Jul-01	38164
Clinton	27-Aug-06	42807
Clinton	04-Feb-01	37714
Clinton	04-Jul-02	39041
Clinton	20-Mar-06	42430
Columbia	23-Jun-05	41790
Columbia	26-Jun-00	37114
Columbia	30-Jun-03	39965
Columbia	31-Oct-06	42950
Columbia	15-Jun-05	41779
Comanche Peak 2	18-Jul-01	38148
Comanche Peak 2	22-Dec-03	40406
Comanche Peak 2	06-Jun-02	38969
Comanche Peak 2	09-Jul-03	39985
Cook 1	26-Apr-05	41639
Cook 1	15-Jan-03	39513
Cook 2	08-Apr-04	40660
Cook 2	30-Dec-03	40419
Cook 2	05-Feb-03	39564
Cook 2	22-Jul-02	39081
Cook 2	19-Jan-02	38640
Cooper	15-Apr-05	41601
Cooper	03-Mar-01	37805
Cooper	14-Oct-00	37429
Crystal River 3	24-Mar-04	40608
Diablo Canyon 1	15-May-00	37001
Diablo Canyon 2	12-Dec-06	43047

Table 2-3 (continued)
Recent Events of Main Generator Tripping In Response To An Event Within An NPP

Recent Events of Main Generator Tripping In Response To An Event Within An NPP		
Reactor Unit	**Date**	**Reference**[1]
Dresden 2	24-Mar-05	41517
Dresden 2	04-Jul-06	42685
Dresden 2	30-Nov-00	ML022170564
Dresden 3	21-Jul-02	39080
Dresden 3	30-Jan-04	40491
Dresden 3	11-Dec-99	36501
Dresden 3	24-Jan-04	40474
Dresden 3	05-May-04	OE18875
Farley 1	27-May-99	35771
Farley 1	28-May-00	37041
Farley 1	01-Mar-04	40558
Farley 2	16-Nov-00	37527
Fermi 2	03-Sep-04	41017
Fermi 2	15-Jun-06	42643
Fitzpatrick	05-Nov-99	36403
Fitzpatrick	14-Sep-05	41987
Fitzpatrick	14-Oct-99	36293
Fort Calhoun	26-Feb-05	41446
Ginna	16-Feb-05	41414
Ginna	23-Apr-99	35623
Ginna	27-Apr-99	35638
Grand Gulf 1	15-Sep-00	ML003777045
Grand Gulf 1	11-Feb-05	41405
Grand Gulf 1	07-Aug-01	ML012820104
Grand Gulf 1	24-Apr-03	ML032790367
Grand Gulf 1	21-Feb-99	35391
Harris	18-May-03	39856
Harris	12-Mar-99	35462
Harris	15-Aug-02	ML022900333
Harris	06-May-04	40730
Harris	19-Sep-06	42848
Hatch 1	10-Jul-00	37155
Hatch 1	29-Oct-05	42096
Hatch 2	05-Apr-06	42471
Hatch 2	25-Dec-01	38592

Table 2-3 (continued)
Recent Events of Main Generator Tripping In Response To An Event Within An NPP

Recent Events of Main Generator Tripping In Response To An Event Within An NPP		
Reactor Unit	**Date**	**Reference[1]**
Hope Creek 1	24-May-00	37030
Hope Creek 1	22-Jun-02	39010
Indian Point 2	31-Aug-99	36104
Indian Point 2	26-Nov-04	41227
Indian Point 2	15-Nov-06	42993
Indian Point 2	31-Aug-99	36104
Indian Point 3	12-Aug-99	36023
Indian Point 3	09-Jun-00	ML003732896
Indian Point 3	06-May-05	41673
Indian Point 3	06-Jul-06	42687
Indian Point 3	04-Jun-00	37054
Lasalle 1	31-Jan-01	37707
Lasalle 1	20-Feb-06	42348
Lasalle 2	22-Jun-00	37102
Lasalle 2	06-Apr-01	37895
Lasalle 2	01-Dec-00	37562
Lasalle 2	27-May-01	38034
Limerick 1	11-Jun-99	35815
Limerick 1	18-Jul-05	41848
Limerick 1	01-May-00	36947
Limerick 1	19-May-02	38927
Limerick 1	20-Apr-99	35611
Limerick 2	12-Oct-05	42054
Limerick 2	08-Jan-00	36573
Limerick 2	31-Dec-99	36553
Nine Mile Point 1	18-Aug-05	41927
Nine Mile Point 1	12-Jun-06	42633
Nine Mile Point 1	23-Jul-99	35954
Nine Mile Point 1	02-May-04	40719
Nine Mile Point 1	07-Mar-05	41464
Nine Mile Point 2	16-May-01	37994
Nine Mile Point 2	09-Mar-06	42403
Nine Mile Point 2	17-Sep-00	37335
Oconee 1	18-Aug-99	36040

Table 2-3 (continued)
Recent Events of Main Generator Tripping In Response To An Event Within An NPP

Recent Events of Main Generator Tripping In Response To An Event Within An NPP		
Reactor Unit	**Date**	**Reference**[1]
Oconee 1	12-Sep-01	38281
Oconee 2	12-Apr-06	42493
Oconee 2	19-Jun-99	35847
Oconee 2	28-Feb-99	35424
Oconee 3	03-Jan-00	36557
Oconee 3	26-Feb-04	40548
Oconee 3	14-Nov-02	39369
Oconee 3	31-Aug-05	41966
Oyster Creek	22-Aug-03	40095
Palisades	01-Dec-02	39414
Palo Verde 1	26-Aug-05	41951
Palo Verde 1	21-Oct-06	42925
Palo Verde 2	26-Jul-06	42730
Palo Verde 2	18-Jun-99	35845
Palo Verde 2	14-Jul-04	40814
Palo Verde 2	18-Nov-00	37533
Palo Verde 3	05-Mar-06	42387
Peach Bottom 2	23-Oct-01	38419
Peach Bottom 2	30-Sep-99	36248
Peach Bottom 2	10-Jul-05	41832
Peach Bottom 2	22-Jul-03	40010
Peach Bottom 2	01-Jul-01	38109
Peach Bottom 3	07-Aug-00	37212
Perry	22-Sep-02	39207
Perry	15-Dec-01	38575
Pilgrim	05-Aug-99	35992
Pilgrim	01-Jun-03	39898
Point Beach 1	15-Jul-03	39996
Point Beach 2	06-Feb-01	37722
Point Beach 2	20-Dec-00	37621
Prairie Island 1	01-Aug-01	38179
Prairie Island 2	31-Oct-01	38448
Prairie Island 2	28-Apr-00	36942
Quad Cities 1	21-May-99	35753

Table 2-3 (continued)
Recent Events of Main Generator Tripping In Response To An Event Within An NPP

Recent Events of Main Generator Tripping In Response To An Event Within An NPP		
Reactor Unit	**Date**	**Reference[1]**
Quad Cities 1	22-Feb-06	42356
Quad Cities 1	17-Jun-05	41782
Quad Cities 2	30-Mar-04	40625
Quad Cities 2	18-Jul-00	ML003768817
River Bend	29-Oct-99	ML993400262
River Bend	19-Oct-06	42921
River Bend	15-Apr-06	42505
River Bend	01-Oct-04	41082
Salem 1	22-May-01	38021
Salem 1	08-Dec-00	37579
Salem 1	28-Feb-99	35420
Salem 1	08-Mar-06	42395
Salem 1	24-Sep-01	ML020160096
Salem 2	09-Sep-04	41028
San Onofre 2	19-Nov-04	41209
San Onofre 2	03-Feb-05	41368
San Onofre 2	01-Feb-03	39553
San Onofre 2	02-Nov-02	39340
San Onofre 3	27-Feb-02	ML021200004
San Onofre 3	09-Sep-04	LER-311-04008
St Lucie 1	29-Oct-99	36369
St Lucie 1	05-Jun-01	38053
St Lucie 2	11-Jun-03	39917
St Lucie 2	20-Jan-06	42277
St Lucie 2	20-Dec-03	LER 389-03-005
St Lucie 2	14-Mar-01	37841
STP 1	12-Sep-99	36148
STP 1	23-Jan-04	40473
STP 1	16-May-99	35722
STP 2	21-Jan-99	35289
STP 2	09-Feb-00	36677
STP 2	07-Jul-02	39045
Summer	25-Aug-05	41946
Summer	22-Nov-06	43004

Table 2-3 (continued)
Recent Events of Main Generator Tripping In Response To An Event Within An NPP

Recent Events of Main Generator Tripping In Response To An Event Within An NPP		
Reactor Unit	**Date**	**Reference[1]**
Summer	04-Jun-99	35796
Summer	12-May-03	39838
Summer	30-Mar-04	40628
Surry 2	25-Jan-03	39536
Surry 2	21-May-04	OE18594
Susquehanna 1	15-Jun-06	42642
Susquehanna 2	08-Jun-99	35806
Susquehanna 2	06-Jun-05	41746
Susquehanna 2	30-Sep-02	39233
Three Mile Island 1	02-Nov-06	42957
Turkey Point 4	27-Jun-05	41800
Vermont Yankee	18-Jun-04	40827
Vogtle 1	11-Jan-05	41323
Vogtle 1	24-Aug-01	38234
Vogtle 2	27-Aug-06	42806
Waterford	13-Feb-01	37742
Watts Bar 1	31-Jul-06	42744
Watts Bar 1	16-Jan-04	40454
Watts Bar 1	25-Aug-03	40100
Watts Bar 1	10-Mar-03	39651
Watts Bar 1	13-Jul-02	39058
Wolf Creek	13-Feb-04	40517
Wolf Creek	18-Aug-03	40086
Wolf Creek	08-May-02	38906
Wolf Creek	07-Oct-04	41100
Wolf Creek	22-Aug-04	40974

1. The five digit numbers are NRC Event Notification Numbers, details are available from http://www.nrc.gov/reading-rm/doc-collections/event-status/event/. The numbers starting with ML are available from the NRC ADAMS system. OE numbers are from INPO.

3 BAYESIAN TREATMENT OF PLANT SPECIFIC CONSEQUENTIAL LOOP

The nature of this analysis allows use of the Binomial probability model. The procedure for converting an industry prior probability of consequential LOOP into a plant specific value starts with Equation 3-1.

$$P(A \mid B) = \frac{P(A) * P(B \mid A)}{P(B)} \qquad \textbf{Equation 3-1}$$

For this analysis, Equation 3-1 can be interpreted as follows:

$$\text{Probability of LOOP given Main Gen. Trip} = \frac{\left\{\begin{matrix}\text{Prior Probability of} \\ \text{LOOP given} \\ \text{Main Gen. Trip}\end{matrix}\right\} * \left\{\begin{matrix}\text{Likelihood of Main} \\ \text{Gen. Trip given a} \\ \text{LOOP}\end{matrix}\right\}}{\text{Normalizing Constant}}$$

The simplest element of Equation 3-1 is the “Likelihood of Main Gen. Trip given a LOOP” because its value is one; a main generator trip is nearly always associated with a dual-safety bus LOOP. The exception is an event at Cooper because the main generator feeds a grid system separated by voltage level from the grid that provides off-site power.

Prior

The “prior probability ” distribution can be based on the overall industry exogenous experience with the number of main generator trips. Of the 232, one reactor plant accounted for five main generator trips that could be used as surrogates for a LBLOCA/LOOP study. Of course, many plants have zero events in the endogenous camp.

Since the individual events are binomially distributed. The distribution for the collection of the events can be represented by the Beta distribution. The Beta distribution is known as a conjugate distribution. Selection of the Beta simplifies the mathematics for the Bayesian process. The beta distribution can be helpful when the actual distribution of an uncertain variable is unknown, but the user has a good idea of the bounds, the mean, and the standard deviation of the uncertain variable. That is the case here because it is assumed that the consequential LOOP data fits the binomial distribution where the mean of a binomial is n*p and the variance is n*p*(1-p). Equation 3-2 is the density function for the beta distribution.

$$P(A)=\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\frac{(A-L_A)^{\alpha-1}(U_A-A)^{\beta-1}}{(U_A-L_A)^{\alpha+\beta-1}}$$ **Equation 3-2**

Here, L_A and U_A are the lower and upper bounds on the range of values for A. $\Gamma(\sigma)$ is the gamma function and $B(\alpha,\beta)=\frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)}$ is the beta function. To calculate mean and standard deviation from the alpha, beta, upper bound, and lower bound parameters of the beta distribution, the following expressions may be used.

$$\mu_B = L_B + \frac{\alpha}{\alpha+\beta}(U_B - L_B)$$ **Equation 3-3**

$$\sigma_B^2 = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}(U_B - L_B)^2$$ **Equation 3-4**

In this paper, μ_B and σ_B^2 are known, they are the mean and variance in the binomial distribution using exogenous trip events, n, and exogenous consequential LOOP events, x. The mean, μ_B, and variance, σ_B^2, of a binomial distribution are well documented and are according to the Equation 3-5 and Equation 3-6 respectively.

$$\mu_B = n * p$$ **Equation 3-5**

$$\sigma_B^2 = n * p * (1-p)$$ **Equation 3-6**

Solving Equation 3-3 and Equation 3-4 in terms of α and β gives:

$$\alpha = (\mu_B - L_B)\frac{(\mu_B - L_B)(U_B - \mu_B) - \sigma_B^2}{\sigma_B^2(U_B - L_B)}$$ **Equation 3-7**

$$\beta = (U_B - \mu_B)\frac{(\mu_B - L_B)(U_B - \mu_B) - \sigma_B^2}{\sigma_B^2(U_B - L_B)}$$ **Equation 3-8**

To show that the beta-distribution is appropriate for this application, Figure 3-1 is provided using the parameters calculated from two successes in 232 trials. The interpretation here is that the number of consequential LOOPs in 232 main generator trips will be something less than 10 using the data provided in this document.

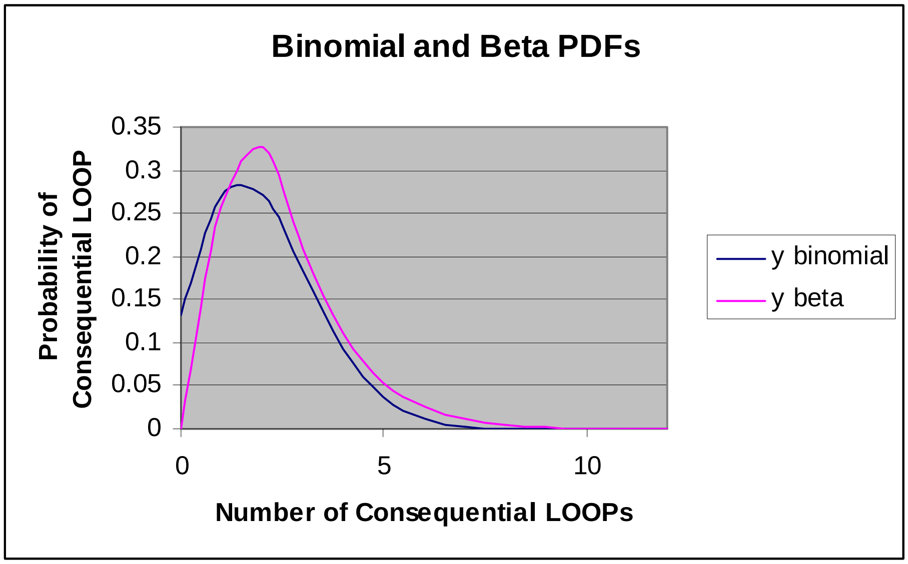

Figure 3-1
Binomial and Beta Distribution PDFs

To simplify the use of Equation 3-2 the terms are rearranged to follow the pattern of the beta distribution function in Equation 3-9, which is the equivalent of Equation 3-2.

$$
\begin{aligned}
P(A) &= \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \frac{(A-0)^{\alpha-1}(U_A-A)^{\beta-1}}{(U_A-0)^{\alpha+\beta-1}} \\
&= \frac{\Gamma(\alpha+\beta)(A)^{\alpha-1}}{\Gamma(\alpha)\Gamma(\beta)} \frac{(U_A-A)^{\beta-1}}{(U_A)^{\alpha+\beta-1}} = \frac{\Gamma(\alpha+\beta)(A)^{\alpha-1}}{\Gamma(\alpha)\Gamma(\beta)} \left(\frac{U_A-A}{U_A}\right)^{\beta-1} \frac{1}{(U_A)^{\alpha}} \\
&= \frac{\Gamma(\alpha+\beta)(A)^{\alpha-1}}{\Gamma(\alpha)\Gamma(\beta)} \left(\frac{U_A-A}{U_A}\right)^{\beta-1} \frac{1}{(U_A)(U_A)^{\alpha-1}} \\
&= \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \left(\frac{A}{U_A}\right)^{\alpha-1} \left(\frac{U_A-A}{U_A}\right)^{\beta-1} \frac{1}{(U_A)}
\end{aligned}
\qquad \textbf{Equation 3-9}
$$

In Equation 3-9, '**A**' will correspond to the exogenous consequential LOOP events in the range of possible values (zero to the total number of exogenous generator trip events). In other words '**A**' could be zero meaning there were no exogenous consequential LOOPs and that every consequential LOOP occurred at the NPP of interest. At the other extreme, '**A**' could be the same as the number of exogenous generator trips, i.e., there was a consequential LOOP each time the NPP had a main generator trip.

Likelihood

Likelihood in a Binomial Distribution is:

$$\binom{n}{x} p^x (1-p)^{n-x} \quad \textbf{Equation 3-10}$$

Where,

$$\binom{n}{x} = \frac{n!}{(n-x)!} \quad \textbf{Equation 3-11}$$

The value of p and (1-p) is the same as $\frac{A}{U_A}$ and $\frac{U_A - A}{U_A}$ respectively in Equation 3-9.

Normalizing Constant

The final term, "normalizing constant" is the most complex. It is introduced in the Bayes process to normalize the results, particularly so the product of the prior and the likelihood is a value between zero and one. As expected, the solving the integral of Equation 3-12 results in a constant because the limits of integration are constants.

$$\text{Normalization Constant} = \int_0^1 \left(\frac{A}{U_A}\right)^{\alpha-1} \left(\frac{U_A - A}{U_A}\right)^{\beta-1} \left(\frac{A}{U_A}\right)^{x} \left(\frac{U_A - A}{U_A}\right)^{n-x} d\left(\frac{A}{U_A}\right) \quad \textbf{Equation 3-12}$$

Combining exponents in Equation 3-12 results in an equation that is more easily recognized.

$$\text{Normalization Constant} = \int_0^1 \left(\frac{A}{U_A}\right)^{\alpha+x-1} \left(\frac{U_A - A}{U_A}\right)^{\beta+n-x-1} d\left(\frac{A}{U_A}\right) \quad \textbf{Equation 3-13}$$

Even a casual attempt at simplifying this integral will cause one to recognize this is no trivial integral. Fortunately, it has the form of the Beta Function.

$$\text{Beta function} = \int_0^1 t^{a-1}(1-t)^{b-1} dt \quad \textbf{Equation 3-14}$$

The solution to integrating the Beta function is well documented. Integrating Equation 3-14 results in Equation 3-15.

$$\int_0^1 t^{a-1}(1-t)^{b-1} dt = \frac{\Gamma(a)\Gamma(b)}{\Gamma(a+b)} \quad \textbf{Equation 3-15}$$

where relationships in Equation 3-7 and Equation 3-8 will help solve Equation 3-12.

The a and b term in Equation 3-15 correspond directly to α, β, x and n-x

$$a-1=\alpha+x-1$$
$$b-1=\beta+n-x-1$$

Equation 3-16

Integrating Equation 3-12 results in a constant as shown below.

$$\int_0^1\left(\frac{A}{U_A}\right)^{\alpha+x-1}\left(\frac{U_A-A}{U_A}\right)^{\beta+n-x-1}d\left(\frac{A}{U_A}\right)$$
$$=\frac{\Gamma(\alpha+x)\Gamma(\beta+n-x-1)}{\Gamma(\alpha+x+\beta+n-x-1)}=\frac{\Gamma(\alpha+x)\Gamma(\beta+n-x-1)}{\Gamma(\alpha+\beta+n-1)}$$

Equation 3-17

Posterior

The Bayesian update of the industry prior into a plant specific posterior value is a matter of algebra.

$$P(A\mid B)=\frac{P(A)*P(B\mid A)}{P(B)}$$
$$=\frac{\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\left(\frac{A}{U_A}\right)^{\alpha-1}\left(\frac{U_A-A}{U_A}\right)^{\beta-1}\frac{1}{(U_A)}*\binom{n}{x}\left(\frac{A}{U_A}\right)^{x}\left(1-\frac{A}{U_A}\right)^{n-x}}{\frac{\Gamma(\alpha+x)\Gamma(\beta+n-x-1)}{\Gamma(\alpha+\beta+n-1)}}$$
$$=\frac{\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\left(\frac{A}{U_A}\right)^{\alpha+x-1}\left(\frac{U_A-A}{U_A}\right)^{\beta+n-x-1}\frac{1}{(U_A)}*\binom{n}{x}}{\frac{\Gamma(\alpha+x)\Gamma(\beta+n-x-1)}{\Gamma(\alpha+\beta+n-1)}}$$
$$=\frac{\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\left(\frac{A}{U_A}\right)^{\alpha+x-1}\left(\frac{U_A-A}{U_A}\right)^{\beta+n-x-1}\frac{1}{(U_A)}*\left(\frac{\Gamma(n+1)}{\Gamma(n-x+1)}\right)}{\frac{\Gamma(\alpha+x)\Gamma(\beta+n-x-1)}{\Gamma(\alpha+\beta+n-1)}}$$
$$=\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\left(\frac{A}{U_A}\right)^{\alpha+x-1}\left(\frac{U_A-A}{U_A}\right)^{\beta+n-x-1}\frac{1}{(U_A)}*\left(\frac{\Gamma(n+1)}{\Gamma(n-x+1)}\right)\left(\frac{\Gamma(\alpha+\beta+n-1)}{\Gamma(\alpha+x)\Gamma(\beta+n-x-1)}\right)$$
$$=\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\frac{1}{(U_A)}*\left(\frac{\Gamma(n+1)}{\Gamma(n-x+1)}\right)\left(\frac{\Gamma(\alpha+\beta+n-1)}{\Gamma(\alpha+x)\Gamma(\beta+n-x-1)}\right)\left(\frac{A}{U_A}\right)^{\alpha+x-1}\left(\frac{U_A-A}{U_A}\right)^{\beta+n-x-1}$$

Equation 3-18

The derivation shown in Equation 3-18 results in a constant times a term that follows the beta function pattern, i.e. $(A/U_A)^{\alpha+x-1}((U_A-A)/U_A)^{\beta+n-x-1}$. The constant causes the plot of the pdf curve to shift, but the shape is dictated by the exponents in $(A/U_A)^{\alpha+x-1}((U_A-A)/U_A)^{\beta+n-x-1}$. Noting that the mean of a beta is only a function of the exponents of $(A/U_A)^{\alpha+x-1}((U_A-A)/U_A)^{\beta+n-x-1}$, the mean posterior simplifies to what is presented here as Equation 3-19.

$$P(A|B)=\frac{P(A)*P(B|A)}{P(B)}$$

$$P(A|B)=\frac{\alpha+x}{\alpha+\beta+n}=\frac{n}{\alpha+\beta+n}\left(\frac{x}{n}\right)+\frac{\alpha+\beta}{\alpha+\beta+n}\left(\frac{\alpha}{\alpha+\beta}\right)$$

Equation 3-19

Where,

n is the number of endogenous main generator trips, and x is the number of conditional LOOP events endogenous to the NPP being studied. The final presentation in Equation 3-19 shows that the posterior is a weighted average of the endogenous and exogenous data respectively.

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