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Design of Biomass Cookstoves Reliability Demonstration Test Plans

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ABSTRACT: An open fireside is estimated to produce smoke equivalent to that of burning 400 cigarettes per hour. To reduce indoor air pollution from improved cookstoves, manufacturers should demonstrate the reliability of various aspects of their product, including thermal efficiency, cooking power, emissions, safety, and durability. This study investigated the optimal design of a reliability demonstration test (RDT) plan for accepting or rejecting a batch of cookstoves based on a target of no more than 5% failures at the end of the warranty period. The planning parameters for the RDT plan included the number of units to be tested (3, 5, 7), the reliability target of 95%, the confidence level of 95%, the maximum number of allowed failures (0, 1, 2, 3), the statistical power of the reliability test, and the values of the Weibull shape parameter ($\beta_1 = 2.5; \beta_2 = 3.0;$ and $\beta_3 = 3.5$). The required number of samples and testing time for a successful reliability demonstration were determined using Minitab statistical software. The study results show that larger sample sizes or Weibull shape parameters lead to shorter required test times. The statistical power results for eleven scenarios demonstrate that the probability of passing the demonstration test increases as the improvement ratio or shape parameter increases. When the improvement ratio was 1.5 and the shape parameter was 2.5, the probability of passing the test increased from 34% to 54% for a fixed number of maximum allowable failures. Moreover, if the stove's actual performance exceeds the standard that the test was designed to measure, the demonstration test's power for one maximum allowable failure would be equivalent to that for three maximum allowable failures.

KEYWORDS: Demonstration testing, Weibull distribution, Probability of test success, Cookstove.

1 INTRODUCTION

Globally, approximately one-third of the world's population, still use solid fuels, such as wood, crop residues, charcoal, coal, and dung, in open fires and inefficient stoves. This practice generates harmful household air pollution that adversely affects both health and climate [1, 2]. Poorly designed stoves cause incomplete combustion, resulting in elevated levels of carbon monoxide (CO) and harmful particles that can damage the respiratory system. In 2020, household air pollution caused an estimated 3.2 million deaths, including over 237,000 deaths of children under the age of 5 [1]. Recent studies suggest that household fine particulate air pollution may contribute to more than 19% of ambient fine particulate matter ($PM_{2.5}$) in Africa and South Asia, and up to approximately 50% in India [3, 4].

Many attempts have been made to improve cookstove technology in sub-Saharan Africa in order to reduce indoor air pollution, improve women's livelihoods, and reduce biomass (fuel) consumption, thereby reducing deforestation and global warming. Additionally, it aims to alleviate the financial burden of energy costs on low-income people, and improve the health of users [5]. Research into cookstove technology has increased in recent years, resulting in different biomass cookstove designs, operational features and performance levels. Examples include the Top Lit Up Draft stove, the Charcoal Stove (ARC), the Side fed fan and the Sunken Pot Rockets [6, 7]. Standards that define an improved biomass cookstove have also evolved to establish better quality and comparability of data on cookstove air pollutant emissions, efficiency, safety, and durability [8, 9].

The success of a cookstove design is strongly influenced by customer behavior, the sustainability of the energy source, and its performance in standardized tests. In today's highly competitive environment with demanding cookstove standards, manufacturers of improved cookstoves need to assess and control the reliability of different areas of cookstove performance. These areas include thermal efficiency, cooking power, fuel burning rate, carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$) emissions, safety and durability [10,11,12]. It is essential to produce cookstoves at an optimum reliability level to achieve the lowest possible lifecycle costs for the user and minimize costs for the manufacturer, without compromising the reliability and quality of the cookstove.

Improved cookstove reliability refers to the consistent performance of a cookstove in terms of efficiency, CO emissions, $PM_{2.5}$ emissions, and other intended functions over time. This is a crucial requirement for cooks, distributors, retailers, and all stakeholders in the stove industry. Product reliability helps businesses build customer loyalty, brand recognition, and cost control. The RDT is used to determine whether a product meets pre-specified reliability requirements and to decide whether a batch of products should be accepted or rejected. This is crucial because customer dissatisfaction with product reliability can have disastrous financial consequences for the manufacturer [13, 14].

This research was initiated by a company involved in the manufacture of micro-gasifier cookstoves in Cameroon which was faced with the problem of unreliable products being sold to customers. Due to feasibility, time requirements and cost constraints, the manufacturer was unwilling to allow a large sample of products to be tested. Within these constraints, reliability tests were conducted on representative sample of improved stoves from the batch. The purpose of this research was to determine the optimal test sample size to demonstrate the reliability of the cookstoves and to decide whether to accept or reject a batch of cookstoves.

A company involved in the manufacture of micro-gasifier cookstoves in Cameroon initiated this research due to the problem of unreliable products being sold to customers. Due to time requirements and cost constraints, the company was unwilling to allow a large sample of products to be tested. Within these constraints, reliability tests were needed for a representative sample of improved stoves from various batches produced, within these constraints. The aim of this research was to determine the optimal sample size for testing the reliability of cookstoves and deciding whether to accept or reject a batch of cookstoves.

2 Literature Review

2.1 Gazifier Cookstoves

The gasification process is a highly effective method of recovering energy from biomass. It involves producing syngas, which is primarily composed of H2, CO, and CH4 [15]. Micro-gasification stoves are designed to facilitate pyrolysis of the top surface of the biomass fuel, allowing the gas generated from the biomass to move upward. Combustion happens in two zones (see Fig. 1): the pyrolysis zone, where the fuel is heated to produce combustible gases, and the combustion zone, where the pyrolysis gases mix with air and combust to produce heat. The Top-Lit-Up-Draft (TLUD) gasifier is one of the most commonly used gasifiers. Figure 2 shows the principle of the gasifier stove.

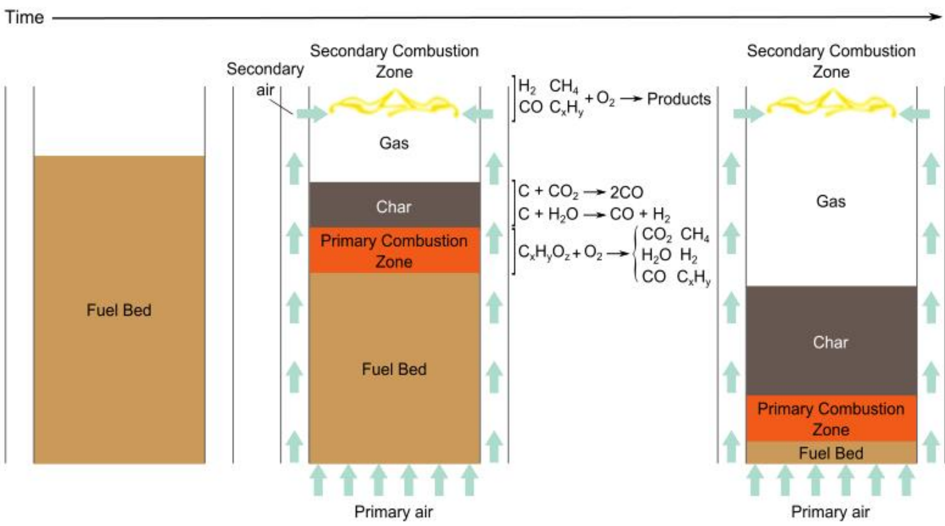

Fig. 1. Schematic of top-lit up draft gasifier cookstove operation [16]

The gasifier stove has several advantages over a conventional ICS. It can burn a wider variety of biomass fuels, such as husks and shells, and has higher efficiency. Additionally, it produces charcoal during the process. Figure 3 displays some of the gasifier stove models that have been developed worldwide in recent years [17].

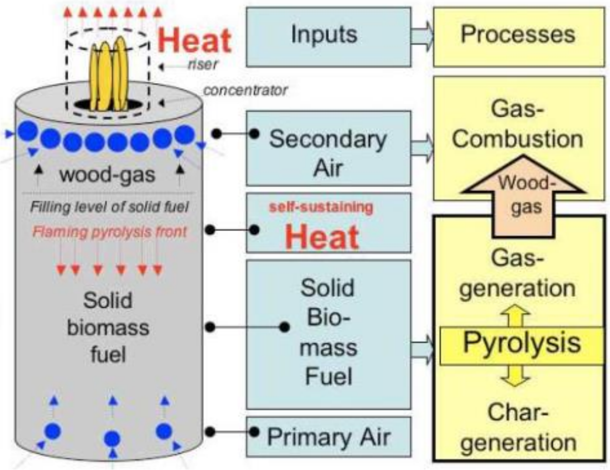

Fig. 2. Basic design of Top-Lit Updraft gasifier stove [18]

Fig. 3. Models of gasifier stoves

2.2 Reliability Demonstration Test Methods

Reliability demonstration test methods can be categorized into non-repairable and repairable system methods based on the failure criterion in product validation testing [19, 20]. Both types of systems have test design methods available that are based on the number of failures and failure time. RDT design methods have been developed mainly for Homogeneous Poisson Processes in repairable systems [20].

Restrictions imposed by limited resources in terms of test sample and/or test equipment commonly limit the quantity of items that can undergo testing. To overcome these limitations, several strategies can be implemented to support the use of small sample sizes for non-repairable systems. These strategies include the test-to-failure method, the test-to-bogey method, the extended life test-bogey method, and the step-stress accelerated life test method [21, 22, 23, and 24].

2.2.1 The Attribute Test Method

The attribute test method, often referred to as the success-failure test or test-to-bogey method is a binomial test method typically used to verify minimum reliability levels for new products prior to production release. In this method, a product is subjected to a minimum durability test or performance criterion or bogey. If a test sample makes it to the bogey, it is a success; if it does not, it is a failure. The Success Run Theorem is a good way to determine sample size when there are no failures. The well-known formula for determining success-testing sample-size is [20]:

$$n = \frac{\ln(1-CL)}{lnR_L} \quad (1)$$

Equation (1) is useful for describing tradeoffs between level of confidence and reliability or for determining sample-size requirements under minimum reliability R_L at specified confidence level CL. Under an exponential distribution assumption, the underlying failure process is typical of constant failure-rate phenomena. If the underlying failure process is Weibull-distributed with shape parameter known, Weibayes Success–Failure Testing Sample Requirement is [22]

$$n = -\frac{\chi^2_{2r+2,1-CL}}{2lnR_L} \quad (2)$$

Where n is the sample size, R_L is the reliability, CL is the confidence level and r is the number of failures, $\chi^2_{2r+2,1-CL}$ is a percentile of a Chi-Square distribution.

The binomial method is a simple test method for demonstrating reliability, but it can be costly because it requires numerous test samples; no test failures are allowed. Most importantly, it does not reveal the product lifetime distribution and failure modes [19].

2.2.2 THE EXTENDED LIFE TEST METHOD

The extended life test method is derived from the Weibull distribution and the success run theorem from the binomial distribution. It assumes that there are no failures in the sample set during testing and that an estimate of the Weibull slope is known [19]. Under extended testing, testing continues for a period, $t_{test} = mt_{target}$; It is not uncommon to have test- to-field ratios (m) or "Bogey Ratio" in the range of 1.25 to 2.0. Our modified extended Success Testing sample-size formula under extended bogey testing, wherein the assumed value for the Weibull shape parameter, β, is [21]:

$$n = -\frac{\chi^2_{2r+2,1-CL}}{2m^{\beta}\ lnR_L} \quad (3)$$

Where m is the ratio of the test duration to the required service life. The extended life test method involves a trade-off between sample size and test time, but like the attribute test method, the extended life test method does not reveal the failure mode and life distribution.

2.2.3 WEIBULL ANALYSIS OF RELIABILITY DATA WITH FEW OR NO FAILURES

The Nelson model [23] is very useful for demonstrating reliability by making trade-offs between sample size, reliability, statistical confidence limits and total test time. The Weibull slope should be known prior to testing and can be estimated from historical data or engineering knowledge; all products to be tested must complete the planned test time without failure in order to successfully demonstrate the reliability/confidence target [19].

2.2.4 MINITAB BASED RELIABILITY TEST PLAN WITH FEW OR NO FAILURES

Methods have been developed in Minitab to design reliability demonstration tests based on both constrained test time and number of failures or constrained sample size and number of failures. Minitab software can be used to calculate the testing time or sample size required to assess the reliability of a new product at a given confidence level, historical reliability standard and with the additional assumption that the shape parameter, β, is known.

3 RESEARCH METHODOLOGY

Minitab statistical software was utilized to develop test plans for the cookstove with the objective of achieving a maximum 5% failure rate within the one-year warranty period. The company has conducted previous studies on similar non-repairable cookstoves, and believes that the underlying failure process is Weibull distributed with a shape parameter close to 3. The planning parameters of the RDT plan were as follows: Number of units to be tested, Reliability target = 95%, Confidence Level = 95%, Maximum number of failures allowed, Statistical power of reliability test = 80%. Figure 4 shows the flowchart of the reliability test plan.

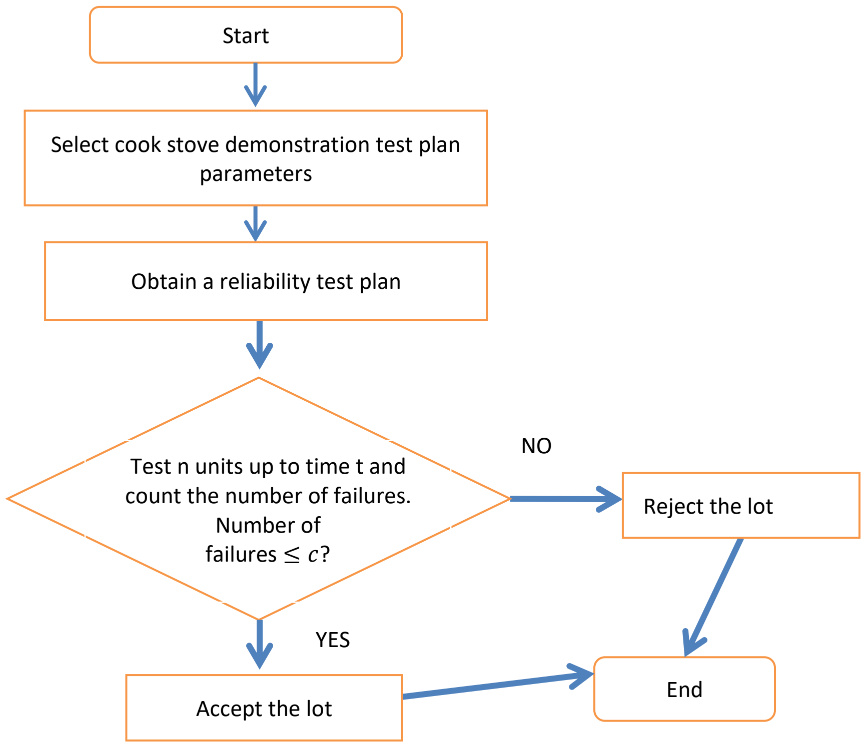

Fig. 4. Flowchart of reliability demonstration test plan

Because of the relatively high level of uncertainty in the knowledge of the shape parameter, the test plans were analyzed considering three values of the shape parameter, i.e. a most conservative value $\beta = 2.5$, and the historical shape parameter of $\beta = 3.0$ and $\beta = 3.5$, in order to determine appropriate sample size requirements. Table 1 displays the reliability testing plan for eleven scenarios considered in this study.

Table 1. Weibull reliability demonstration test plans

Demonstration Test plans	Number of Units tested	Number of failures
A	3	0
B	5	0
C	7	0
D	3	1
E	5	1
F	7	1
G	3	2
H	5	2
I	7	2
K	5	3
L	7	3

4 Research Outcomes

Table 2 displays the test duration results for various demonstration test plans after conducting analysis in Minitab software. Furthermore, an analysis was conducted to determine the potential impact of uncertainties in estimating the shape parameter β on the test duration and the necessary number of test specimens.

4.1 Required Test Duration For Various Scenarios

It is interesting to note from the results of the test duration for different scenarios shown in Fig.5 that for a fixed number of maximum allowable failures, the required test time decreases as the sample size increases. Similarly, for a fixed number of maximum allowable failures, the sample size decreases as the shape parameter increases. In other words, the larger the sample size or the shape parameter is, the shorter the required test time. For example, the test time decreases from 6217 hours to 4156 hours, as the sample size increases from 3 units tested to 7 units tested for $\beta_1 = 2.5$.

Tableau 1. Weibull reliability demonstration test plans

Demonstration test plans	Number of units tested	Number of failures	Test duration (hours)		
			$\beta_1 = 2.5$	$\beta_2 = 3$	$\beta_3 = 3.5$
A	3	0	3541.21	2905.34	2522.33
B	5	0	2886.77	2450.46	2179.80
C	7	0	2523.26	2190.48	1980.00
D	3	1	4675.22	3662.17	3075.95
E	5	1	3642.09	2974.15	2573.44
F	7	1	3133.41	2623.72	2311.25
G	3	2	6216.56	4643.68	3770.26
H	5	2	4344.4	3444.92	2918.86
I	7	2	3647.37	2977.74	2576.11
K	5	3	5169.6	3982.15	3304.93
L	7	3	4156.24	3320.12	2827.99

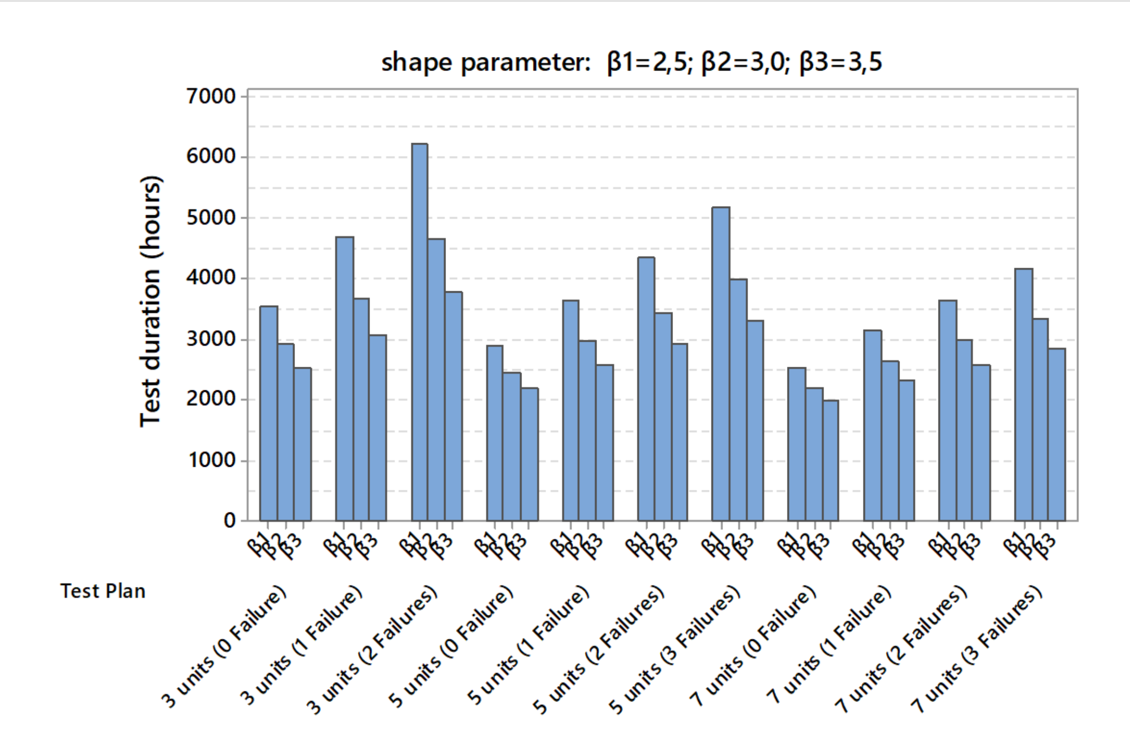

Fig. 5. Required test duration for scenarios demonstration test plans

It is interesting to note from these results that for a fixed sample size, as the maximum allowable number of failures increases, the required test time also increases as well. In other words, to accommodate for more (potential) failures, the technician has to test the cookstoves for a longer period of time. For example, the test time increases from 1980 hours to 2828 hours, as the maximum number of failures allowed increases from 0 failures to 3 failures for 7 units tested with for $\beta_3 = 3.5$.

4.2 Probability Of Passing Demonstration Test

A comparison of the power of the demonstration test of the test plans for 0 maximum allowable failure and 1, 2 and 3 maximum allowable failures for 3 units tested, 5 units tested and 7 units tested. The power gives us an indication of how reliable the test is [25]. For the ratio of improvement of 1.50 and 2.0 for shape parameter values of $\beta_1 = 2.5$; $\beta_2 = 3.0$; and $\beta_3 = 3.5$ the percentages (y axis), representing the power of the demonstration test are shown in Figs. 6, 7, 8, 9, 10, 11.

Figures 6, 7, and Table 3 summarize the comparison of the power of the tests for 0 maximum allowable failure and 1, 2 maximum allowable failures for 3 units tested.

Tableau 2. ***Exemplary comparison of the impact of uncertain distribution parameters on the success probability for 3 units tested***

Shape parameter β	2.5						3.0						3.5					
Maximum Failures	0		1		2		0		1		2		0		1		2	
Ratio of Improvement	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2
Power	33.7	58.9	47.6	78.7	53.9	86.4	41.2	68.8	57.9	87.5	65.5	93.6	48.4	76.7	67.1	93.0	75.3	97.2

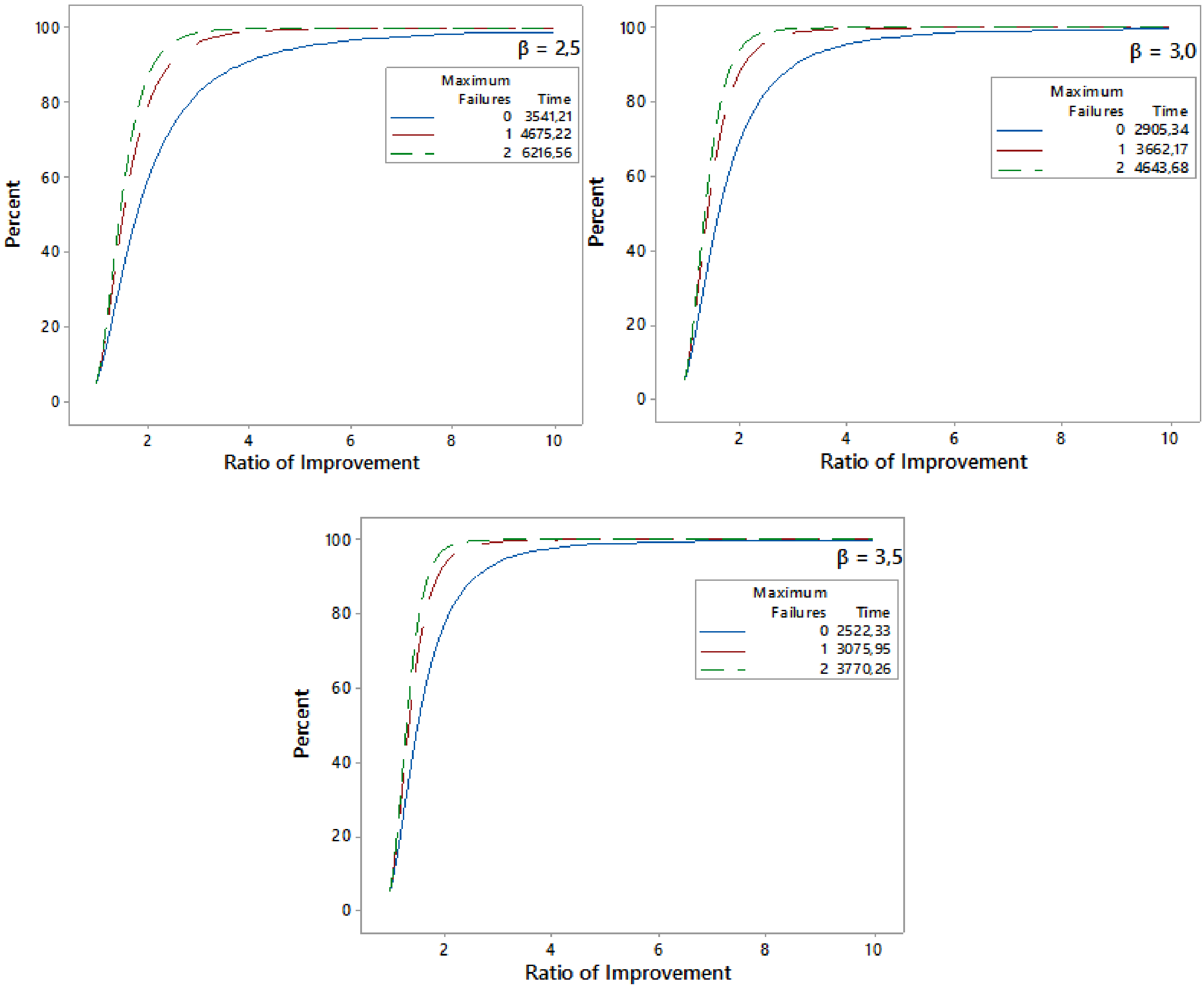

Fig. 6. ***Probability of passing the demonstration test for 3 units tested, respectively for $\beta_1 = 2.5$, $\beta_1 = 3$ and $\beta_1 = 3.5$***

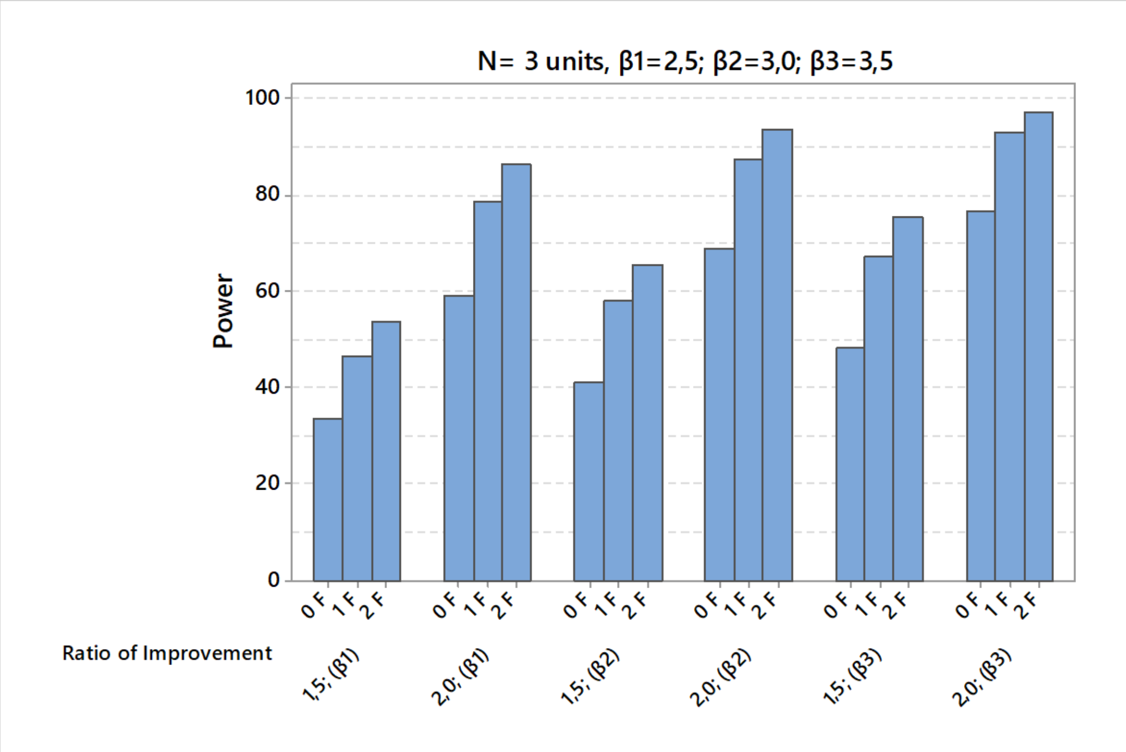

Fig. 7. Probability of passing the demonstration test for 3 units tested for selected levels of improvement

The values in Table 3 are taken from Fig. 6 for selected improvement ratios, while Fig. 7 is a graphical summary of Table 3. It is interesting to note from the power results for different scenarios shown in Fig.7 that for a fixed number of maximum allowable failures and shape parameter β, the power of the test increases as the improvement ratio increases. Similarly, for a fixed number of maximum allowable failures, the power of the test increases as the shape parameter increases. For example, for an improvement ratio of 1.5 and shape parameter β_1 (see Table 3), the power of the test is approximately 34% for 0 maximum allowable failures and approximately 54% for 2 maximum allowable failures.

Figures 8, 9 and Table 4 summarize the comparison of the power of the tests for 0 maximum allowable failure and 1, 2, 3 maximum allowable failures for 5 units tested.

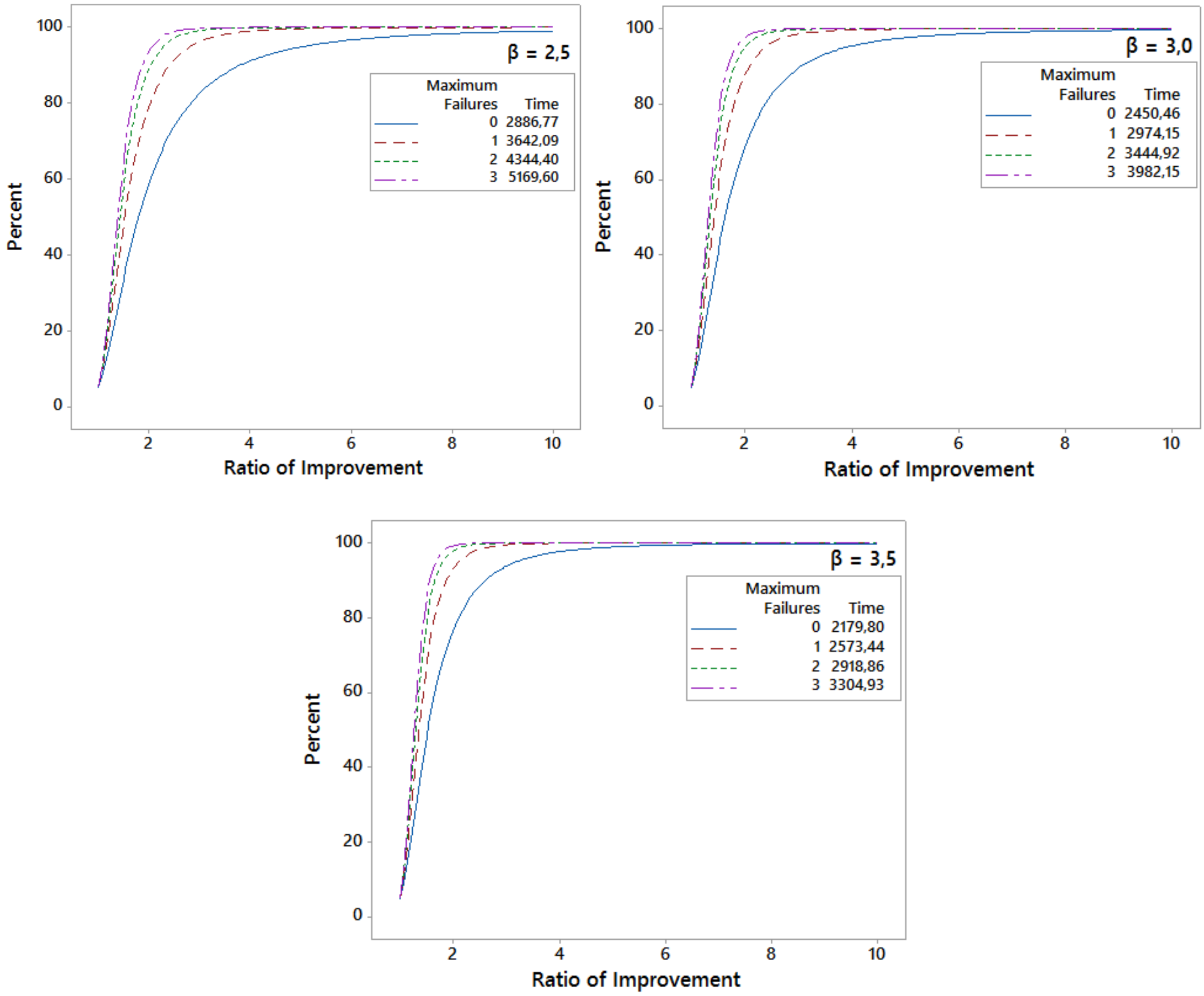

Fig. 8. Probability of passing the demonstration test for 5 units tested, respectively for $\beta_1 = 2.5$, $\beta_1 = 3$ and $\beta_1 = 3.5$

Figures 10, 11 and Table 5 summarize the comparison of test power for 0 maximum allowable failure and 1, 2, 3 maximum allowable failures for 7 units tested. Figure 9 is a graphical summary of Table 4; similarly, Fig. 11 is a graphical summary of Table 5.

For the improvement ratio of 1.5 ($\beta_1 = 2.5$), (see Table 3), the power of the test, for 2 and 3 maximum allowable failures is approximately 59% and 68% respectively. It is interesting to note from the power results for the different scenarios shown in Fig.7 and Fig. 11 that for a fixed number of maximum allowable failures and shape parameter β, the power of the test increases as the improvement ratio increases. Similarly, for a fixed number of maximum allowable failures, the power of the test increases as the shape parameter increases.

Tableau 3. ***Exemplary comparison of the impact of uncertain distribution parameters on the probability of success for 5 units tested***

Shape parameter β	**2.5**						**3.0**						**3.5**					
Sample size	5						5						5					
Maximum Failures	0		1		2 ; 3		0		1		2 ; 3		0		1		2 ; 3	
Ratio of Improvement	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2
Power	33.7	58.9	43.3	79.2	58.7 65.1	89.1 93.7	41.2	68.8	58.7	87.9	70.1 76.8	95.1 97.8	48.4	76.7	67.9	93.2	79.3 85.5	97.9 93.2

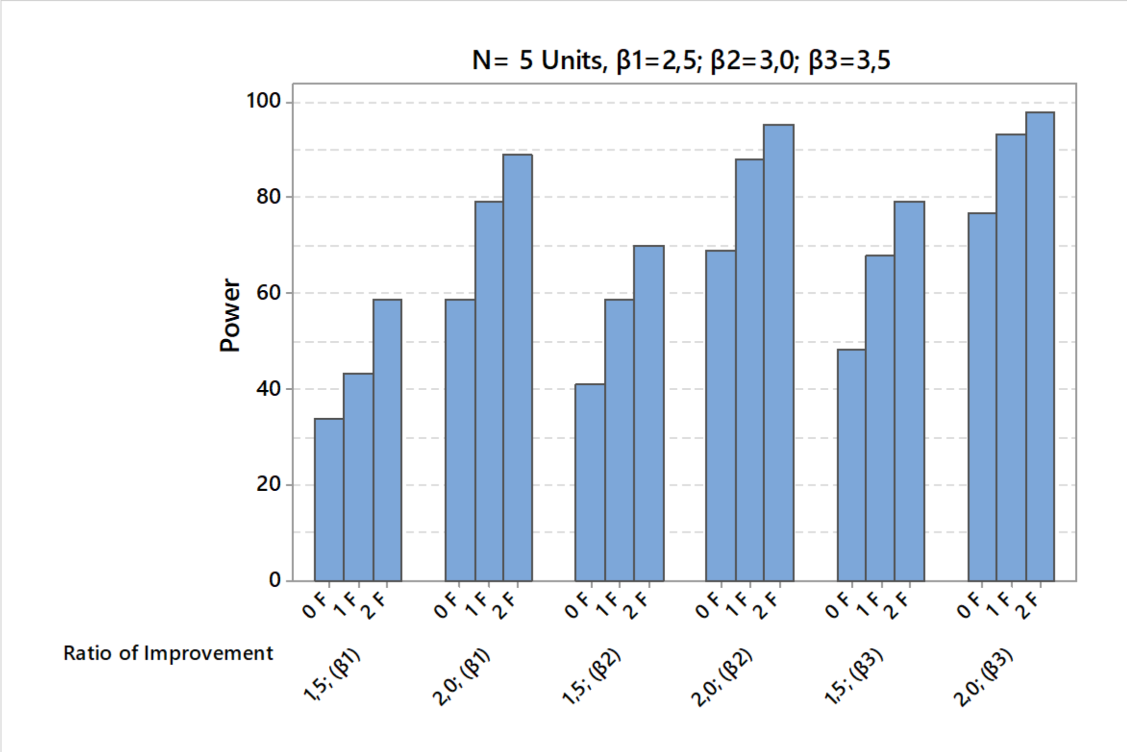

Fig. 9. ***Probability of passing the demonstration test for 5 units tested for selected levels of improvement***

In other words, in terms of the probability of passing the demonstration test, the test with the maximum number of failures allowed is more reliable than the test with the minimum number of failures allowed, although the former is also more expensive. Furthermore, the maximum number of failures allowed becomes less relevant as the ratio of improvement increases, see, Figs 6, 8, and 10. For example, if the true performance of the stove is much higher than the standard that the test is intended to demonstrate, the power of the demonstration test with 0 maximum allowable failures is the same as with 3 maximum allowable failures.

Tableau 4. ***Exemplary comparison of the effects of uncertain distribution parameters on the probability of success for 7 units tested***

Shape parameter β	**2.5**						**3.0**						**3.5**					
Sample size	7						7						7					
Maximum Failures	0		1		2 ; 3		0		1		2 ; 3		0		1		2 ; 3	
Ratio of Improvement	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	2
Power	33.7	58.9	48.5	79.4	59.4 67.5	89.5 94.5	41.2	68.8	58.8	88.0	70.8 78.9	95.3 98.1	48.4	76.7	68.0	93.3	79.9 87.0	98.0 99.4

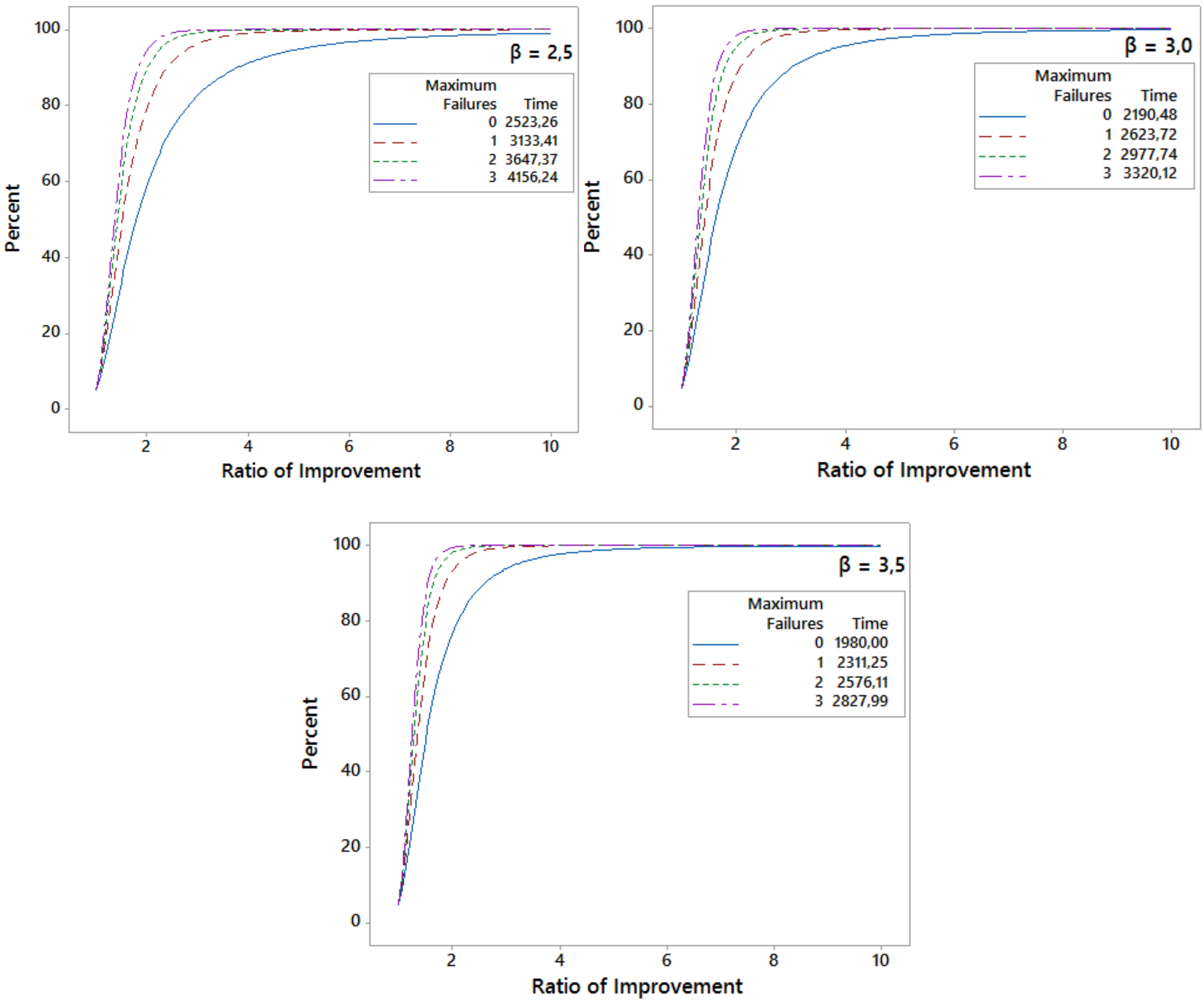

Fig. 10. Probability of passing the demonstration test for 7 units tested, for $\beta_1 = 2.5$, $\beta_1 = 3$ and $\beta_1 = 3.5$ respectively

For 0 maximum allowed failures, the power is about 41.2% ($\beta_2 = 3.0$) and for 2 maximum allowed failures, the power is about 65.5% ($\beta_2 = 3.0$). In other words, the test with 2 maximum allowed failures is more reliable than the test with 0 maximum allowed failures; the former is also more expensive.

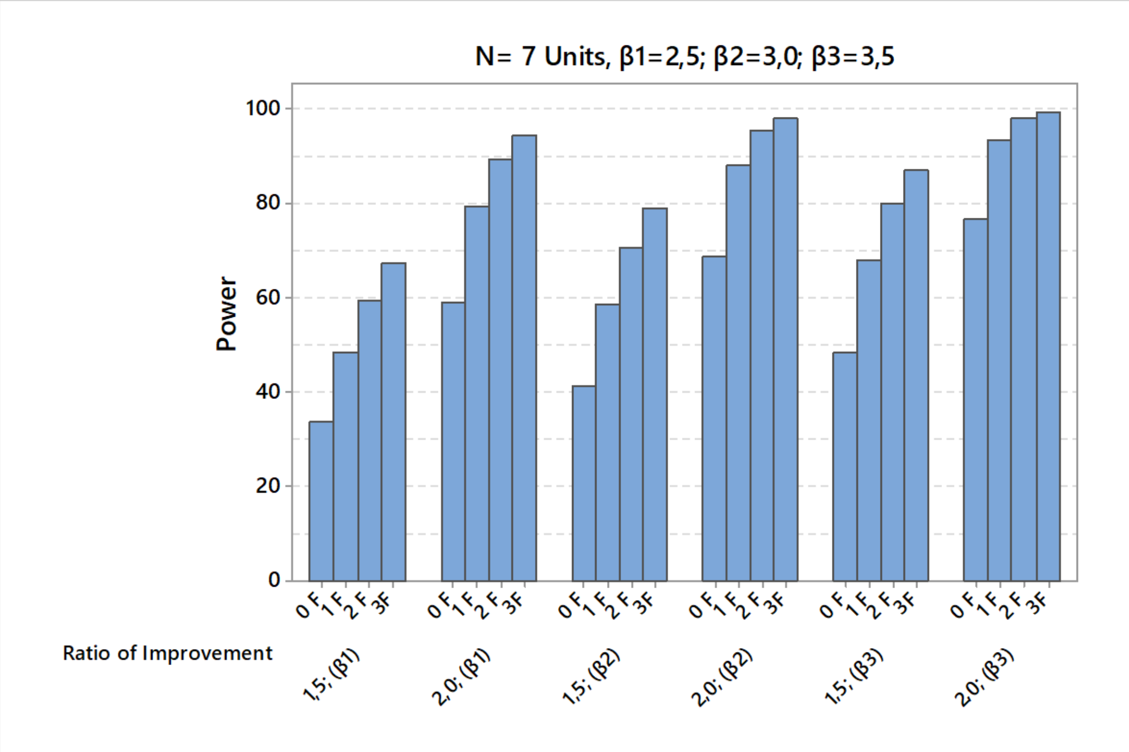

Fig. 11. Probability of passing the demonstration test for 7 units tested and selected levels of improvement

5 Conclusion And Recommendations

As part of the reliability demonstration test plans for cookstoves, we investigated 11 sampling plans using Minitab, to determine the required test durations for different scenarios when the test sample size and the number of failures are constrained. Our analysis revealed that larger sample sizes or shape parameters result in shorter required test times, based on the assumed Weibull shape parameter. The conclusions drawn from the results of the reliability demonstration test may not be very robust if the actual performance of the cookstove is close to the standard. This may lead to a risky product release with the potential for poor product performance in the field. To minimize this risk, appropriate measures, such as an adequate sample size, should be taken. However, if the true performance of the stove is much higher than the standard that the test is intended to demonstrate, then the power of the demonstration test for one maximum allowable failure is the same as that for three maximum allowable failures, because the probability of passing the 0-failure increases steadily as the improvement ratio increases from zero to six. This study identifies an area where Reliability Demonstration Testing can promote a successful product launches by smaller companies and start-ups.

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