DIABLO CANYON POWER PLANT: STEAM GENERATOR REPAIR/REPLACEMENT COST/BENEFIT ANALYSIS

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ABSTRACT

Nuclear power plant steam generator replacement decisions involve roughly $1 B in capital and replacement power costs. SDG has been engaged in helping utilities make this type of decision for the past 20 years. For PG&E, we decided to change our analytic approach to include a Monte Carlo simulation. This paper discusses the results and the strengths and limitations of this analytic approach. Before this case, a California utility decision of this size had never included a Monte Carlo simulation. In contrast, another utility in California filed for steam generator replacement using a base case approach and has had very different results.

1 INTRODUCTION

Managing nuclear power plants in the US present a unique set of potentially very expensive challenges. As nuclear power plants have aged, critical components have needed to be replaced and/or updated. The most expensive component to replace is a unit's steam generators. The total cost of replacement can reach $1 B once replacement power costs are included. Deciding the optimal time to replace requires trading off potentially higher costs of earlier replacement when the time value of money is included with the higher risk of extended unplanned outages if replacement is delayed. Furthermore, whatever analysis is used to justify the decision, it must be flexible enough to respond to the public review process and clearly address the concerns raised by ratepayers. For the Diablo Canyon steam generator replacement decision, a Microsoft® Excel spreadsheet model was created and a probabilistic analysis was done using Crystal Ball. This paper first provides an overview of the model structure, followed by a discussion of the results. It concludes with an appraisal of the approach and the strengths of weaknesses of using Crystal Ball and Monte Carlo simulation.

2 OVERVIEW OF EXCEL SPREADSHEET MODEL FOR DIABLO CANYON

The steam generator replacement model represents the complex relationships among technical, economic, and regulatory factors related to tube repair and steam generator replacement. While this model was specifically created for Diablo Canyon, SDG has created similar models for several other clients in the United States that use Westinghouse steam generators. The recommendation has consistently been to replace the steam generators between Fuel Cycles 12 to 16, where a fuel cycle corresponds to 1.5 years of operation followed by a one-month refueling outage. As expected, Diablo Canyon's optimal replacement schedule turned out to be FC 15 and FC 14 for Units 1 and 2 respectively. This decision-focused model is not intended, and should not be used, for operational or budgetary purposes that depend on much shorter time horizons and typically require greater detail. Furthermore, this model is not a detailed cash flow model and is primarily intended to capture incremental costs between different replacement schedules and remedial measures so as to demonstrate the economic benefits of optimal replacement timing.

Each Diablo Canyon Power Plant unit has four operational steam generators, one of which has significantly worse tube degradation than the other three. The worst steam generator will most likely be the cause of a unit's eventual mandatory shutdown if it is not replaced before the overall degradation limit is reached in that steam generator. To accurately reflect the impact of the worst steam generator, SDG modeled it separately. The other three steam generators in the unit were modeled as a collective average. Each of the four steam generators in a unit could be modeled individually, but SDG has found this complicates the model and does not affect any eventual recommendations. To be conservative, whenever the model uses simplifying assumptions about the aggregate, the simplifications are always made to favor "no replacement." Thus, the model assumptions do have a bias in favor of not replacing.

Inputs to the model include strategy alternatives, global financial assumptions, initialization parameters, and uncertain variable range assessment. These inputs are categorized into technical, system, and economic parameters (Figure 1). A strategy consists of a tube repair program, the time or occurrence of the steam generator replacements, the selection of the alternative repair criteria (ARC), etc. Technical inputs include functions that describe how fast the tubes are experiencing defects, and the ultimate output of the technical model is how many tubes need to be either repaired or plugged. Technical inputs were provided by Dominion Engineering, an outside consulting firm. System inputs focus on plant operations and are provided by the nuclear plant operators. The system model produces as its primary output electricity needs for each fuel cycle. Economic inputs are global financials such as the standard PG&E tax rate, discount rate, and inflation rate.

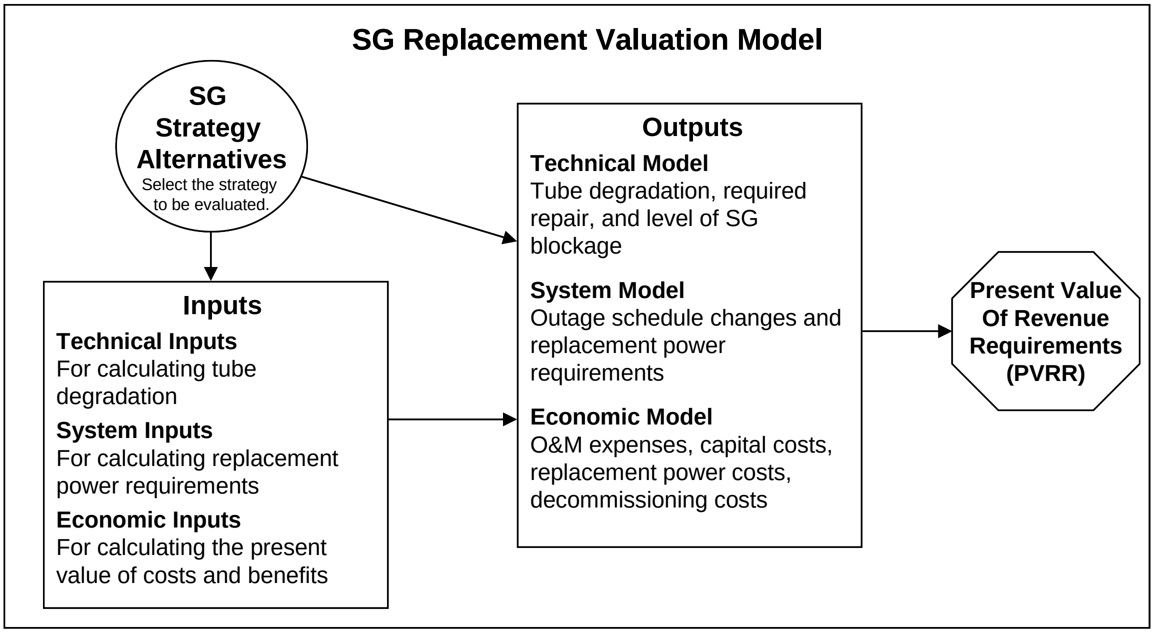

Figure 1: Pacific Gas and Electric Company overall steam generator model structure

The ultimate output of the economic model is the incremental cash flow of costs. Initialization parameters describe the current state of the system, such as number of tubes plugged and the effective length of time in operation. Uncertain variables, more than 100 of which are included in the model, are assessed to describe current judgments about the future of various technical, system, and economic conditions. Low, base, and high estimates for each uncertainty are uniformly defined based on the probability of their occurrence and are the primary inputs for the Monte Carlo simulation. Uniform definition allows for a sensitivity analysis to determine which of the uncertainties have the greatest impact on the selected value measure, which is the present value of the revenue requirements. An influence diagram or value map (Figure 2) captures the interrelationships among the variables, and it was used as a road map to build and discuss the model structure on a high level.

The model forecasts tube degradation and repair over the life of the steam generator. Tube degradation is modeled as a function of temperature (T-hot) and the effective full-power years (EFPY) the steam generator is in service. EFPY is affected by outage length and operational capacity factor.

The costs of tube repair, steam generator replacement, replacement energy required during system outages, and replacement capacity due to derates and steam generator replacement are combined to arrive at an incremental present value of revenue requirements (PVRR), which is directly related to the NPV of incremental costs, another value measure. Other results include system blockage over time and a breakout of the components of PVRR.

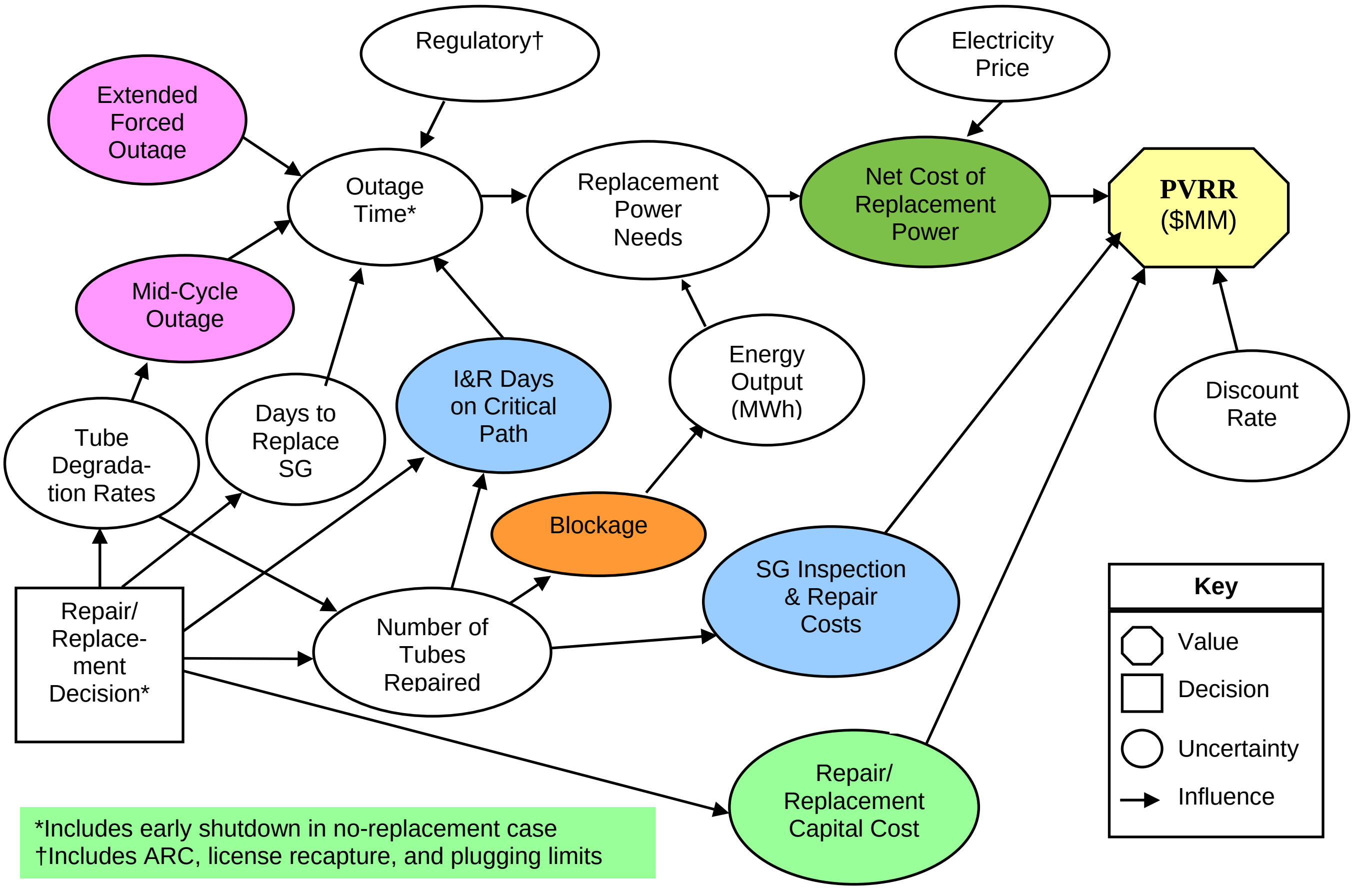

Figure 2: Pacific Gas and Electric Company steam generator model relationships

3 ANALYZING VARIATION

Sensitivity analysis is used to determine the impact of a particular variable on the model results. For example, PVRR is sensitive to tube degradation; that is, running a strategy using low degradation vs. high degradation produces significantly different PVRR results. In addition, the low-cost strategy can be different under different degradation scenarios. Under low degradation the best strategy may be to sleeve all defects and plan to replace further out into the future, whereas under high degradation the optimal strategy may be to plug defects and replace the tube as soon as possible.

Variables whose low vs. high runs produce widely different results and/or optimal strategies are said to be "sensitive" variables. Those variables whose swing from high to low produces insignificant changes in the strategy results are called "insensitive" variables. Since a variable's low and high are 10/90 percentiles, insensitive variables could be those with wide ranges that do not drive PVRR or variables that have an extremely narrow low-to-high range when an input is well understood and has very little inherent variation. This 10/90 low/high approach is very different from the other typical approach, which is to simply assume a +/– percentage from the base case (typically 10 percent).

This +/– approach is very limited, however. First, it does not allow for easy comparison across variables. Further, symmetric distributions rarely occur in economic examples. For example, scenarios exist where cost overruns that are over 100 percent of the base or median case occur, but no scenario can be imagined where an incurred cost would be less than $0. (The only symmetric distribution associated with a business problem that immediately comes to mind is actuarial charts.)

It is sometimes desirable to assess the sensitivity of the model outputs to variations in a large number of variables. Because making the necessary runs individually can be time consuming and confusing, automating the process is advisable whenever possible. Many spreadsheet packages including Crystal Ball have features that enable the user to perform variation analysis automatically and obtain the results in the concise format of a tornado diagram (Figure 3). The impact of all the inputs was tested for the PG&E model using Risk Detective from Rhythm Technologies. We did not use the tornado diagram function from Crystal Ball because our formatting macros for tornados were written for Risk Detective. We now have new macros for Crystal Ball tornado formatting.

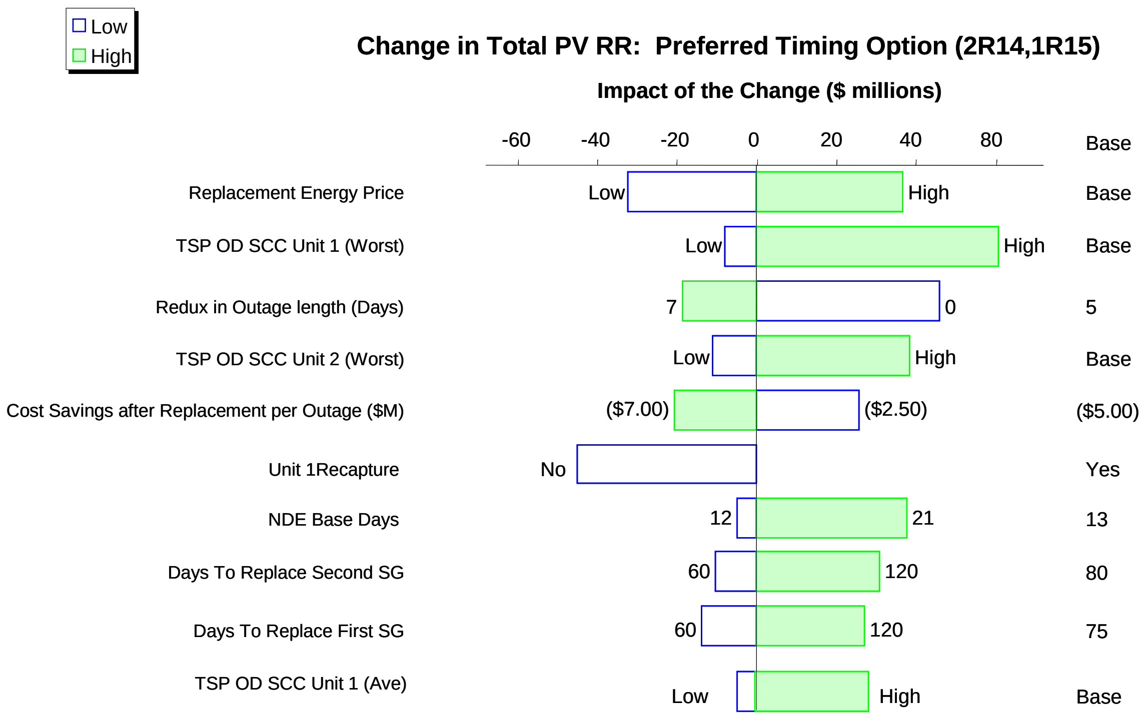

Figure 3: Pacific Gas and Electric Company sample sensitivity output

4 CALCULATING THE EXPECTED VALUE AND THE RANGE OF OUTCOMES

The PVRR output for the median case (where all inputs are set to their base or median values) is roughly $550 M; however, this result is misleading because it does not address the overall risk. As can be seen from Figure 4, the overall risk is skewed toward greater PVRR and thus greater overall ratepayer savings . Fundamentally, most assessed variables are skewed toward higher PVRR.

For example, all the degradation modes have far greater pessimistic than optimistic cases. In fact, having one pessimistic mode while having all the others in their optimistic mode results in an overall scenario that is typically slightly worse than having all the degradation modes in their base case. In part, these asymmetric ranges are a result of the nature of degradation processes (described by the Weibull function for each degradation mode). Weibull functions are exponential in nature, and thus small changes in parameters can result in large net changes in the pessimistic degradation case. On the optimistic side, tube degradation can never be less than zero. Because each steam generator had roughly 10 different ways that a tube could degrade, there were 40 low/base/high assessments that were used to generate these results. In fact, in only 3% of the scenarios do fewer overall tubes need repair than the all base case for degradation.

Likewise, outage times, energy prices, and repair costs have significantly greater potential to raise PVRR. Another asymmetric assumption surrounds unplanned outages. The base case does not contain any “unplanned” outages. However, for each fuel cycle, unplanned outages have a probability of occurring, which is taken into account during the Monte Carlo simulation. As a result, the base case PVRR is significantly understated, and a better measure of overall PVRR is the probability-weighted average or mean case.

To determine the mean value, it is necessary to consider each variable because of the variables’ inherent asymmetrical nature. Because our model contains well over 100 variables, each with a low/base/high input, we used a Monte Carlo simulation rather than the alternative tree-based approach. We selected Crystal Ball for the Monte Carlo simulation because it is the macro for Excel that is used at a majority of businesses performing Monte Carlo simulations. Since each input has only a low/base/high assessment, SDG does not have enough points to determine a continuous distribution for inputs into the simulation. Furthermore, selecting different distributions for different inputs can often bias the results or be used to “game” the overall conclusions. Instead, SDG assumes a discrete probability for the low, base, and high cases of 25 percent, 50 percent, and 25 percent, respectively. This approximation is good for a wide range of distributions. For example, for a normal distribution, integration by parts reveals that a less than 1 percent error is introduced. This discretization approach is part of SDG's standard methodology and has been commonly used in decision analysis since the 1960s.

The standard output from the Monte Carlo simulation is a cumulative probability distribution (Figure 4). The y-axis is the cumulative probability and the x-axis is the PVRR. For a given value of PVRR, the corresponding y-coordinate is the probability the PVRR will be equal to or less than the selected PVRR. The number of trials performed for each Monte Carlo simulation was determined from the mean standard error of the simulation, and each conclusion is at least at the 95 percent level of confidence. In general, we ran enough trials to reduce the mean error to under $10 M.

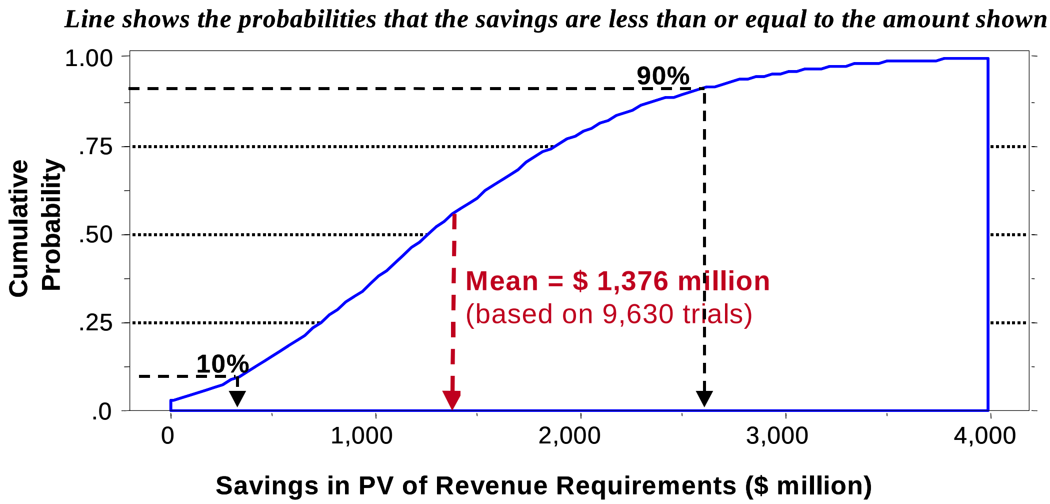

Figure 4: PG&E Cumulative probability distribution for the PVRR of No Replacement vs. Replacement

5 OPTIMIZING THE RESULT

While the case for replacing the steam generators can clearly be demonstrated, the question then becomes what the optimal time is to replace. The first question to ask is when replacement is possible from a regulatory standpoint. This question can be answered by determining what percentage of the cases can make a planned time of replacement without exceeding the NRC-mandated blockage limits. For planning purposes, we felt that in a least 95 percent of the scenarios the planned time of replacement should not exceed NRC blockage limits. As can be seen in Figure 5, the green region is considered the safe zone. Unit 1 and Unit 2 can be replaced anytime through 2010 and 2009, respectively, with little chance of incurring an extended shutdown while waiting for the new steam generators, which have a lead time for ordering of roughly 5 years. In the scenarios where NRC blockage limits were exceeded before replacement, a financial penalty was imposed for having to order the steam generators on a rush basis.

		Replace Unit 1 Year								
Replace Year Unit 2	Replace FC Unit 2	2005 1R 13	2007 1R 14	2009 1R 15	2010 1R 16	2012 1R 17	2014 1R 18	2015 1R 19	2017 1R 20	2019 1R 21
2006	2R 13	100%	100%	100%	97%	64%	47%	29%	14%	5%
2008	2R 14	100%	100%	100%	98%	65%	47%	30%	15%	6%
2009	2R 15	100%	100%	100%	97%	65%	47%	29%	16%	6%
2011	2R 16	82%	82%	82%	80%	53%	39%	26%	13%	4%
2013	2R 17	68%	68%	67%	65%	44%	33%	21%	9%	3%
2014	2R 18	44%	46%	44%	45%	29%	22%	16%	7%	2%
2016	2R 19	20%	19%	20%	19%	13%	9%	6%	3%	1%
2018	2R 20	12%	11%	12%	12%	8%	6%	3%	2%	0.5%
2019	2R 21	9%	10%	10%	10%	6%	5%	3%	1%	0.5%

Figure 5: Pacific Gas and Electric Company probability of reaching a given replacement timing

The next step was to determine the lowest cost timing of replacement (Figure 6). The lowest cost of replacement is defined as zero and occurs for a replacement in 2008 for Unit 2 and 2009 for Unit 1. The blue region in this chart corresponds to replacing the steam generators in consecutive years. In general, replacing steam generators back to back greatly reduces costs because the crews who replaced the first unit will also be replacing the second unit. Costs for the ratepayer increase significantly with further delay because of the inability of the generators to meet the replacement plan, the increasing likelihood of unplanned outages, and decreasing overall steam generator performance.

2100 Trials **UNIT 1 Replacement Timing**

	Year		2009	2010	2012	2014	2015	2017
		FC	15	16	17	18	19	20
	2008	14	0	84	107	129	160	193
UNIT 2	2009	15	13	49	105	124	161	182
Replacement	2011	16	69	61	91	140	177	193
	2013	17	102	117	125	156	204	221
	2014	18	140	162	192	189	236	261
	2016	19	157	180	208	238	260	283
	2018	20	181	202	228	244	287	306

Figure 6: Pacific Gas and Electric Company the increasing cost of delaying SG replacement ($MILLIONS)

6 CONCLUSION

In the case of steam generator replacement, a Monte Carlo approach was clearly appropriate to fully assess the impact of any decision on the ratepayer. Using this approach enabled us to understand the range of results for operational lifetime instead of relying on the base-case assumptions. Only 3 percent of the scenarios had tube degradation scenarios better than the base case and, thus, longer operational lifetimes. Understanding this bias in the degradation results led us to explore earlier replacement timing in order to avoid lengthy unplanned outages that could result.

However, understanding the technical output is just a first step in understanding the overall financial impact. It was also necessary to work with the plant operators to understand how operations would be affected by the aging steam generators. Finally, we had to get input from PG&E corporate to monetize the impact of the degrading steam generator performance. By having a consistent definition for the low/base/high, we were then able to compare assessments made by these several different groups in a rigorous and consistent manner. In addition, by using the expected and *not* the base case to explain the motivations for replacement, we were able to make a much stronger case for early replacement as well as more accurately assess the overall potential benefits and risk exposure to the rate payer.

In contrast to our transparent and consistent low/base/high Monte Carlo approach, the other application for steam generator replacement employed a base case analysis, which required very subjective judgment in their assessments. Their "base" case had to be modified to NOT be their best guess or median numbers but a quasi expected case. This adjustment needed to be made to reflect the asymmetry in tube degradation uncertainty as well as the natural uncertainty in estimating costs. Because these numbers were based upon subjective modification, they have been a source of ongoing contention in the adversarial intervener process.

For PG&E, the preliminary judgment for replacement has been approved, and the final decision is expected in September 2005.

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BIOGRAPHY

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