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Use of Probabilistic Engineering Methods in the Detailed Design and Development Phases of the NASA Ares Launch Vehicle

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ABSTRACT

The United States National Aeronautics and Space Administration (NASA) is in the midst of a space exploration program called Constellation to send crew and cargo to the international Space Station, to the moon, and beyond. As part of the Constellation program, a new launch vehicle, Ares I, is being developed by NASA Marshall Space Flight Center. Designing a launch vehicle with high reliability and increased safety requires a significant effort in understanding design variability and design uncertainty at the various levels of the design (system, element, subsystem, component, etc.) and throughout the various design phases (conceptual, preliminary design, etc.).

In a previous paper [1] we discussed a probabilistic functional failure analysis approach intended mainly to support system requirements definition, system design, and element design during the early design phases. This paper provides an overview of the application of probabilistic engineering methods to support the detailed subsystem/component design and development as part of the "Design for Reliability and Safety" approach for the new Ares I Launch Vehicle.

Specifically, the paper discusses probabilistic engineering design analysis cases that had major impact on the design and manufacturing of the Space Shuttle hardware. The cases represent important lessons learned from the Space Shuttle Program and clearly demonstrate the significance of probabilistic engineering analysis in better understanding design deficiencies and identifying potential design improvement for Ares I. The paper also discusses the probabilistic functional failure analysis approach applied during the early design phases of Ares I and the forward plans for probabilistic design analysis in the detailed design and development phases.

1.0 BACKGROUND

This section provides some background on the new NASA launch vehicles, and an overview of some of NASA applications of probabilistic methods since the Challenger accident.

1.1 New NASA Launch Vehicles

The new NASA launch vehicles, the Ares I and Ares V, are shown in Fig. 1 in comparison with the heritage vehicles, the Saturn V and the Space Shuttle. The arrows between the vehicles in the graphic indicate hardware commonality.

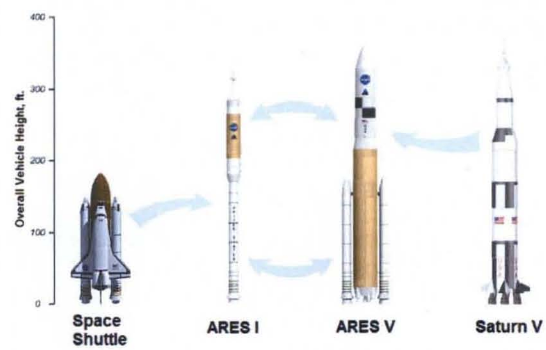

Figure 1. Ares I and Ares V Launch Vehicles in Comparison to Heritage Launch Vehicles

The Ares I launch vehicle, being developed by NASA's Marshall Space Flight Center (MSFC), consists of three major elements as shown in Fig. 2: A solid First Stage (FS), an Upper Stage (US), and an Upper Stage Engine (USE). Its payload will be a crew exploration vehicle, called Orion, which is being developed by the NASA Johnson Space Center (JSC). Orion consists of a crew exploration module, a service module, a spacecraft adapter, and a launch abort system (LAS).

The intended purpose of the Ares I is to safely deliver crew and cargo to a specified ascent target. This capability will support two separate missions: to carry the payloads to the International Space Station (ISS); and to deliver crew to orbit for rendezvous with elements of Ares V and lunar modules for lunar missions. Primary objectives of the Ares I design are to significantly increase safety and reliability and reduce the cost of accessing space.

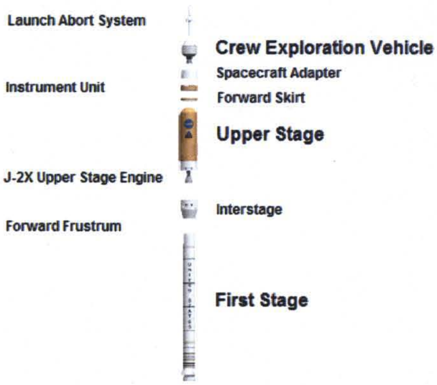

Figure 2. Ares I Expanded View

The Ares V, also being developed by MSFC, consists of the following as shown in Fig. 3: a liquid Core Stage with 6 RS-68 engines augmented by 2 five-and-one-half segment Solid Rocket Boosters (SRB); an Interstage; an Earth Departure Stage (EDS) with a single J-2X liquid rocket engine; and a large Shroud.

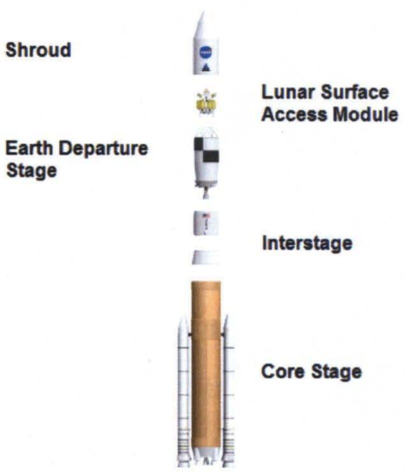

Figure 3. Ares V Expanded View

The intended purpose of the Ares V is to deliver a lunar module to earth orbit with the EDS then performing a trans-lunar injection of the module for lunar missions. The Ares V will also deliver cargo to orbit and potentially deliver a single-launch solution to the Moon with combined CEV and lunar lander payloads.

Before getting into the discussion of the subject of this paper, it is important to note that the Constellation Program has in place ambitious quantitative requirements for Loss of Mission (LOM) and Loss of Crew (LOC). The LOM and LOC requirements (or equivalents) have been allocated to the Ares I and its major elements, the FS, the US, and the USE. Satisfying these requirements will constitute an ambitious goal that has forced a paradigm shift at NASA. This has set the stage for establishing a working environment that integrates various disciplines (safety, reliability, design, etc.) and various organizations (engineering design organizations, project office, and safety and mission assurance organization) more effectively to support the design process. Within this integrated environment, this paradigm shift has also set the stage for a new era at NASA in applying a sound probabilistic design approach to analyze, understand, and influence the design up front and throughout the different phases of the design. This paper discusses the application of probabilistic engineering methods that have been used to support the early phases of design and will be used to support the detailed subsystem/component design and development as part of the "Design for Reliability and Safety" approach for the new Ares I Launch Vehicle.

1.2 Overview of NASA Applications of Probabilistic Methods

After the Space Shuttle Challenger accident in 1986, NASA began incorporating quantitative risk assessments (QRA) in decisions concerning the Space Shuttle and other NASA projects. For example, QRA has been extensively used in areas such as risk management of flight hardware, trade studies, and reliability prediction of new hardware. In the risk management area, life limits based on QRA are being used in the Space Shuttle Main Engine (SSME) program [2]. Some of these cases are partially or fully discussed in this paper.

At the system level, NASA Headquarters has led several studies to predict the overall Space Shuttle risk. The first of these Space Shuttle QRA studies was conducted in 1988 by Planning Research Corporation [3]. In 1995, Science Applications International Corporation (SAIC) conducted a comprehensive QRA study [4]. In July 1996, NASA conducted a two year study (October 1996 - September 1998) to develop a model that provided the overall Space

Shuttle risk and estimates of risk changes due to proposed Space Shuttle upgrades [5].

After the Columbia accident, NASA conducted a QRA on External Tank (ET) foam. This study was the most focused and most extensive risk assessment that NASA has conducted in recent years. It used a dynamic, physics-based, integrated system analysis approach to understand the integrated system risk due to ET foam loss in flight [6]. Most recently, a probabilistic risk assessment (PRA) for Ares I has been performed in support of the Constellation program.

In the following sections we discuss some of the Space Shuttle applications in probabilistic engineering design analysis and the current and potential future application of probabilistic engineering design analysis for Ares I vehicle

2.0 THE NEED FOR PROBABILISTIC ENGINEERING DESIGN ANALYSIS – DETERMINISTIC VERSUS PROBABILISTIC DESIGN

To determine the factor of safety for a design, the designer traditionally assumes a single value for stress that is equal to some maximum or nominal value S_o, depending on how the individual defines the factor of safety for a particular application. Similarly, the strength is assumed to be deterministic and equal to some nominal or minimum value R_o. As shown in Fig. 4, if nominal values are used we can end with two different designs that have the same factor of safety but different reliabilities. This illustrates why a probabilistic engineering design analysis approach is recommended in support the conventional deterministic approach to account for the uncertainty in the design parameters [7,8].

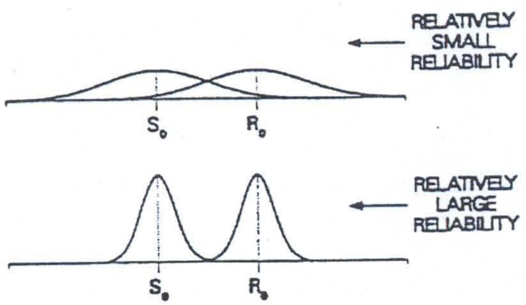

Figure 4. Situation Where Factors of Safety are the Same but Reliabilities are Different

Probabilistic engineering design analysis can be applied at the various phases of the design as long as information is available on the strength or capability (materials properties, etc.) and stress or demand (loads, environments, etc.) parameters. Generally this would be during the preliminary design (PD) phase forward. For instance, during the subsystem and component design and development, probabilistic design analysis can be used to assist the designer in making decisions on the best material or on the best balanced design with respect to several design criteria. At the hardware certification stage, probabilistic design can be used to determine if a component meets its life requirements. Finally, probabilistic design can be used to manage the risk of a product or system put into service. In this paper, probabilistic design will be discussed for the situation in which it is felt to have the greatest potential for a large influence on the design, namely in the detailed design and development phases.

In the probabilistic engineering design approach during design and development, each parameter controlling design life can be defined and treated as a random variable. These life-controlling parameters are uncertain for two reasons. First, it is known that there will be some amount of variability regardless of how well the parameter is known. Secondly, it is not known at this phase how well the engineering analyses and models being used will correlate with the actual component parameters. Both of these uncertainties contribute to variability. This would mandate the use of engineering safety factors in traditional deterministic design. Probabilistic design analysis permits the assessment of the actual distributions of these life-controlling factors and of the interactions with each other, thus providing an evaluation of component risk.

For example, if it were desired to calculate the low cycle fatigue (LCF) life of a specific feature of an impeller rotor, it would be a function of rotor geometry and material properties (e.g., density, modulus of elasticity, and coefficient of thermal expansion) and the cyclic stress from rotor speed and other loads. In simplistic terms, it is necessary to assign distributions to each of these basic life drivers, (e.g., modulus of elasticity, coefficient of thermal expansion, rotor speed), have a set of equations to map these basic life drivers into the high level life-controlling parameters (e.g., crack growth rate), transform the high level life controlling parameters into an LCF life via a failure model, and then iterate through these steps several times until a distribution of lifetimes is constructed.

To describe the probabilistic design approach, a generalized probabilistic design analysis model structure is shown in

Fig. 5. Although no two probabilistic models are identical, all of them contain similar elements of Fig. 5.

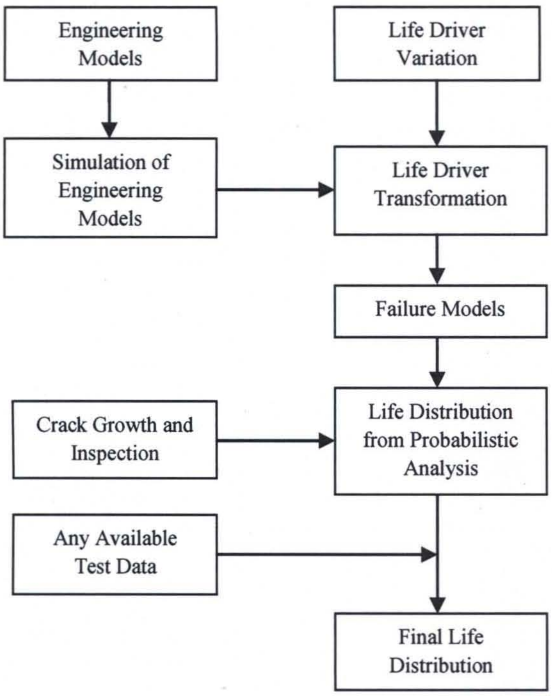

Figure 5. Generalized Probabilistic Design Analysis Model Structure

As indicated by the life driver variation element, all important parameters which affect life are assigned a range or distribution of realistic values rather than some "worst case" value. Note that several different probability/ statistical distributions exist, such as Weibull, normal, lognormal, beta, uniform, etc., for describing the pattern of variation of life drivers.

3.0 THE SPACE SHUTTLE APPLICATIONS

Right after the *Challenger* accident an extensive probabilistic engineering analysis methodology development was conducted by the NASA Jet Propulsion Laboratory (JPL). This included several applications to Space Shuttle hardware [9]. Since then a large number of probabilistic engineering design analysis cases have been performed within NASA in support of the decision-making process for the Space Shuttle program. A few examples will follow.

In 1987 an extensive probabilistic engineering analysis effort was conducted to evaluate the reliability of the turbine wheels for the auxiliary power units (APU) of the Space Shuttle SRBs [10]. In 1994 NASA conducted a probabilistic study on the potential removal of External Tank weld inspections [11]. In 1998 the reliability of a critical weld of the Space Shuttle SRB aft skirt was analyzed using the probabilistic analysis software known as NESSUS [12]. Also in 1998, as part of SSME upgrades introduced after the engine was put in service, NASA and Rocketdyne developed probabilistic engineering models to evaluate the reliability of several failure modes for the channel wall nozzle option. Between 1998 and 2000, as part of their support to the Space Shuttle risk assessment, Pratt &Whitney developed probabilistic models for about 30 failure modes for the SSME turbo-pumps [13]. Many other application of probabilistic engineering analysis at NASA can be found in [14].

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3.1 The SSME Alternate Turbopumps (ATD) Case

In this section we discuss an application of probabilistic engineering modeling and analysis during the design and development of the SSME ATD. This example application addresses the fracture failure mode of the inner race on the roller bearing of the Pratt & Whitney High Pressure Fuel Turbopump (HPFTP). The inner race fracture location is shown in Fig. 6.

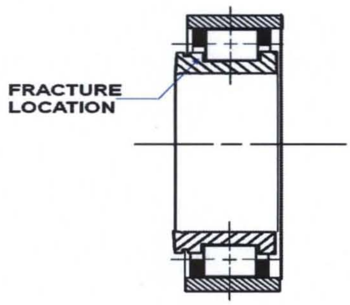

Figure 6. Roller Bearing Inner Race Fracture Location

The analysis intent was to estimate the probability of fracture due to the hoop stress exceeding the material strength. A Monte Carlo simulation model of the failure logic was developed with probabilistic models applied to the stress contributors and material capability, expressed as allowable loads. Fig. 7 illustrates the model.

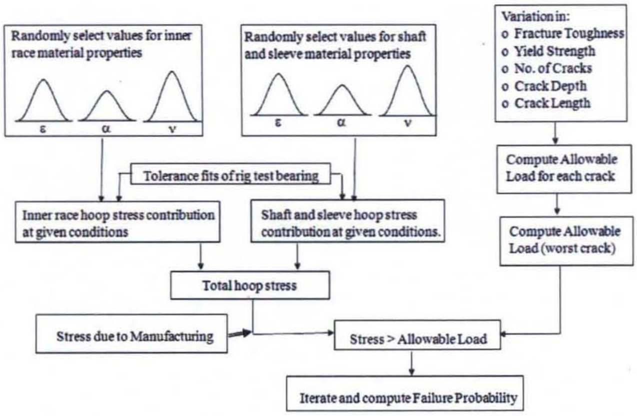

Figure 7. HPFTP Roller Bearing Inner Race Probability Model

In order to calculate the hoop stress it was necessary to determine materials properties variability. Of those materials properties that affected the total inner race hoop stress such as, for example, the modulus of elasticity and the coefficient of thermal expansion, a series of equations was derived which mapped these life drivers into the total inner race hoop stress. Similarly, a distribution on the materials capability was derived. In this case, life drivers such as fracture toughness, crack depth and length, yield strength, among others, were important. The resulting materials strength distribution was then obtained through a series of similar equations.

A Monte Carlo simulation was then used to calculate a random hoop stress and random materials strength. If the stress exceeded the strength in the simulation, a failure was assigned to the run. Otherwise, a success was recorded. After a large number of simulation runs was conducted, a failure distribution was established for the inner race.

To summarize, engineering information with statistical models can be used to probabilistically characterize design parameters and determine design reliability. The probabilistic models can be used for both prediction as well as performing sensitivity analyses to identify design improvements. In fact, the analysis detailed above led to uncovering a major material capability problem for the turbo pump bearing cage caused by induced manufacturing stresses. The material could not withstand the predicted flight loads which resulted in a crack in the bearing cage. A material with different properties was used which reduced the probability of a crack to near zero and significantly improved the reliability of the turbo pump bearing cage.

4.0 THE ARES I APPLICATIONS

In this section we provide an overview of Ares I probabilistic engineering design applications during the system design phase and discuss the current and forward plans for the detailed design and development phases

4.1 The Ares I Probabilistic Analysis during Early Design Phases

The following is an overview of the probabilistic functional failure analysis (PFFA) approach that was adopted by the Ares I project during initial design in preparation for the preliminary design phase.

The PFFA approach is a dynamic top-down scenario-based approach intended to identify, model, and understand high system risk drivers for the purpose of influencing both system design and system requirements. This approach is implemented upfront during the initial system design phase preceding the preliminary design review (PDR). The focus of the Ares I PFFA was on energetic or dynamic events and significant changes of state for the launch vehicle that could lead to LOM or LOC.

The first step in the PFFA was to define the mission timeline of system level functions. The applicable Ares I mission timeline includes the pre-launch and ascent phases. The system level functions during the phases include fuel load, crew load, pre-start, launch, staging (FS separation and USE start), LAS jettison, main engine cutoff (MECO), and orbit insertion with Orion separation from the Upper Stage.

Given the mission timeline of system level functions, the next step in the PFFA was to identify for each system level function the lower-level functions to a selected level of indenture. These lower-level functions were then transformed into a failure structure by restating each as functional failure or failure event. Next, the functional failures are analyzed for their effects on the applicable physical design. The resulting failure effects, labeled as hazards or undesired conditions, were grouped by commonality of their effect on an element or the launch vehicle. These groupings were labeled as failure bins which are listed for further analysis.

Given the list of failure bins, the next step in the PFFA was to determine the "bounding" failure scenario for each bin. The "bounding" failure scenario is selected based on the frequency of occurrence, the impact on system risk, and the potential for design improvement.

Given the "bounding" failure scenarios, a short list (a handful of scenarios) was established, based on project priorities, for further in-depth focused analysis. Specifically, the items on the short list were subjected to in-depth physics based dynamic simulation modeling to understand the physics of failure, the probability of launch vehicle failure or break up, and the launch abort system capability to save the crew [1].

4.2 The Ares I Current and Forward Plans for the Detailed Design and Development Phases

During the early design phase through the system PDR, several mission events or issues were identified and pursued for in-depth analysis. Examples of these critical areas/issues are first stage separation and the system thrust oscillation. In the separation study an integrated probabilistic analysis was performed which supported the design solution. In the thrust oscillation case probabilistic analysis was used to evaluate the risk of the various viable design solutions from which one was chosen. Both areas were addressed by the time of the system PDR.

Because of the extensive heritage hardware used in the Ares I vehicle, the Ares I elements (FS, USE, and US) had completed their PDR and were starting their critical design review (CDR) while the system design and system PDR was underway. As a result, concurrent with the PFFA and integrated probabilistic design analysis, an extensive probabilistic design analysis (PDA) effort has been performed at the component level. Examples include US tank buckling, US tank weld structural failure, USE gas generator fuel valve failure, fire/explosion due to fuel and oxidizer leaks within the interstage (part of the US), and USE oxidizer turbopump (OTP) and fuel turbopump (FTP) inducer high-cycle fatigue (HCF). Because of export control restrictions details of the cases listed above cannot be released at this time.

With regard to future work, a tremendous amount of PDA is planned for the detailed and development phases. The J-2X PDA activity is a good example of how NASA has been applying and will continue applying PDA to support design decisions during the detailed and development phases.

The J-2X program applies PDA as part of their physics-based reliability modeling to a selective set of J-2X failure modes. The complexity of their detailed PDA can range from a full scale probabilistic design model that addresses all critical engineering random variables through computer simulations to probabilistic accumulation of the fatigue life damage fraction that correlates to the mission failure probability, or to a simple stress-strength interference failure probability calculation. The analysis ties the prediction to the engine operating parameters, such as temperature, pressure, speed, dynamic loads, and correlates the prediction data with future engine development test data for reliability model anchoring. The J-2X program screening criterion for identifying the PDA candidate items includes the following:

1) High failure probability and consequence;
2) Failure history in similar parts;
3) Uncertainty in material properties, loads, environment and manufacturing;
4) New designs or risk items tracked by program or IPTs.

Based on the screening criterion, a short list of candidates for probabilistic design analysis is established as forward work to support the design process. The short list includes critical failure modes on the OTP, FTP, main combustion chamber, and nozzle.

4.0 CONCLUSION

The authors of this paper tried to describe a changing environment with regard to using probabilistic engineering design analysis to support the design process. This changing environment has started after the Challenger accident and evolved over the last twenty years to reach a broader design community of both the Space Shuttle and the Ares I. The literature and applications of probabilistic engineering design analysis to the Space Shuttle hardware has provided a significant amount of learning and guidance to the Ares I community to continue maturing the probabilistic design technology. Currently a significant amount of probabilistic design work is planned as part of the forward work for all the Ares I elements.

5.0 ACKNOWLEDGEMENT

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