NOT MEASUREMENT-SENSITIVE

KSC-STD-Z-0015
Revision A

ENGINEERING ANALYSIS,

STANDARD FOR

EAR 99 -- NO LICENSE REQUIRED

This information or item is controlled under the Export Administration Regulations (EAR) as EAR99. It may be exported without a license, except to countries subject to embargoes and other special controls or general prohibitions per 15 CFR Parts 736 and 746. The designation of EAR99 does not constitute approval for public release.

Reference EDR Log #: 8602 NASA KSC Export Control Office, 321-867-9209

February 12, 2021

Engineering Directorate

National Aeronautics and
Space Administration

John F. Kennedy Space Center

KSC-STD-Z-0015
Revision A

ENGINEERING ANALYSIS,

STANDARD FOR

Approved by:

SHAWN QUINN Digitally signed by SHAWN QUINN
Date: 2021.02.12 14:58:40 -05'00'

Shawn M. Quinn
Director, Engineering

February 12, 2021

JOHN F. KENNEDY SPACE CENTER, NASA

RECORD OF REVISIONS/CHANGES

REV LTR	CHG NO.	DESCRIPTION	DATE
		Basic issue.	May 5, 2012
A		Added “sustaining” to Section 1.1. Added applicable NASA and KSC documents to Section 2.1. Added definition for “analysis of record” in Section 3. Updated Section 4.3 to recommend for Analysis Plan. Updated Nomenclature List in Section 4.4.2. Added Section 4.4.3 to discuss Engineering Math Models for hand calculations. Removed “checker” as signatory for analysis briefs or reports, in Section 4.5. Added new Section 4.5.1, Analysis Cursory Review. Changed Section 4.5.2 from Analysis Verification to Analysis Model Spot Check and added more definition. Added new Section 4.6.1, Analysis Presentation. Changed Section 4.6.2 Analysis Memo, and removed “Brief”, which is now obsolete. Updated Section 4.6.3 for clarification, reports now expected at 30% review. Added new Section 4.7, NASA-STD-7009 Compliance. Added new Appendix F and G. Updated document layout for better flow.	February 12, 2021

CONTENTS

FIGURES

ABBREVIATIONS, ACRONYMS, AND SYMBOLS

'	foot
"	inch
°F	degree Fahrenheit
°R	degree Rankine
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
Btu	British thermal unit
CAD	computer-aided design
CFD	computational fluid dynamics
CM	configuration management
csv	comma separated value
DAR	design analysis report
EGS	Exploration Ground Systems
ft	foot
GHe	Gaseous helium
hr	hour
in	inch
KDP	Kennedy Documented Procedure
KDDMS	KSC Design Data Management System
KSC	John F. Kennedy Space Center
lbm	Pound mass
LDE	lead discipline engineer
LN2	liquid nitrogen
LO2	liquid oxygen
MLI	multilayered insulation
M&S	model and/or simulation
MSFC	George C. Marshall Space Flight Center
NA	Not applicable/available
NASA	National Aeronautics and Space Administration
PDR	preliminary design review
psi	pound per square inch
psia	pound per sqaure inch absolute
psig	pound per square inch gauge
sec	second
SRR	System Requirement Review
TA	technical authority
TBD	to be determined
VJ	vacuum–jacketed

1. SCOPE

1.1 Purpose

This document describes the general methods and procedures that are required to document all analyses and calculations performed for system design, development and sustaining engineering. Analysis products generated in accordance with this document are intended to become the analysis of record. This standard may be levied/imposed by a Program for all or specific projects conducted under the Program.

Analyses not directly related to system design (e.g. cost estimates, safety and mission assurance, and 3-D visualization) are outside the scope of this document. To ask questions or make suggestions about this standard or to request a variance to it, please refer to the Standardization Document Improvement Proposal at the end of the document.

1.2 Background

This document establishes uniform procedures to be followed to perform and fully document all hand and computer analyses. This standard was created to reduce variation, promote consistent methods among analysts, and facilitate error checking.

2. APPLICABLE DOCUMENTS

The following documents form a part of this document to the extent specified herein. When this document is used for procurement, including solicitations, or is added to an existing contract, the specific revision levels, amendments, and approval dates of said documents shall be specified in an attachment to the Solicitation/Statement of Work/Contract.

Supplemental publications, those documents related to topics discussed in this document but not directly cited, are listed in Appendix G.

NASA Technical Standards

NASA-STD-7009	Standard for Models and Simulations

John F. Kennedy Space Center (KSC)

KSC-DE-512-SM	Ground Systems Development Standard
KSC-STD-Z-0017	Engineering Analysis, Thermal/Fluid, Standard for
KDP-P-2718	Engineering Documentation Electronic Approval, Release and Revision Process
KTI-5031	Design and Development Technical Instructions

GSDO-SPEC-1262	Exploration Ground Systems Program Engineering Model Delivery Standard
GSDO-SPEC-1262-ANX-01	Exploration Ground Systems Program Subsystem Modeling and Simulations Criticality Assessment Results
GSDO-RPT-1272	Exploration Ground Systems Program Critical Engineering Model Log
GSDO-FM-1271	Exploration Ground Systems Model Criticality Assessment Worksheet
GSDO-TEMPL-046	Exploration Ground Systems Program Engineering Model Metadata Template

(Copies of specifications, standards, drawings, and publications required by suppliers in connection with specified procurement functions should be obtained from the procuring activity or as directed by the Contracting Officer.)

2.1 Non-Governmental

Not applicable.

3. DEFINITIONS

For the purpose of this document, the following definitions shall apply.

engineering analysis: mathematical calculations or models used to assist in the design and development of a system and to verify the system meets its specific requirements. Examples of engineering analyses include (but are not limited to) mechanical, structural, dynamic, electrical, thermal, fluid, and launch environments. These are captured in a design analysis report (DAR) or analysis memo.

lead analyst: the responsible party for all engineering analyses performed on a system design at the system level.

primary analysis: the analysis performed for milestone reviews. Following the final review, this analysis will become the analysis of record.

subsystem analyst: the analyst responsible for engineering analysis in support of the lead analyst. The subsystem analyst is responsible for concurrence on all engineering analysis performed in their specific discipline on a system design.

supporting analysis: an analysis performed to support the primary analysis. This may be a component to the overall primary analysis.

analysis of record: the analysis used to document the system being analyzed passed its functional verification and validation objectives for a level of certification determined by the stakeholder.

system: a general term that is used to describe ground support systems (GSS), ground support equipment (GSE), facility ground support systems, special test equipment, tools, or flight systems. This typically does not include facility or collateral equipment as defined in KSC-DE-512-SM.

design margins: the difference added onto a requirement during the design or pre-testing phase of a project, to protect that requirement from being violated due to a change. Commonly used to protect a system from uncertainty in operation, environment, loads, or manufacturing tolerances.

engineering math model: an analytical model based on mathematical calculations used to assist in the design, development, or sustaining functions of a system and are used to verify the system meets codes and requirements. These may be hand calculations, or computer generated and may be validated against real world system.

loads document: a higher level document, usually a CM level 2, that is controlled through a technical authority board that houses boundary conditions (i.e. blast, thermal, vibration, acoustic, wind, and dead loads) to be used in analyses.

4. DETAILED REQUIREMENTS

4.1 Primary Analysis

The primary analysis is the engineering analysis of record for a design and is performed for milestone reviews. Subcomponents of the primary analysis will be prepared by the lead analysts and may include hand calculations, products of system analysis tools, software models, and references. Analysis of these subcomponents may be delegated at the lead analyst's discretion. All of these will become part of the final analysis product, which will be archived and documented as outlined in 4.6.2 and 4.6.3. Supporting analyses will be performed as needed.

Standards for specific disciplines are identified in 4.4.6.

4.2 Supporting Analysis

A supporting analysis is an analysis performed to assist, or check the primary analysis. These analyses include hand calculations and alternative software models used to corroborate the results of the primary analysis. The results of supporting analyses shall be documented in appendices for the reports outlined in 4.6.2 and 4.6.3.

4.3 Analysis Plan

An analysis plan for each system is recommended for each milestone in the design review. The analysis plan shall outline all analysis to be completed for the project, and will assist with scheduling and resource planning. This should include identification of the responsible parties, a project description, milestones, deliverables, analysis requirements, resources required, project-specific analysis tasks and list, data exchange policy, risk, analysis acceptance criteria and/or credibility, and waterfall schedule. An example of an analysis plan is provided in Appendix A.

4.4 Analysis Criteria

This section defines the criteria for an analysis to be deemed acceptable by the lead analyst.

4.4.1 Boundary Conditions

All model boundary conditions shall be agreed upon by the analysis team and based, whenever possible, on the governing documents defined in Section 2.

When operational boundary conditions are defined, the combination of conditions that produces the worst performance for the component or system being evaluated shall be analyzed. This ensures either that the operational requirements are achievable across the range of boundary conditions or that operational rules can be established to prevent operation in adverse conditions.

4.4.2 Nomenclature

The nomenclature requirements pertain to all equations, and discussions of analysis methods in this document. Nomenclature in each discipline can vary depending on the topic being addressed (e.g., σ identifies both the surface tension of a fluid, and also the convolute width in metal bellows) and shall always be identified in each analysis. Nomenclature used in each analysis shall be defined in any analysis documentation, as outlined in 4.6.2 and 4.6.3.

4.4.3 Design Margins

Design margins differ from discipline to discipline. During the preliminary design review (PDR) phase of a project, these are used to protect a system design from uncertainty, and provide a robust design that requires less iterations and is more resistance to late design changes. A higher percentage of margin should be used earlier in the design (SRR), and a reduced margin later in the design (90%).

Some examples of margin use are as follows:

- Percentage added to flight vehicle weight, so supporting systems are not under capacity
- Percentage added to flow rate of a fluid system capacity
- Percentage above MoS for bolt calculations to select sufficient bolt material

4.4.4 Hand Calculations

All hand calculations shall be documented as part of an analysis memo in accordance with 4.6.2, unless they are included in a Design Analysis Report (DAR). References for all hand calculations shall be provided. Analyses performed using software such as MathCAD or Excel are considered hand calculations and shall be documented accordingly. Any exceptions to these software tools being considered hand calculations is at the discretion of the lead analyst. Hand calculations performed on paper will be scanned into digital form (PDF preferred). Separate Engineering Math Model (EMM) numbers are not required for each hand calculation, and may be placed into single or multiple math models at the discretion of the lead analyst. It is recommended to have a separate EMM for crucial hand calculations that may have large project or program impacts.

4.4.5 Model Configuration Control

All engineering math models that are used to verify requirements of a project, or subsystem shall be configuration controlled in the home organization's official configuration management system. For the Engineering Directorate, this is the KSC Design Data Management System (KDDMS).

4.4.5.1 Engineering Math Model (EMM)

An engineering math model is the unique file identifier assigned for analytical models in KDDMS. The EMMs are associated to their respective KDDMS product structure end items (at their system, assembly, sub-assembly, Part, etc. level as applicable). These are assigned a six digit permanent number with a set prefix for models (e.g. KSC-EMM-000002), which are then referenced in reports and tracked for criticality. The number is good for the full life cycle of the model, and shall be updated similar to documents that require revision. New EMM's should not be pulled when changes are made to the initial or existing model, but existing numbers should be updated to the next iteration. The EMM will be used to store the native files performing the analysis, not a PDF or other image only file, at the discretion of the lead analyst.

Models that must be assessed for criticality or are crucial with large project or program impacts, shall have their own EMM.

4.4.5.2 Model Configuration Management Level

The configuration management (CM) level of a math model shall be either a level 2 or level 3 per KDP-P-2718. The default CM level for any math model is a level 3. If a math model is deemed critical per a NASA-STD-7009 assessment through design, development, or sustaining functions of a system, the CM level shall be updated to a level 2 and the discipline Chief Engineer will be included on the release of the model.

4.4.5.3 Cross Program Model Transmission

Models that are to be transmitted to a different program, other than the creating program, shall be sent to an IERB for approval prior to transmission. Both a criticality assessment and metadata sheet as outlined in Section 4.7.1 shall be completed prior to IERB and transmission.

4.4.5.4 Model Defined Attributes

For all models uploaded into KDDMS the attributes of the Statement of Intended Use and Technical Description of the model, shall be filled out. The KDDMS fields are limited to 500 characters, any statements beyond that should be added to the model content and attachments as a Microsoft word file, or similar text file.

For details on what is needed in the statement of intended use and technical description of model see 4.7.2.1 and 4.7.2.2. For EGS the statement of intended use shall include the element, subsystem, and vehicle configuration the model represents.

4.4.6 Discipline Analyses

Below are the standards used for specific analysis disciplines.

4.4.6.1 Thermal/Fluid Analysis

Thermal and fluid analysis performed shall conform to KSC-STD-Z-0017. For most fluid systems, the primary analysis, discussed in 4.1, will include a software model as one of the final analysis products.

4.4.7 Analysis Software

All analysis software used shall meet the requirements of 4.4. Software acceptable for deliverables shall be determined by the lead analyst and shall be listed in the Analysis Plan or contract, whichever is applicable. Unless otherwise stated by the lead analyst, the most current version of any analysis software is to be used. The software version used in the analysis shall be recorded and become part of the analysis record.

All computer models shall be documented with comments describing how the model is to be set up and used and limitations in the use and utility to enable review and checking. All available documentation methods shall be used to the greatest extent possible, including the following:

- descriptive variable names,
- comment fields,
- visual documentation (i.e., laying out the model to parallel system schematics, which allows particular subsystems to be identified quickly), and
- the date the unique model was validated (if applicable)

Analysis software that include setup and execution files shall be included in an EMM.

4.5 Review Criteria

All analyses shall be peer-reviewed, where possible and practical under the direction of the lead analyst. The reviewer will sign any analysis memos or reports pertaining to the analysis. In addition, all contractor-performed analyses and associated reference materials, including project-related e-mails, shall be made available to the lead analyst at any time upon request. Analyses performed by computer shall be provided to the reviewer in an immediately executable form suitable to the needs of the lead analyst. All supplemental files shall also be provided.

4.5.1 Analysis Cursory Review

Analysis cursory review is a cursory look at completed analysis documentation (presentations, memos, DAR) without digging too deeply into the underlying mathematical calculations. These checks are utilized to provide sanity checks, and identify any potential superficial mistakes with the results.

4.5.2 Analysis Model Spot Check

Analysis model spot check occurs when a reviewer checks another person’s analysis, without necessarily performing independent calculations. This check shall include, but is not limited to, a review of boundary and load conditions, assumptions and references, and equations used. There are three types of spot checks that shall be completed using the peer review checklist, for the respective discipline of analysis. These different checks are:

1. Single case/scenarios checks
2. Multiple case/scenario checks
3. Full model case/scenario checks

4.5.3 Analysis Verification

Analysis verification occurs when a reviewer performs an independent analysis and/or calculations to verify the results. The need for analysis verification is determined by the lead analyst.

4.6 Analysis Documentation

This section outlines the level of documentation and review required for analysis.

4.6.1 Analysis Presentation

Presentations, (e.g. PowerPoint presentations) may be used to present analysis results to management and the technical authority (TA), but are not considered to be an officially documented analysis of record.

4.6.2 Analysis Memo

An analysis memo is required for all analysis conducted, including hand calculations, which are already not included in a design analysis report (DAR). A memo is meant to be an expedited means of documenting an analysis, and if acceptable to stakeholders, may be used to close program requirements. This is conditional on it being released in the appropriate configuration management system and still meeting the requirement tracing per KTI-5031. In some instances, a memo may document a pending revision to a DAR, or loads document, followed that a problem report is placed against the parent document affected (K-PR in KDDMS, or equivalent). The analysis memo should include a statement of purpose, a reference to design requirements and adequately summarize all calculations performed. This should include the method used, any boundary conditions, assumptions, correlations, equations and references. An example of an analysis memo is provided in Appendix C. The following sections are suggested to include in an Analysis Memo:

- Analysis title/program
- Performed by: and checked/verified by:
- Design Verification Matrix (DVM) Requirements Traceability Matrix
- Software name and version
- Model name, revision, and date
- Engineering Math Model (EMM) number
- Problem statement
- Discussion
- Assumptions (with references)
- Boundary and/or load conditions (with references)

- Design margins (with references)
- Uncertainties (with references)
- Detailed analysis and subsections
- Conclusions/summary
- References and nomenclature

The configuration management (CM) level of a memo should be a CM level 5 in KDDMS, since they are typically not revised.

4.6.3 Design Analysis Report

A DAR for each system or subsystem is required for each milestone in the design review and at the completion of any failure analysis. The subsystem team may determine if it is appropriate to have one or multiple DAR's broken down into specific disciplines (e.g. structures, dynamics, fluid and/or thermal, and electrical). While it is not compulsory the discipline based approach, described above, is recommended. Suggested sections and material to include in an analysis report are shown below. The minimum items required in a 30% or 45% preliminary design review (PDR) DAR are underlined below.

- Nomenclature
- Introduction
    - Purpose
    - Scope
    - Design Verification Matrix (DVM) Requirements Traceability Matrix
    - Results Summary
    - Recommendations
    - Future Work
- Applicable documents
- Description of physical system
- Contributors (performed by, checked by, verified by)
- Model description (software, version, and date)
    - Engineering Math Model (EMM) number
- Methodology
    - Assumptions
    - Boundary or load conditions (with references)
    - Material properties (with references)
    - Design margins (with references)
    - Uncertainties (with references)

- Results
    - Probability based on error or uncertainty
    - Sensitivity
    - Confidence interval
    - Satisfaction of Design Requirements (traceability to those requirements)
- References
- Appendix
    - Data/calculations
    - Corrections to experiment or data

The analysis report shall include a description of the methodology used, imparted initial conditions, boundary conditions, reference documentation, assumptions, correlations, pertinent system equations (with references) and a detailed description of the analysis. Supporting analyses shall be documented in the appendices.

For analyses performed with computer software, a full listing of node numbers, locations, or results, either within the main body of the text or in appendices, is not acceptable as a design review deliverable. It is not acceptable to list this information as "results" in an analysis memo or analysis report without elaboration of the results. This information can be added in an appendix upon customer request, but exists in the math models, which should be called out in the DAR. For this reason documenting this information is redundant.

Analysis reports are revised and supplemented at each milestone. New analysis reports that refer to previous versions of the same report shall not be used. An analysis report for a 90% design review shall include documentation of any new analysis as well as updates to the existing 60% analysis. If an analysis performed at the 60% review phase remains the analysis of record, it shall remain in the document and be considered a 90% analysis product. Previous analyses that are no longer applicable or have been superseded do not require documentation.

The configuration management (CM) level of a DAR should be a CM level 3 in KDDMS, since they are typically revised. A CM level of 5 may be used if the report will not be revised.

4.7 NASA-STD-7009 Compliance

The primary purpose of NASA-STD-7009 is to reduce the risks associated with model and/or simulation (M&S)-influenced decisions by ensuring there is complete communication of the credibility of M&S results. The application and acceptance of NASA-STD-7009 is at the discretion of NASA programs, who can choose to implement, not implement, or provide a tailored version of NASA-STD-7009.

At a minimum, it is recommended that projects follow the guidelines in this standard. For analysis efforts supporting the EGS program, Section 4.7 and its subsections are required.

4.7.1 Exploration Ground Systems (EGS)

Exploration Ground Systems (EGS) has implemented a tailored version of NASA-STD-7009, which is GSDO-SPEC-1262. In this document, engineering analysis models are considered a Type #1 model, and the flow diagram showing how the assessment of the models shall be performed for criticality is shown in Figure 1.

If a subsystem is defined as critical, per GSDO-SPEC-1262-ANX-01, but does not have a "critical requirement" as defined in GSDO-SPEC-1262, then a critical assessment should not be required, except under the following conditions.

- The model is a cross program model
- An assessment is requested by the stakeholders
- The project/program technical authority believes an assessment is required

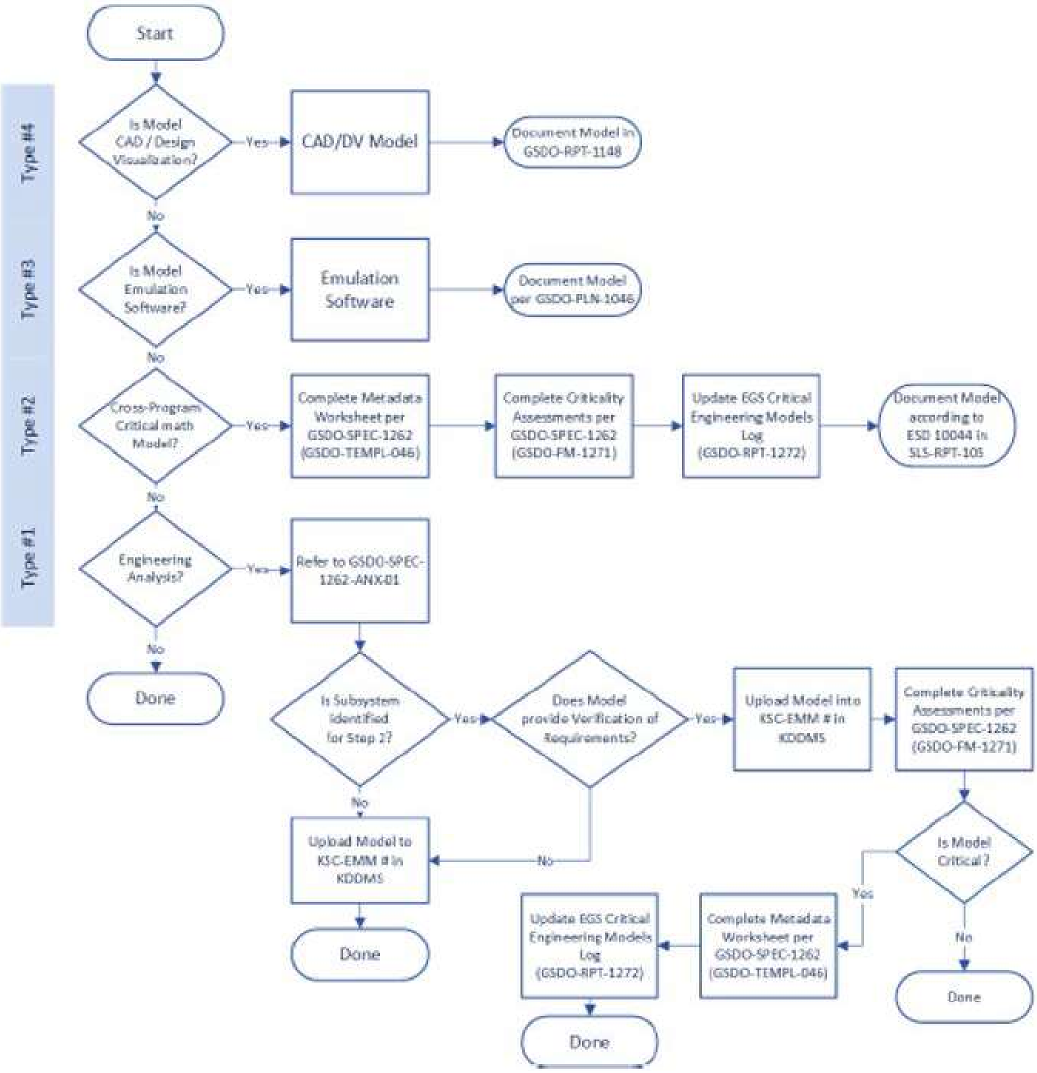


Figure 1. GSDO-SPEC-1262 Analysis Model Assessment Process

4.7.1.1 Criticality Approval Process

A criticality assessment must follow the directions in GSDO-SPEC-1262 Appendix A and be completed using the form GSDO-FM-1271, which can be found in TechDoc. The approval process for the criticality assessment is shown below in Figure 2. Once completed, the criticality assessment shall be added as an attachment of the EMM in KDDMS.

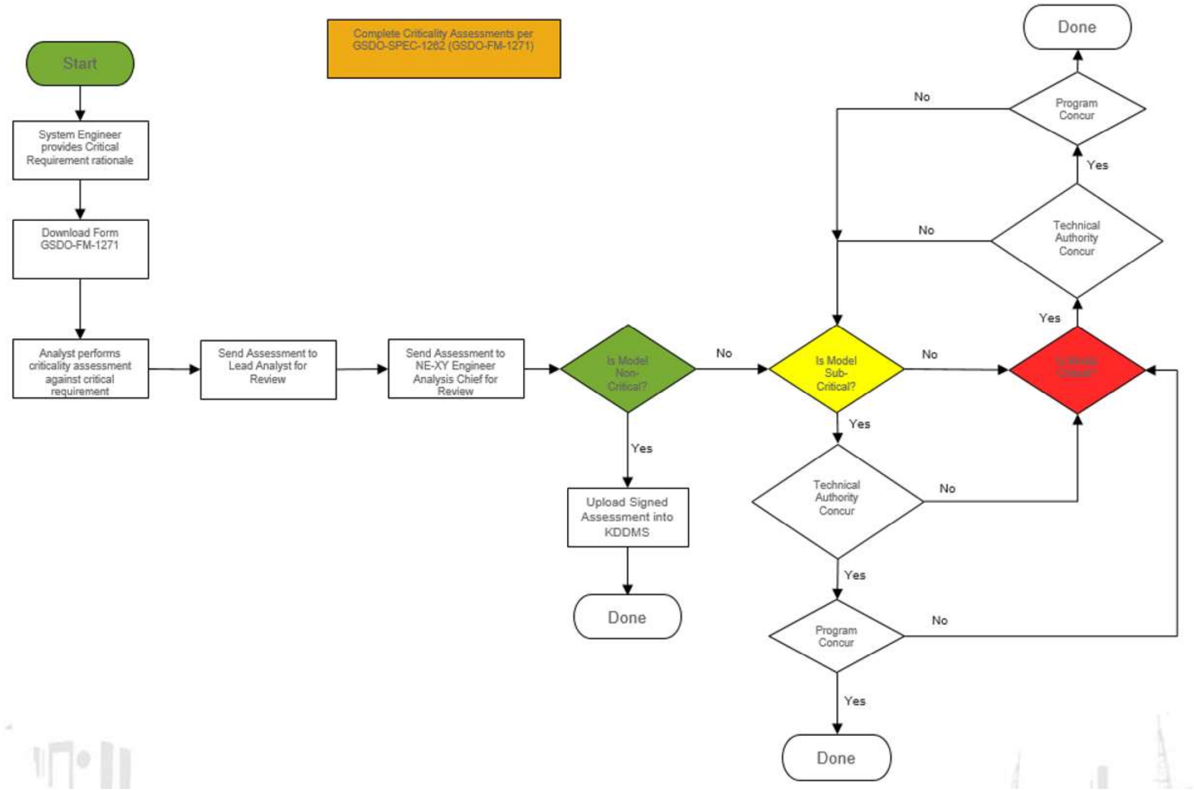


Figure 2. Approval Process Criticality Assessment

4.7.1.2 Metadata Approval Process

Model metadata shall be filled out to the guidelines in GSDO-SPEC-1262 Section 4. Once the model metadata is captured it can be submitted to the lead analyst and/or to the chief of engineering analysis for approval. Once completed the metadata shall be added as an attachment to the EMM in KDDMS.

4.7.1.3 EGS Math Model Log

Engineering math models with completed criticality assessments and metadata, should then be released in KDDMS. Both assessment forms are provided to the book holder of GSDO-RPT-1272, and the assessment finding will be captured in the next revision of the report. The program model log captures assessed models that are both critical and non-critical.

4.7.2 KSC External Contractor

Analysis performed for systems and subsystems that engineering is the responsible technical authority of, shall follow this section. Models provided by external contractors to NASA shall at a minimum, have the following documentation. This section provides the minimum expectations for an external contractors work to meet NASA-STD-7009.

4.7.2.1 Statement of Intended Use

Provide a statement describing how the design model is to be employed. This shall describe the system and environmental elements to be modeled, and what data is produced by the model.

4.7.2.2 Technical Description of Model

Provide a qualitative summary of aspects, details, cases, steps, conditions, and states that describe the model, element selection, mesh density, load cases, and boundary conditions. Describe statistical methods and outputs, or rationale for the use of deterministic methods.

4.7.2.3 Software Version

Provide a statement identifying the software in which the model was created, along with the version and if the model is backward compatible with previous versions of that software.

4.7.2.4 Revision History

Provide a revision history of changes that have occurred to the model between deliveries to NASA. Include changes in boundary conditions, meshing, geometry, and other parameters that can effect model results.

APPENDIX A. GENERAL EXAMPLE ANALYSIS PLAN

Analysis Plan - Project Title

Lead Analyst – Name, Org, ph number
Subsystem Analyst – Name, Org, ph number
Lead Designer – Name, Org, ph number
Project Manager – Name, Org, ph number
System Engineer – Name, Org, ph number

Project Description
Provide a description of the system, key components, and interfaces. Provide a short summary of the analysis portion of the project with commentary on how detailed of an analysis is expected. Include relevant background and expected limitations of analysis.

Milestones (This section should not change much from project to project except dates)

TBD	Analysis Plan Peer Review
TBD	Technical Table Top Review
TBD	System Requirement Review (SRR)
TBD	Preliminary Design Review (PDR)
TBD	Critical Design Review (CDR)

Include reviews, Engineering Review Board meetings, major presentations, etc.

Deliverables (This section should not change much from project to project)
Official items sent out from the analysis team. Detailed data, loads, spreadsheets, etc., should be listed in the Data Exchange section.

30% Phase

- Conceptual/trade study details
- 30% Design Analysis Report

60% Phase

- Dynamic or FEA Models
- 60% Design Analysis Report

90% Phase

- Dynamic or FEA Models
- 90% Design Analysis Report

Final Phase

- Dynamic or FEA Models
- Final Design Analysis Report
- Model validation/calibration
- Acceptance testing

Analysis Requirements

List of requirements needed to complete the analysis. This can be the document name, specifics taken from the document, or both – depending on how they apply to the project. This should not need to list every design requirement – just the ones that specifically drive analysis.

Program Requirements

- Specs
- Standards
- Etc.

Internal Requirements

- System engineering requirements
- Requirements from Requirements Verification Matrix
- Performance requirements
- Requirements from design
- Example of requirements driving analysis
    - The kinetic energy of retract will be optimized to a minimum.
    - The electrical cables may not carry tension loads.
- Example of design requirements or details that are important, but do not need to be listed in the analysis plan
    - The vehicle shall have a lock out device to prevent premature release.
    - Maintenance requirements will be kept to a minimum.
    - The winch maximum payload is 200 lbm.

Resources

Bulleted list of resources (people, software, test materials, developmental instrumentation, etc.) needed to complete the analysis.

- Name, organization
- Software, version

Project Specific Analysis Tasks

Insert excel table of analysis tasks (see “analysis plan.xls”). Sort and group by 30/60/90 and component as applicable. Due date can also be TBD or reference the review listed in the milestones section. Use paste (not “paste special”) - may need to resize in Excel to fit the Word doc. Things to consider:

- All structures and components
- Connections (welds, fasteners)
- Off-the-shelf items
- Dynamics

- Kinematics
- Vibration
- Acoustics
- Etc.

Methodology

Describe the planned analysis method/overview for each component. Include planned safety factors, knockdown factors, load cases.

Data Exchange

Input/output (external and internal) between individuals needed to complete analysis, such as loads, testing data, etc. This should only include significant data that would have major impact on the flow of the analysis or things that will be helpful to planning the analysis. Examples include:

Item: Vehicle Loads
Provider: MSFC – Lisa Roth/Tim Olive
Recipient: KSC – Jeff Suhey
Date: TBD
Reason: Loads from flight of the vehicle are needed to perform structural analysis of the flight plates.

Item: Plate Edge Temperature Distribution
Provider: MSFC – Julia Khodabendeh / KSC – Max Kandula
Recipient: KSC – Max Kandula / MSFC – Julia Khodabendeh
Date: TBD
Reason: Iterative process needed to determine temperature distribution at the interface between the plate and vehicle.

Item: LO2 Plate Model Design Drop
Provider: Cliff Manley
Recipient: Chris Brown
Date: TBD
Reason: Design model is needed to complete 30% analysis.

Project-Specific Work Flow **(as necessary depending on project complexity)**

Make a flow chart specific to project

- Shows interface/iteration with design group
- Shows input from other NASA groups/contractors
- Checking process
- Internal methodology review

Analysis Risks and Credibility

Should document any risk associated with an analysis, and outline the criteria for determining if an analysis is acceptable and/or credible.

APPENDIX B. SPECIFIC EXAMPLE ANALYSIS PLAN

Analysis Plan – Space Launch System (SLS) LO2 Propellant Loading System
Project: Mobile Launcher Cryogenic Delivery Project
Customer: Exploration Ground Systems (EGS)

Lead LO2 Analyst – Craig Fortier, NE-M1, 321-861-4456
Fluid Analyst – Jared Congiardo, NE-M1, 321-867-0820
Contractor Analyst–Michael Harris, 321-867-9578

Lead Designer – Christian O'Connor, NE-F2, 321-867-7293
Operations Engineer – Miles Ashley, NE-F4, 321-861-4186
Project Manager – David Grau, NE-P, 321-867-5062 Systems
Engineer – Dennis Lobmeyer, 321-867-3797

Project Description

The analysis for the cryogenic propellant loading system will be divided into two different subsystems, the liquid oxygen (LO2) system will be addressed in this document. NE-M1 will be responsible for generating the end-to-end models from the pad cryogenic storage tanks to the first and second stage flight vehicle tanks. Preliminary analysis may be completed with hand calculations and sizing analysis. Models developed by NE-M1 will be generated in SINDA/FLUINT or AFT Impulse.

The LO2 system analysis will compose of generating models for the existing system that is to be reused and transfer system in development. Modeling of the current LO2 system will include the LO2 storage tank, vaporizer, pump and transfer area, cross-country line, dump line, and dump basin, as well as, any new added components, piping and valve skids, etc.

The deliverables for the project will be an analysis report and continually updated analysis plan. The NE-M1 lead analyst has signature authority on all analysis prior to its acceptance as a deliverable.

Milestones

5/11/2012	Analysis Plan Peer Review
5/15/2012	Technical Table Top Review
5/24/2012	System Requirements Review (SRR)
6/21/2012	30% Internal Drop Date
8/2/2012	30% Design Review
4/8/2013	60% Internal Drop Date
5/17/2013	60% Design Review
9/27/2013	90% Internal Drop Date
8/29/2013	90% Design Review
12/3/2013	100% Design Review

Deliverables

Milestone deliverables (noted below) will be submitted at the formal drop date for each design phase. All analysis deliverables will be uploaded into KDDMS. Each analyst will be responsible for version control and all submittals will represent “locked down” configurations. A configuration will be locked down 30 days prior to the formal drop. Reports will integrate all analysis products and be compiled into a single document by the lead analyst. The design phase deliverables include but are not limited to the following:

SRR
- Analysis Plan

30% Phase
- Analysis Summary Letter
- Updated Analysis Plan

60% Phase
- Updated Analysis Plan
- Analysis Models
- Analysis Report

90% Phase
- Updated Analysis Plan
- Updated Analysis Models
- Updated Analysis Report

Final Phase
- Final Analysis Plan
- Final Analysis Models
- Final Report

Analysis Requirements

Relevant documentation pertaining to requirements, program level and internal, include but are not limited to the following:

Program Requirements
- TBD

Project Requirements
- K0000061737: Interface Data Book
- 732FMM00002: LO2 Interface Table

- R.GX.L.LO2-1000: The LO2 subsystem shall provide the capability to fill and drain LO2 for the propellant loading of the Upper Stage.
    - Flow Rate: 9 to 93 lbm/sec
    - Pressure: 0 to 250 psi
    - Temperature: –298 to 100˚F

- R.GX.L.LO2-1000: The LO2 Subsystem shall provide the capability to fill and drain LO2 for propellant loading of the Upper Stage for the following six cases.

Loading Phase	Flow Rate	Temperature	Pressure
Chilldown	0.0–3.0 lbm/sec	162.3–560.0 ˚R	0.0–18.6 PSIG
Slow Fill (0–5% Volume)	2.5–6.0 lbm/sec	162.3–181.0 ˚R	0.0–18.6 PSIG
Fast Fill (5–95% Volume)	15.0–63.0 lbm/sec	162.3–176.0 ˚R	0.0–18.6 PSIG
Topping (95–100% Volume)	2.5–6.5 lbm/sec	162.3–176.0 ˚R	0.0–18.6 PSIG
Replenish	0.0–1.0 lbm/sec	162.3–176.0 ˚R	0.0–18.6 PSIG
Drain	0.0–63.0 lbm/sec	NA	0.0–18.6 PSIG

- R.GX.L.LO2-1003: The GHe purge system shall be capable of providing purging gas to the LO2 Tank at the following conditions.
    - 0.0-0.042 lbm/sec
    - 75 ± 5 PSIG
    - Ambient Temperature
- R.GX.L.LO2-1029: The LO2 Subsystem shall provide the capability to fill and drain LO2 for the propellant loading of the Core Stage for the following six cases.

Loading Phase	Flow Rate	Temperature	Pressure
Chilldown	0–4800 lbm/min	163.0–580.0˚R	0–36.0 PSIG
Slow Fill (0–2% Volume)	2220–3040 lbm/min	163.0–170.0˚R	10.0–50.0 PSIG
Fast Fill (2–95% Volume)	11880 ± 1440 lbm/min	163.0–170.0˚R	45.0–90.0 PSIG
Topping (95–100% Volume)	9500 lbm/min (MAX)	163.0–170.0˚R	65.0–90.0 PSIG
Replenish	2366 lbm/min (MAX)	NA	NA
Drain	NA	NA	NA

Internal Requirements:

- KSC-STD-Z-0015, Standard for Engineering Analysis
- KSC-STD-Z-0017, Standard for Engineering Analysis, Thermal/Fluid
- NE-M1 Analysis Best Practices Manual

Resources

All resources owed to the lead analyst must be provided to the lead analyst 30 days prior to the formal drop date (reference attached matrix). Additionally any changes in the resources owed to the lead analyst shall be communicated to the lead analyst at a minimum of a biweekly basis, but should be communicated as soon as they become available. Any alteration to the list of resources owed to the lead analyst is at the discretion of the lead analyst with concurrence from the project manager. Items required to meet the milestones, include but are not limited to the following:

- Software Tools
    - (1) SINDA/FLUINT Solver
    - (1) Sinaps
    - (1) Thermal Desktop w/FlowCAD
    - (1) AutoCAD
    - (1) Fortran Compiler
    - (1) MATLAB
    - (1) NX NASTRAN 7.5.3
    - (1) Pro/E Creo 5.0
    - (1) AFT Impulse
    - (4+) ANSYS FLUENT/OpenFoam
- Design Team Deliverables to Analysts
    - All test data for, but not limited to the following:
        - Acceptance Tests
        - Performance Tests
        - Verification and Validations
    - Component Data/Information
- LO2 Vaporizer Performance Test Information
    - All test data available for 10–hour performance test
    - All information available on new vaporizer in procurement
- All analysis resources required by contractors and the design team have been included in the attached sheet titled “SLS LO2 System Analysis Resources.”
    - Per the attached sheet all CFD required must be submitted to the lead analyst by the 30% drop date. CFD analysis can be a long lead item and must be planned for in advance.

Project Specific Analysis Tasks

All analysis tasks currently planned to be completed have been included in the attached sheets titled, “SLS LO2 System Fluid/Thermal Analysis Tasks” and “SLS LO2 System Structure Analysis Tasks.” All tasks assigned to personnel other than the lead analyst must be completed and available to the lead analyst 30 days prior to the formal drop date. Any alterations to the list of analysis tasks, is at the discretion of the lead analyst with concurrence from the project manager. In addition to this sheet, other tasks that must be completed are listed below. These include but are not limited to the following:

- Vaporizer Modeling and Analysis for Frost Accumulation Testing
- Vaporizer LN2 Performance Test Pass/Fail Analysis

Task	Need Date	Task Required For	Responsible Party
60% Deliverables			
Flex Hose FIV HC	8/31/2012	Flex Hose Pressure Drop	Contractor
Flex Hose Pressure Drop HC	9/24/2012	Flex Hose Pressure Drop Analysis	Contractor
Orifice Sizing HC	9/11/2012	Orifice Sizing Analysis	Contractor
Valve Sizing HC	9/25/2012	Valve Sizing Analysis	Contractor
Piping Heat Leak HC	10/2/2012	Piping Heat Leak Analysis	Contractor
Flex Hose FIV HC (Updated)	2/21/2013	60% Analysis Report	Contractor
US WH Calculations	2/21/2013	60% Analysis Report	Contractor
CS WH Calculations	2/21/2013	60% Analysis Report	Contractor
Chilldown HC (Updated)	2/21/2013	60% Analysis Report	Contractor
S/F RV Sizing Analysis	2/21/2013	60% Analysis Report	Contractor
Geysering Analysis	2/21/2013	60% Analysis Report	Contractor
90% Deliverables			
Piping Heat Leak HC (Update)	4/15/2013	Piping Heat Leak Analysis/VJ Piping Contact	Contractor
Orifice Sizing HC (Update)	4/22/2013	Orifice Sizing Analysis	Contractor
Valve Sizing HC (Update)	5/6/2013	Valve Sizing Analysis	Contractor
US WH HC (Update)	8/27/2013	90% Analysis Report/Skid Procurement	Contractor
CS WH HC (Update)	8/27/2013	90% Analysis Report	Contractor
Geysering Analysis	8/27/2013	90% Analysis Report	Contractor
S/F RV Sizing Analysis	8/27/2013	90% Analysis Report	Contractor

Methodology

All analysis performed shall be in accordance with the lead analyst and shall adhere to methods and documentation outlined in NASA Engineering and Analysis Branch Standard Analysis Procedures (ESAP). Analysis tools used for certain tasks, include but are not limited to the following:

- SINDA/FLUINT using Sinaps for end-to-end transient loading and contingency operations modeling.
- SINDA/FLUINT using Thermal Desktop for vaporizer transient performance and acceptance test modeling.
- AFT Impulse for analyzing transient water hammer effects and to develop valve opening and closing timing.

Data Exchange

Analysts will work with lead designer to ensure analysis models reflect appropriate design maturity. The lead designer and operations engineer will work with the lead analyst to develop the system environments and flow scenario lists. Furthermore, the lead designer and operations engineer will provide analysts with component and system down-selection decision as well as guidance on preliminary values and assumptions (e.g., line sizes, diameters). Analysts will be responsible to document and reference this guidance in their interim and final reports.

All data requests from the analysis team will be disseminated to the lead designer. The lead designer will determine if the information is already known; if not, they will make a request to the necessary parties for the information. The lead designer and operations engineer are noted in the beginning of the analysis plan.

SLS LO2 SYSTEM
FLUID/THERMAL ANALYSIS TASKS

Lead Analyst: Craig Fortier	*Responsible Party*					
Co-Lead Analyst: Jared Congiardo						
Items		**Cryo - LO2**				
		Pre-30%	*30%*	*60%*	*90%*	*100%*
Flow Scenarios (Hot & Cold Cases/High & Low Flow Cases)	**Lead Analyst**	**X**	**X**	**X**	**X**	**X**
Pipe/tube sizing analyses (System Resistance Flow Analysis)	**Contractor Analyst**		**X**			
End-to-end model "straw man" (Basic Model)	**Lead Analyst**		**X**			
Commodity Usage (hand calculations)	**Contractor Analyst**		**X**			
System Chilldown Time and Commodity Usage (hand calculations)	**Contractor Analyst**		**X**			
Potential Geysering Issues (hand calculations only)	**TBD**			**X**	**X**	**X**
Vaporizer Performance/ Net Positive Suction Head for Pumps	**Lead Analyst**			**X**	**X**	**X**
AFT IMPULSE water hammer analyses	**Lead Analyst**				**X**	**X**
SINDA/FLUINT SINAPS end-to-end analysis (Higher Fidelity)	**Lead Analyst**			**X**	**X**	**X**
Flex-hose flow induced vibration (hand calculations only)	**FIB Analyst/Lead Analyst**			**X**	**X**	**X**
Flex-hose flow pressure drop analysis (hand calculations + integrated end-to-end analysis)	**Lead Analyst**			**X**	**X**	**X**
Relief valve/burst disk sizing analyses (hand calculations only)	**TBD**			**X**	**X**	**X**
Relief valve/burst disk sizing analyses (hand calculations + integrated end-to-end analysis)	**Lead Analyst**				**X**	**X**
Orifice sizing analyses (hand calculations only)	**TBD**			**X**	**X**	**X**
Orifice sizing analyses (hand calculations + integrated end-to-end analysis)	**Lead Analyst**				**X**	**X**
Purge sizing analyses (hand calculations only)	**Pneumatic Lead Analyst/Lead**			**X**	**X**	**X**
Purge sizing analyses (hand calculations + integrated end-to-end analysis)	**Pneumatic Lead Analyst/Lead**				**X**	**X**
Valve/control valve sizing analyses (hand calculations only)	**TBD**			**X**		
Valve/control valve sizing analyses (hand calculations + integrated end-to-end analysis)	**Lead Analyst**				**X**	**X**
Piping Heat Leak Analysis (hand calculations only)	**TBD**			**X**		
Piping Heat Leak Analysis (hand calculations only + integrated end-to-end analysis)	**Lead Analyst**			**X**	**X**	**X**
System Chilldown Time (end-to-end analysis)	**Lead Analyst**				**X**	**X**
Commodity Usage from end-to-end SINDA/FLUINT models	**Lead Analyst**				**X**	**X**
Sensitivity Analysis	**Lead Analyst**			**X**	**X**	**X**
Error Analysis	**Lead Analyst**				**X**	**X**
Performance Box	**Lead Analyst**				**X**	**X**

SLS LO2 SYSTEM
STRUCTURAL ANALYSIS TASKS

Lead Analyst: Craig Fortier	*Responsible Party*					
Co-Lead Analyst: TBD						
Items		**Cryo - LO2**				
		Pre-30%	*30%*	*60%*	*90%*	*100%*
Wind Loads Analysis (Static) (hand calculations only)	**TBD**			**X**	**X**	**X**
Wind Induced Vibration Analysis (hand calculations only)	**TBD**			**X**	**X**	**X**
Pipe Thermal Expansion/Contraction (hand calculations only)	**TBD**			**X**		
Pipe Thermal Expansion/Contraction (hand calculations + end-to-end model)	**TBD**				**X**	**X**
Evaluate Pipe Constraints, Bends, and Expansion Joints (hand calculations only)	**TBD**			**X**		
Evaluate Pipe Constraints, Bends, and Expansion Joints (hand calculations + end-to-end model)	**TBD**				**X**	**X**
Fluid Line Support Fatigue Analysis from Thermal Cycling and Launch Conditions (hand calculations only)	**TBD**			**X**	**X**	**X**
Pressure Induced Stress Analysis with Material Temperature Conditions (hand calculations only)	**TBD**			**X**	**X**	**X**
Water Hammer Impact Forces Mitigation (hand calculations only)	**TBD**				**X**	

SLS LO2 SYSTEM ANALYSIS RESOURCES

Lead Analyst: Craig Fortier	*Responsible Party*				
Co-Lead Analyst: Jared Congiardo					
Items		**Cryo - LO2**			
		Pre-30%	*30%*	*60%*	*90%*
System Schematic	**Lead Designer**	**X**	**X**	**X**	**X**
Operations based requirements	**Systems Engineer/ Operations Engineer**	**X**	**X**	**X**	**X**
Loading Phases Flow Rate Requirements	**Systems Engineer**		**X**	**X**	**X**
Program Requirements	**System Engineer**	**X**	**X**	**X**	**X**
Project Requirements	**System Engineer**	**X**	**X**	**X**	**X**
Loading Phases Timeline Requirements/Constraints	**Systems Engineer**			**X**	**X**
Operations Criteria for Primary Phases of Loading	**Operations Engineer**		**X**	**X**	**X**
Operation Criteria for Contingency Procedures Requiring Analysis	**Operations Engineer**			**X**	**X**
Requested work for CFD Analysis must be submitted	**Lead Designer/Project Manager**		**X**		
CAD Files for Components Requiring CFD work	**Lead Designer/Project Manager**			**X**	
Updated Piping Layout and Valve Placement	**Lead Designer**	**X**	**X**	**X**	**X**
Updated Component List	**Lead Designer**	**X**	**X**	**X**	**X**
Location of Instruments used to Verify Requirements	**Lead Designer/System Engineer**		**X**	**X**	**X**
Uncertainty in All System Components	**Lead Designer**			**X**	**X**
Uncertainty in All Transducers and Flow Meters	**Lead Designer**			**X**	**X**
Formal Drop Dates	**Project Manager**	**X**	**X**	**X**	**X**
Deliverable Schedule Changes	**Project Manager**	**X**	**X**	**X**	**X**
Pneumatic System Analysis Results	**TBD**		**X**	**X**	**X**

SLS LO2 System Analysis Schedule

Jun 26, 2012
http://

Project managers:
Dates: Aug 6, 2012 - Aug 26, 2014

Complete: 0%
Tasks: 106
People: 5

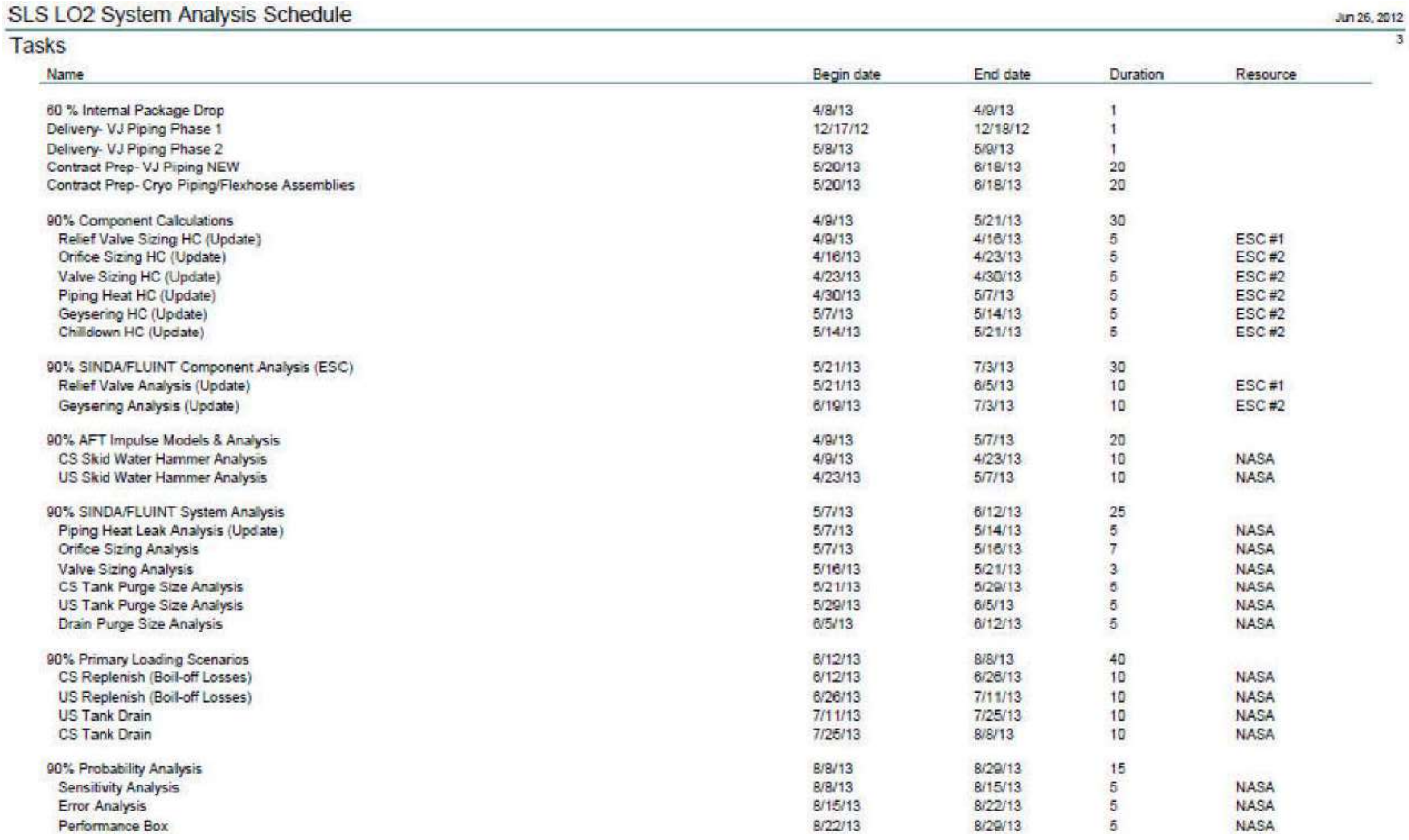
SLS LO2 System Analysis Schedule

Jun 26, 2012

Tasks

2

Name	Begin date	End date	Duration	Resource
60% Component Calculations	8/6/12	3/7/13	145	
Flex-Hose FIV HC	8/6/12	9/1/12	20	ESC #1
Flex-Hose Pressure Drop HC	9/4/12	9/25/12	15	ESC #1
Flex-Hose FIV HC Update	2/28/13	3/7/13	5	ESC #1
CS WH HC	9/25/12	10/17/12	15	ESC #1
US WH HC	10/17/12	10/31/12	10	ESC #1
Relief Valve Sizing HC	10/31/12	11/15/12	10	ESC #1
Orifice Sizing HC	8/6/12	8/25/12	15	ESC #2
Valve Sizing HC	8/27/12	9/11/12	10	ESC #2
Piping Heat Leak HC	9/11/12	9/18/12	5	ESC #2
Geysering HC	9/18/12	10/10/12	15	ESC #2
Chilldown HC	10/10/12	10/17/12	5	ESC #2
60% SINDA/FLUINT Component Analysis (ESC)	10/17/12	12/14/12	40	
Relief Valve Sizing Analysis	11/15/12	11/30/12	10	ESC #1
Geysering Analysis Vertical Line Analysis	10/17/12	12/14/12	40	ESC #2
60% SINDA/FLUINT System Analysis	8/6/12	11/8/12	66	
LO2 System End-to-End Model Development	8/6/12	9/25/12	35	NASA
Flex-Hose Pressure Drop Analysis	9/25/12	9/27/12	2	NASA
Orifice Sizing Analysis	9/27/12	10/6/12	7	NASA
Valve Sizing Analysis	10/9/12	10/11/12	2	NASA
Piping Heat Leak Analysis	10/11/12	10/18/12	5	NASA
LO2 Vaporizer Model Development	10/11/12	11/8/12	20	NASA
60% Primary Loading Scenarios	11/8/12	1/15/13	44	
CS Fast Fill	11/8/12	11/20/12	7	NASA
US Fast Fill	11/20/12	11/30/12	7	NASA
CS Replenish	11/30/12	12/21/12	15	NASA
US Replenish	12/21/12	1/15/13	15	NASA
60% Probability Analysis	1/15/13	2/6/13	15	
Sensitivity Analysis	1/15/13	1/23/13	5	NASA
Error Analysis	1/23/13	1/30/13	5	NASA
Performance Box	1/30/13	2/6/13	5	NASA
60% AFT Impulse Models & Analysis	2/6/13	3/14/13	25	
Water Hammer Model Development	2/6/13	2/28/13	15	NASA
Flex-Hose Water Hammer Analysis	3/7/13	3/14/13	5	NASA
60% Analysis Report	3/14/13	4/11/13	20	
Complete 60% Deliverable Analysis Report	3/14/13	4/11/13	20	NASA



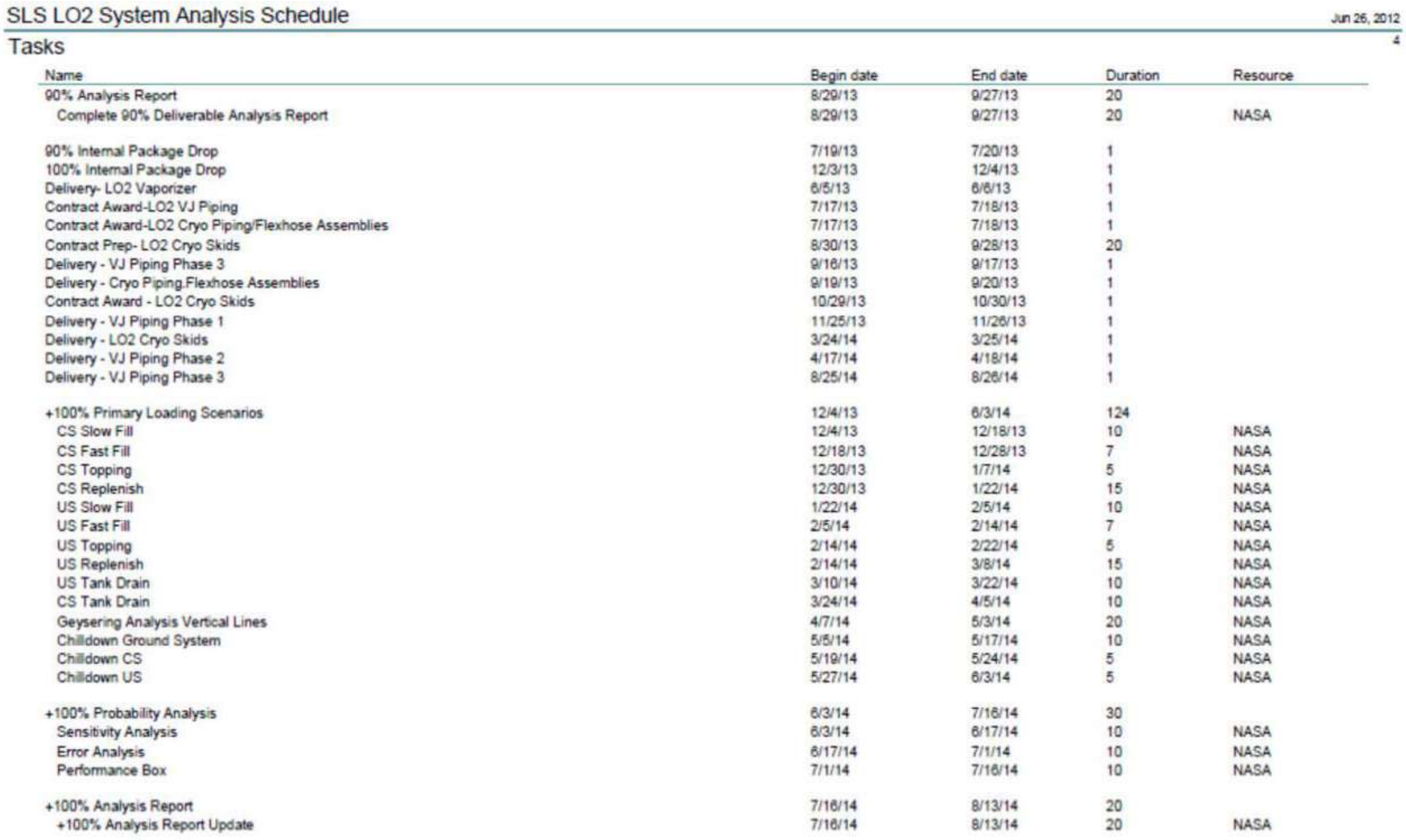
SLS LO2 System Analysis Schedule

Jun 26, 2012

3

Tasks

Name	Begin date	End date	Duration	Resource
60 % Internal Package Drop	4/8/13	4/9/13	1	
Delivery- VJ Piping Phase 1	12/17/12	12/18/12	1	
Delivery- VJ Piping Phase 2	5/8/13	5/9/13	1	
Contract Prep- VJ Piping NEW	5/20/13	6/18/13	20	
Contract Prep- Cryo Piping/Flexhose Assemblies	5/20/13	6/18/13	20	
90% Component Calculations	4/9/13	5/21/13	30	
Relief Valve Sizing HC (Update)	4/9/13	4/16/13	5	ESC #1
Orifice Sizing HC (Update)	4/16/13	4/23/13	5	ESC #2
Valve Sizing HC (Update)	4/23/13	4/30/13	5	ESC #2
Piping Heat HC (Update)	4/30/13	5/7/13	5	ESC #2
Geysering HC (Update)	5/7/13	5/14/13	5	ESC #2
Childown HC (Update)	5/14/13	5/21/13	5	ESC #2
90% SINDA/FLUINT Component Analysis (ESC)	5/21/13	7/3/13	30	
Relief Valve Analysis (Update)	5/21/13	6/5/13	10	ESC #1
Geysering Analysis (Update)	6/19/13	7/3/13	10	ESC #2
90% AFT Impulse Models & Analysis	4/9/13	5/7/13	20	
CS Skid Water Hammer Analysis	4/9/13	4/23/13	10	NASA
US Skid Water Hammer Analysis	4/23/13	5/7/13	10	NASA
90% SINDA/FLUINT System Analysis	5/7/13	6/12/13	25	
Piping Heat Leak Analysis (Update)	5/7/13	5/14/13	5	NASA
Orifice Sizing Analysis	5/7/13	5/16/13	7	NASA
Valve Sizing Analysis	5/16/13	5/21/13	3	NASA
CS Tank Purge Size Analysis	5/21/13	5/29/13	5	NASA
US Tank Purge Size Analysis	5/29/13	6/5/13	5	NASA
Drain Purge Size Analysis	6/5/13	6/12/13	5	NASA
90% Primary Loading Scenarios	6/12/13	8/8/13	40	
CS Replenish (Boil-off Losses)	6/12/13	6/26/13	10	NASA
US Replenish (Boil-off Losses)	6/26/13	7/11/13	10	NASA
US Tank Drain	7/11/13	7/25/13	10	NASA
CS Tank Drain	7/26/13	8/8/13	10	NASA
90% Probability Analysis	8/8/13	8/29/13	15	
Sensitivity Analysis	8/8/13	8/15/13	5	NASA
Error Analysis	8/15/13	8/22/13	5	NASA
Performance Box	8/22/13	8/29/13	5	NASA



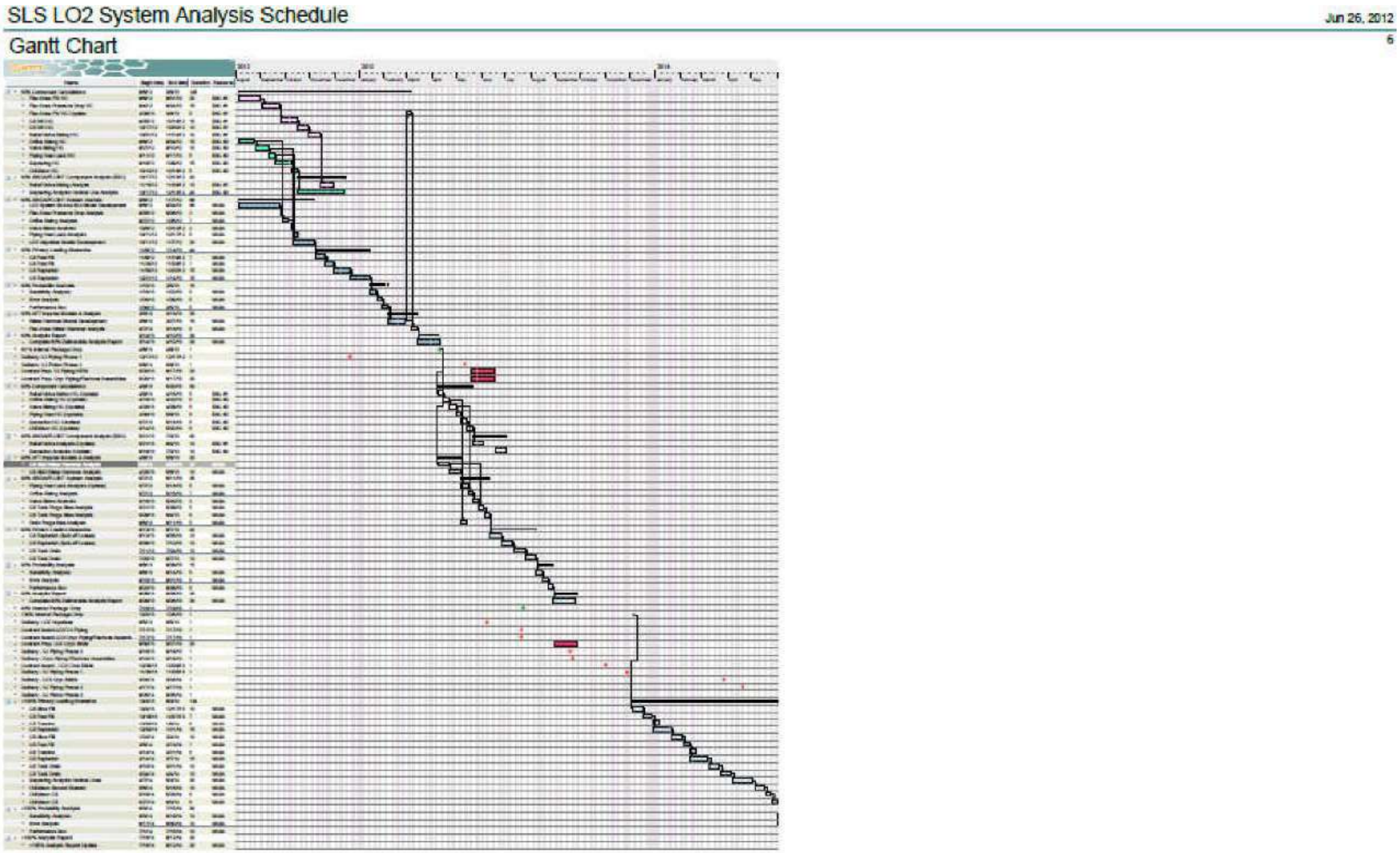
SLS LO2 System Analysis Schedule

Jun 26, 2012

Tasks

4

Name	Begin date	End date	Duration	Resource
90% Analysis Report	8/29/13	9/27/13	20	
Complete 90% Deliverable Analysis Report	8/29/13	9/27/13	20	NASA
90% Internal Package Drop	7/19/13	7/20/13	1	
100% Internal Package Drop	12/3/13	12/4/13	1	
Delivery- LO2 Vaporizer	6/5/13	6/6/13	1	
Contract Award-LO2 VJ Piping	7/17/13	7/18/13	1	
Contract Award-LO2 Cryo Piping/Flexhose Assemblies	7/17/13	7/18/13	1	
Contract Prep- LO2 Cryo Skids	8/30/13	9/28/13	20	
Delivery - VJ Piping Phase 3	9/16/13	9/17/13	1	
Delivery - Cryo Piping.Flexhose Assemblies	9/19/13	9/20/13	1	
Contract Award - LO2 Cryo Skids	10/29/13	10/30/13	1	
Delivery - VJ Piping Phase 1	11/25/13	11/26/13	1	
Delivery - LO2 Cryo Skids	3/24/14	3/25/14	1	
Delivery - VJ Piping Phase 2	4/17/14	4/18/14	1	
Delivery - VJ Piping Phase 3	8/25/14	8/26/14	1	
+100% Primary Loading Scenarios	12/4/13	6/3/14	124	
CS Slow Fill	12/4/13	12/18/13	10	NASA
CS Fast Fill	12/18/13	12/28/13	7	NASA
CS Topping	12/30/13	1/7/14	5	NASA
CS Replenish	12/30/13	1/22/14	15	NASA
US Slow Fill	1/22/14	2/5/14	10	NASA
US Fast Fill	2/5/14	2/14/14	7	NASA
US Topping	2/14/14	2/22/14	5	NASA
US Replenish	2/14/14	3/8/14	15	NASA
US Tank Drain	3/10/14	3/22/14	10	NASA
CS Tank Drain	3/24/14	4/5/14	10	NASA
Geysering Analysis Vertical Lines	4/7/14	5/3/14	20	NASA
Chilldown Ground System	5/5/14	5/17/14	10	NASA
Chilldown CS	5/19/14	5/24/14	5	NASA
Chilldown US	5/27/14	6/3/14	5	NASA
+100% Probability Analysis	6/3/14	7/16/14	30	
Sensitivity Analysis	6/3/14	6/17/14	10	NASA
Error Analysis	6/17/14	7/1/14	10	NASA
Performance Box	7/1/14	7/16/14	10	NASA
+100% Analysis Report	7/16/14	8/13/14	20	
+100% Analysis Report Update	7/16/14	8/13/14	20	NASA



SLS LO2 System Analysis Schedule

Gantt Chart

Jun 26, 2012

6

SLS LO2 System Analysis Schedule

Jun 26, 2012

Resources Chart

7

Name	Default role
Craig Fortier	Lead Analyst
Jared Congiardo	Lead Analyst
ESC #1	Design Engineer
Jared Berg	Fluid Analyst
ESC #2	Design Engineer

APPENDIX C. GENERAL EXAMPLE ANALYSIS MEMO

Performed by: Name
Checked/Verified by: Name
Software: Name
Model Name: Name.xyz Model Revision/Date

Problem:
Problem statement of what is being performed.

Discussion:
Provide a technical discussion and/or background of the system or component that is being evaluated. Describe how this is supposed to work and give any further pertinent details.

Assumptions:
The assumptions used in the analysis should be listed here.

Boundary/Load Conditions:
The boundary conditions, design margins, and uncertainties used in this analysis should be listed here.

Detailed Analysis:
Provide a detailed explanation of the analysis that was performed. This should include equations with references and walk the reader through the work.

Results:
Should include the data from the M&S here in either graphical or tabular form, whichever is most suitable to the application.

Conclusions:
Summary of the results and what is determined through the analysis.

Nomenclature:

PSIG	Pounds per square inch

Reference:

APPENDIX D. SPECIFIC EXAMPLE ANALYSIS MEMO

Analysis of Heat Leak Through a Vacuum Jacketed Pipe

Performed by: Jared Congiardo
Checked by: Justin Oliveira
Software: Sinaps (Sinda/Fluint) Version
5.2 Model: VJheatleak Rev B (5/13/2010)

Problem:
Vacuum-jacketed (VJ) pipe is commonly used for cryogenic applications to minimize heat leak into the pipe system. This reduces commodity loss and allows better control of conditions at the process interface. Tightly constrained project interface requirements necessitate a detailed analysis of the heat leak through the pipe into the system, including the end caps on the pipe spool segments.

Discussion:
The typical design of VJ pipe consists of the fluid-carrying inner pipe, several thicknesses of multilayer insulation, and an outer pipe. The ends of each spool are enclosed. One or more pump-out ports are installed to allow the removal of the atmosphere within the enclosure and to maintain vacuum level. The MLI is commonly aluminized polyester film or plastic sheet (Mylar) with a low thermal-conductivity spacer to minimize contact between the polyester film or plastic sheet layers (Mylar). MLI configured in this manner acts as a shield against thermal radiation.

Vacuum jacketed pipes are not perfectly insulated, though they are often treated as adiabatic for preliminary analyses. This assumption may be appropriate for systems with short running lengths but often invalid for cross-country systems. The major sources of heat leak are the end enclosures, because they provide a direct thermal path between the outer and inner pipes. Additionally, structural spacers placed along the length of the pipe create a thermal path. These are typically made of a low thermal conductivity material, and exist only to maintain the spacing between the inner and outer pipe. The MLI also provides a path for conduction. Last, a perfect vacuum cannot be created. Some atmosphere will remain and outgassing from materials in the enclosure will cause additional pressure. This creates the possibility for heat transfer via gas conduction, or in some cases, natural convection. Each of these heat transfer paths must be considered when performing a heat leak analysis.

In this case, a discretized SINDA model was used to characterize the heat leak into a vacuum jacketed pipe spool.

Assumptions:

- Radiation shields are aluminized polyester film or plastic sheet (Mylar) with an emissivity of 0.04.
- Twenty two layers of MLI with a total thickness of 0.28947".

- Interstitial gas assumed to be helium.
- Cone enclosures are assumed to be 304 stainless steel.
- MLI has a thermal conductivity of 0.0153 Btu/(hr*ft^2*R)

Convection heat transfer on inner and outer surfaces is neglected. Inner and outer pipe surfaces are held to be equal to the temperature of their respective environments.

Boundary Conditions:

- Pipe spool is 60 ' long with a 4" nominal inner pipe and a 6" nominal outer pipe.
- The spool contains eight thermally active spacers made of G-10CR fiberglass epoxy.
- Cone enclosure is 18" long, 0.125" thick.
- External temperature is between 70 °F and 158 °F.
- Internal fluid temperature is 37 °R (liquid hydrogen temperature).

Figure 3 shows a partial cross section of the VJ pipe with a section through the cylindrical spacers. The MLI resides between the outer and inner pipes.

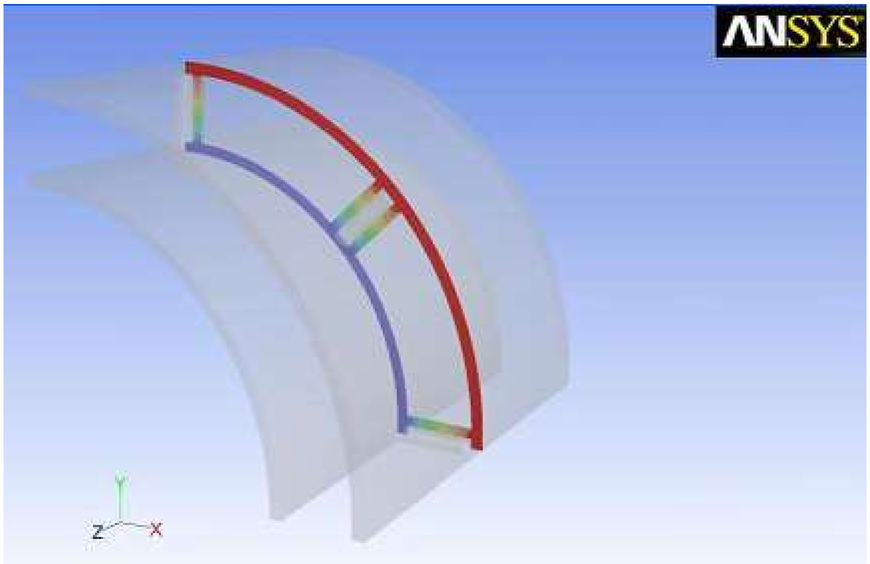


Figure 3. ANSYS Model of VJ Pipe Cross Section

Detailed Analysis:

The model is a SINDA model only, and is shown in Figure 4. No fluid flow is necessary. The hot-side boundary node represents the outer pipe. The cold-side boundary node represents the inner pipe. There are five discretized conductance paths through three materials. The first represents one of the fiberglass spacers within the spool. The middle three are cloned nodes representing the MLI. The conductance paths are MLI contact conduction, radiative heat transfer, and gas conduction, respectively. The final path is conduction through the cone enclosure at the end of the pipe spool.

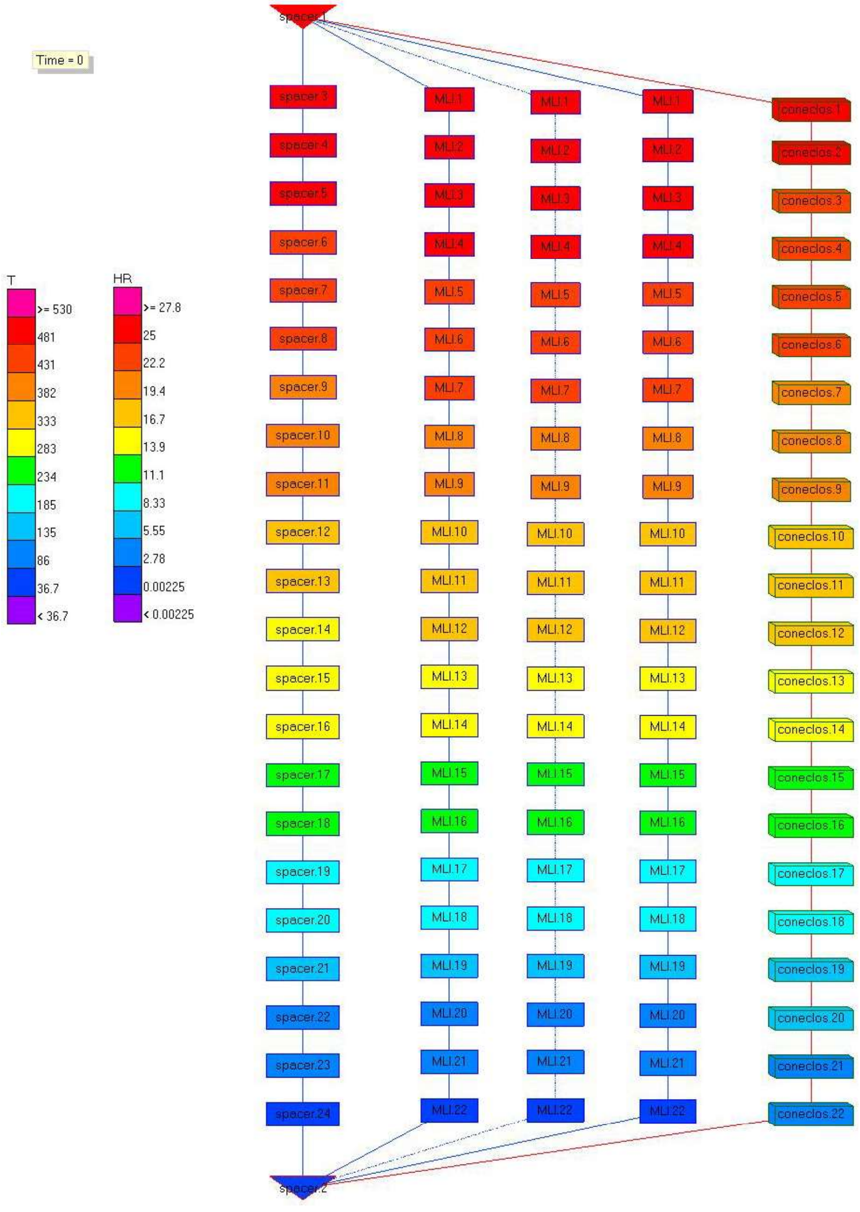


Figure 4. SINDA Model of VJ Pipe Cross Section

For ease of analysis, the model is configured to output a CSV file that can be interpreted by Microsoft Excel. The model is parameterized such that it is measuring the heat through 1 foot of pipe, with one spacer and one end cap enclosure. The results for this condition are shown in Figure 4.

Warm Side Temperature	spacer conduction	MLI conduction	MLI radiation	MLI gas conduction	Endcap conduction	Interstitial Pressure	Total Heat Leak	Notes
Deg F	Btu/hr	Btu/hr	Btu/hr	Btu/hr	Btu/hr	torr	Btu/hr	
70	1.46862	0.40752	0.1629196	2.309E-06	27.72517	1.00E-08	29.76423	
70	2.145	0.408	0.163	0.000	27.725	1.00E-08	30.44098	warp
158	1.879	0.479	0.297	0.000	34.353	1.00E-08	37.00807	
158	2.729	0.479	0.297	0.000	34.353	1.00E-08	37.85751	warp

Figure 5. SINDA Results for 1’ Pipe Stool with One Spacer and One End Cap Enclosure

The results are then simply multiplied to give the results for a 60-foot spool with eight spacers and two end cap enclosures, and are shown in Figure 5.

Warm Side Temperature	spacer conduction	Total MLI heat leak	Endcap conduction	Interstitial Pressure	Total Heat Leak	Notes
Deg F	Btu/hr	Btu/hr	Btu/hr	torr	Btu/hr	
70	11.74895	0.57044187	55.45035	1.00E-08	67.769742	
70	17.16298	0.7758426	55.45035	1.00E-08	73.389173	warp
158	15.03505	0.7758426	68.7057	1.00E-08	84.516593	
158	21.8306	0.7758426	68.7057	1.00E-08	91.312143	warp

Figure 6. SINDA Results for 60’ Pipe Stool with Eight Spacers and Two End Cap Enclosures

Vacuum pressure within the interstitial space was also varied between 1×10–1 torr and 1×10–8 torr in order to evaluate sensitivity to gas conduction. Gas conduction starts to become significant at 1×10–2 torr. These results are shown in Figure 6.

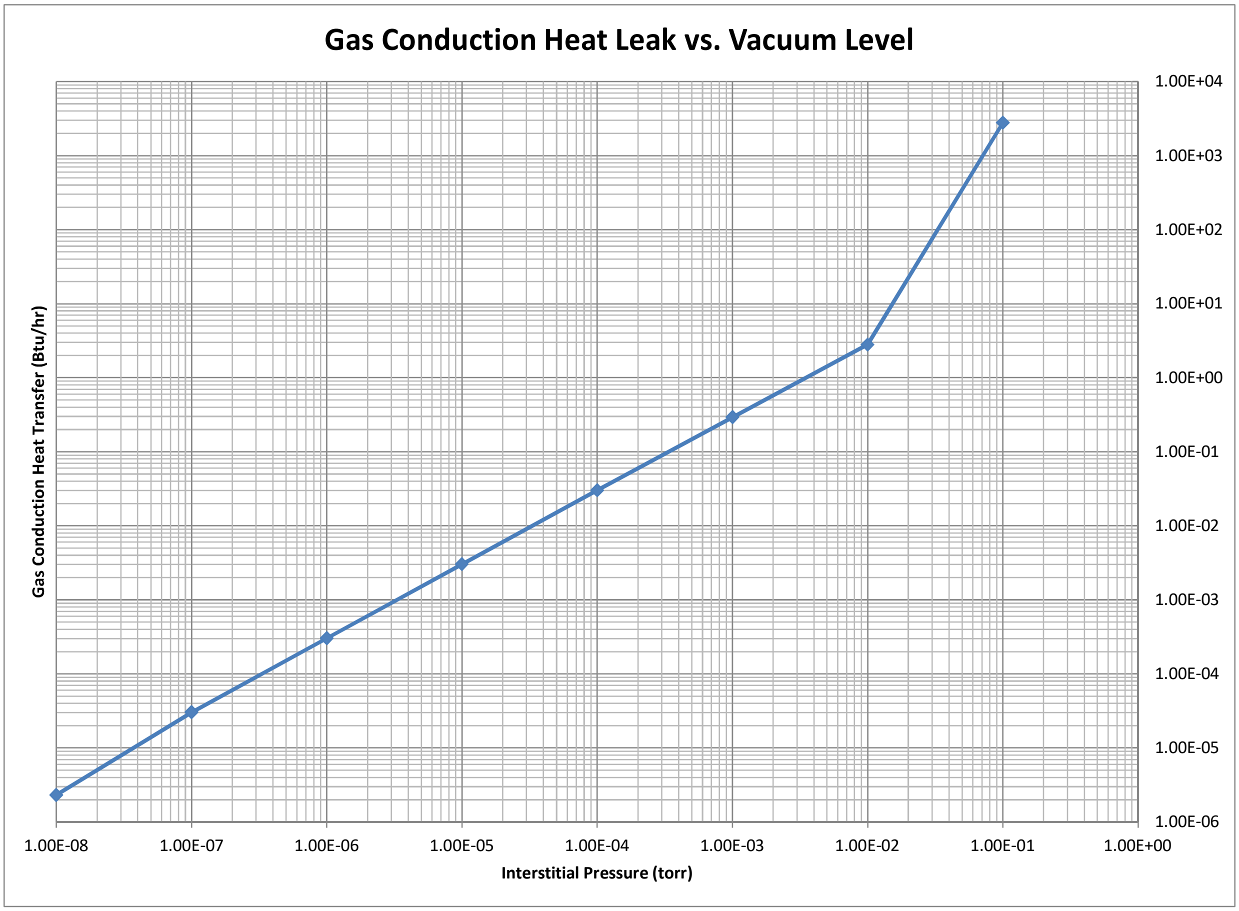


Figure 7. SINDA Results for Interstitial Gas Conduction Heat Transfer

Validation Subsection:
Conduction through the spacer is straightforward linear conduction. A sample calculation is provided below:

$OD_{spacer} := 0.49in$	cylindrical spacer outer diameter
$ID_{spacer} := 0.25in$	cylindrical spacer inner diameter
$len := 0.875in$	cylindrical spacer length
$k_{G10} := 0.24 \frac{mBTU}{hr \cdot ft \cdot R}$	thermal conductivity of G10 fiberglass epoxy
$T_{hot} := 618R$	hot side temperature
$T_{cold} := 37R$	cold side temperature
$area := \frac{\pi \cdot \left(OD_{spacer}^{2} - ID_{spacer}^{2}\right)}{4} = 9.687 \times 10^{-4} ft^{2}$	spacer cross sectional area
$Q_{spacer} := k_{G10} \cdot \frac{area \cdot \left(T_{hot} - T_{cold}\right)}{len}$	heat transfer through spacer
$Q_{spacer} = 1.852 \frac{mBTU}{hr}$	

MLI conduction is evaluated using the thermal resistance equation for a cylindrical wall and the temperature differential (Incropera, DeWitt):

$$R_{t,cond} = \frac{ln\left(\frac{r_2}{r_1}\right)}{2\pi L k} \qquad \text{Eq. 1}$$

Analysis of Heat Leak Through a Vacuum Jacketed Pipe

Performed by: Jared Congiardo
Checked by: Justin Oliveira
Software: Sinaps (Sinda/Fluint) Version
5.2 Model: VJheatleak Rev B (05/13/2010)

Problem:

Vacuum-jacketed (VJ) pipe is commonly used for cryogenic applications to minimize heat leak into the pipe system. This reduces commodity loss and allows better control of conditions at the process interface. Tightly constrained project interface requirements necessitate a detailed analysis of the heat leak through the pipe into the system, including the end caps on the pipe spool segments.

Discussion:

The typical design of VJ pipe consists of the fluid-carrying inner pipe, several thicknesses of multilayer insulation, and an outer pipe. The ends of each spool are enclosed. One or more pump-out ports are installed to allow the removal of the atmosphere within the enclosure and to maintain vacuum level. The MLI is commonly aluminized polyester film or plastic sheet (Mylar) with a low thermal-conductivity spacer to minimize contact between the polyester film or plastic sheet layers (Mylar). MLI configured in this manner acts as a shield against thermal radiation.

Vacuum jacketed pipes are not perfectly insulated, though they are often treated as adiabatic for preliminary analyses. This assumption may be appropriate for systems with short running lengths but often invalid for cross-country systems. The major sources of heat leak are the end enclosures, because they provide a direct thermal path between the outer and inner pipes. Additionally, structural spacers placed along the length of the pipe create a thermal path. These are typically made of a low thermal conductivity material, and exist only to maintain the spacing between the inner and outer pipe. The MLI also provides a path for conduction. Last, a perfect vacuum cannot be created. Some atmosphere will remain and outgassing from materials in the enclosure will cause additional pressure. This creates the possibility for heat transfer via gas conduction, or in some cases, natural convection. Each of these heat transfer paths must be considered when performing a heat leak analysis.

In this case, a discretized SINDA model was used to characterize the heat leak into a vacuum jacketed pipe spool.

Assumptions:

- Radiation shields are aluminized polyester film or plastic sheet (Mylar) with an emissivity of 0.04.
- Twenty two layers of MLI with a total thickness of 0.28947".
- Interstitial gas assumed to be helium.

- Cone enclosures are assumed to be 304 stainless steel.
- MLI has a thermal conductivity of 0.0153 Btu/(hr*ft^2*R)

Convection heat transfer on inner and outer surfaces is neglected. Inner and outer pipe surfaces are held to be equal to the temperature of their respective environments.

Boundary Conditions:

- Pipe spool is 60 ' long with a 4" nominal inner pipe and a 6" nominal outer pipe.
- The spool contains eight thermally active spacers made of G-10CR fiberglass epoxy.
- Cone enclosure is 18" long, 0.125" thick.
- External temperature is between 70 °F and 158 °F.
- Internal fluid temperature is 37 °R (liquid hydrogen temperature).

Figure 8 shows a partial cross section of the VJ pipe with a section through the cylindrical spacers. The MLI resides between the outer and inner pipes.

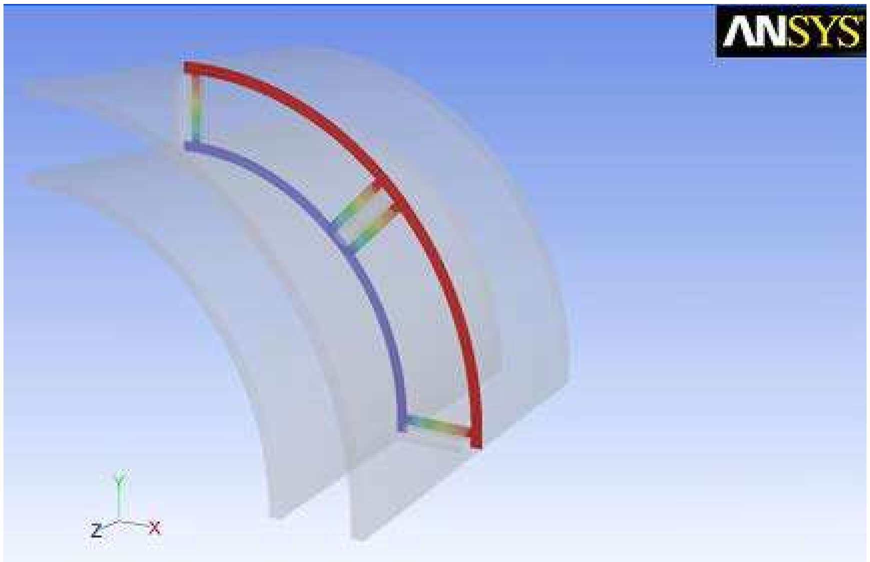


Figure 8. ANSYS Model of VJ Pipe Cross Section

Detailed Analysis:

The model is a SINDA model only, and is shown in Figure 2. No fluid flow is necessary. The hot-side boundary node represents the outer pipe. The cold-side boundary node represents the inner pipe. There are five discretized conductance paths through three materials. The first represents one of the fiberglass spacers within the spool. The middle three are cloned nodes representing the MLI. The conductance paths are MLI contact conduction, radiative heat transfer, and gas conduction, respectively. The final path is conduction through the cone enclosure at the end of the pipe spool.

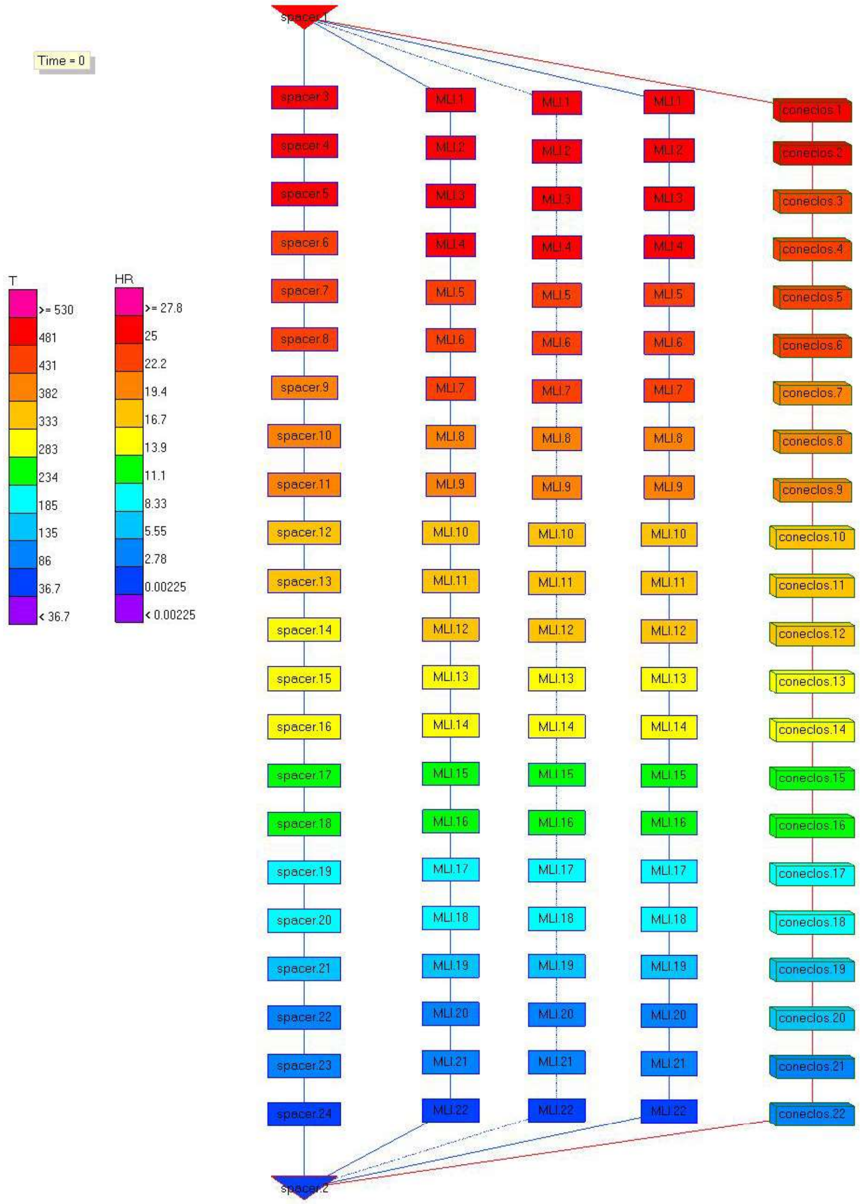


Figure 9. SINDA Model of VJ Pipe Cross Section

For ease of analysis, the model is configured to output a CSV file that can be interpreted by Microsoft Excel. The model is parameterized such that it is measuring the heat through 1 foot of pipe, with one spacer and one end cap enclosure. The results for this condition are shown in Figure 3.

Warm Side Temperature	spacer conduction	MLI conduction	MLI radiation	MLI gas conduction	Endcap conduction	Interstitial Pressure	Total Heat Leak	Notes
Deg F	Btu/hr	Btu/hr	Btu/hr	Btu/hr	Btu/hr	torr	Btu/hr	
70	1.46862	0.40752	0.1629196	2.309E-06	27.72517	1.00E-08	29.76423	
70	2.145	0.408	0.163	0.000	27.725	1.00E-08	30.44098	warp
158	1.879	0.479	0.297	0.000	34.353	1.00E-08	37.00807	
158	2.729	0.479	0.297	0.000	34.353	1.00E-08	37.85751	warp

Figure 10. SINDA Results for 1’ Pipe Spool With One Spacer and One End Cap Enclosure

The results are then simply multiplied to give the results for a 60-foot spool with eight spacers and two end cap enclosures, and are shown in Figure 4.

Warm Side Temperature	spacer conduction	Total MLI heat leak	Endcap conduction	Interstitial Pressure	Total Heat Leak	Notes
Deg F	Btu/hr	Btu/hr	Btu/hr	torr	Btu/hr	
70	11.74895	0.57044187	55.45035	1.00E-08	67.769742	
70	17.16298	0.7758426	55.45035	1.00E-08	73.389173	warp
158	15.03505	0.7758426	68.7057	1.00E-08	84.516593	
158	21.8306	0.7758426	68.7057	1.00E-08	91.312143	warp

Figure 11. SINDA Results for 60’ Pipe Spool With Eight Spacers and Two End Cap Enclosures

Vacuum pressure within the interstitial space was also varied between 1×10^{-1} torr and 1×10^{-8} torr in order to evaluate sensitivity to gas conduction. Gas conduction starts to become significant at 1×10^{-2} torr. These results are shown in Figure 5.

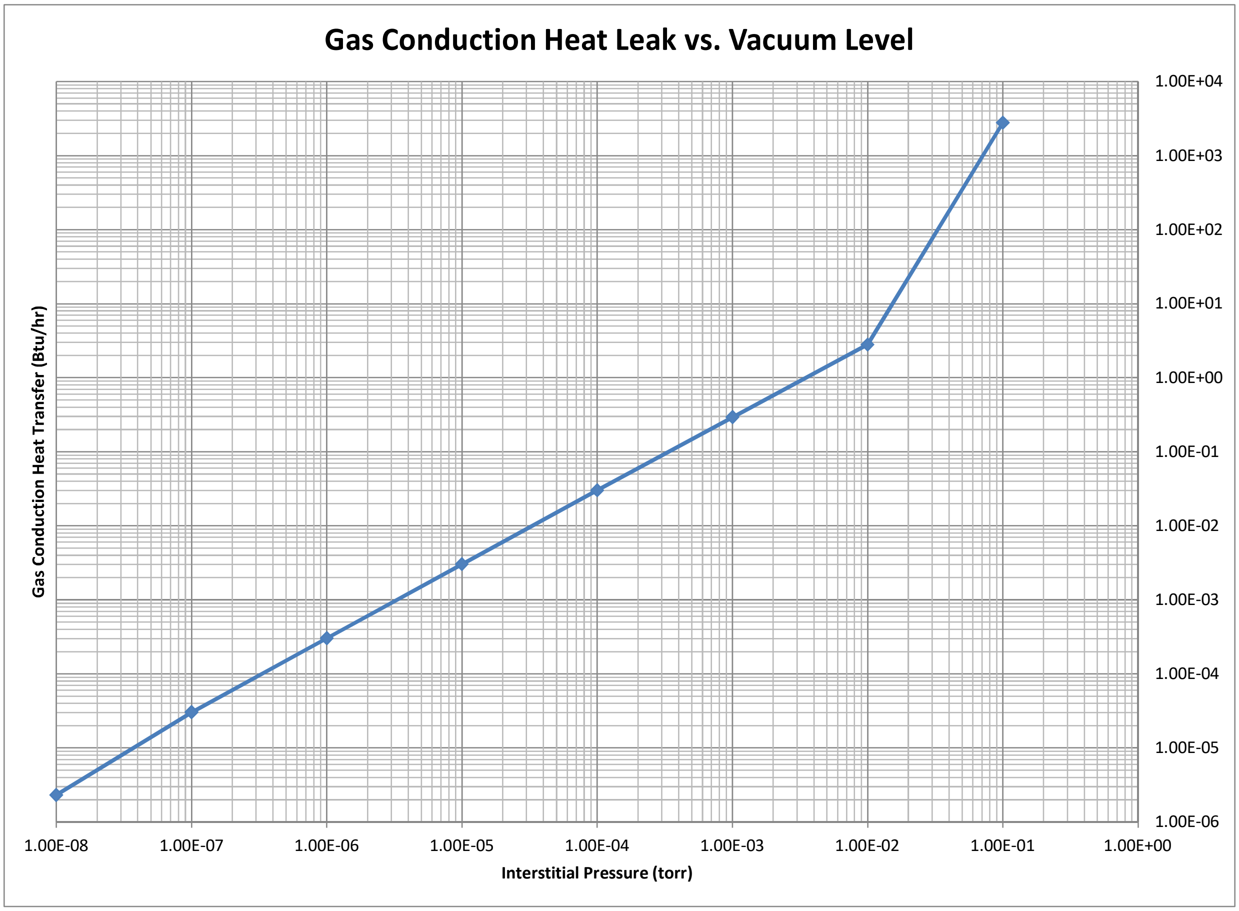


Figure 12. SINDA Results for Interstitial Gas Conduction Heat Transfer

Validation Subsection:
Conduction through the spacer is straightforward linear conduction. A sample calculation is provided below:

$OD_{spacer} := 0.49in$	cylindrical spacer outer diameter
$ID_{spacer} := 0.25in$	cylindrical spacer inner diameter
$len := 0.875in$	cylindrical spacer length
$k_{G10} := 0.24\frac{mBTU}{hr \cdot ft \cdot R}$	thermal conductivity of G10 fiberglass epoxy
$T_{hot} := 618R$	hot side temperature
$T_{cold} := 37R$	cold side temperature
$area := \frac{\pi \cdot \left(OD_{spacer}^{2} - ID_{spacer}^{2}\right)}{4} = 9.687 \times 10^{-4}\,ft^{2}$	spacer cross sectional area
$Q_{spacer} := k_{G10} \cdot \frac{area \cdot \left(T_{hot} - T_{cold}\right)}{len}$	heat transfer through spacer
$Q_{spacer} = 1.852\frac{mBTU}{hr}$	

MLI conduction is evaluated using the thermal resistance equation for a cylindrical wall and the temperature differential (Incropera, DeWitt):

$$R_{t,cond} = \frac{ln\left(\frac{r_2}{r_1}\right)}{2\pi L k} \qquad \text{Eq. 1}$$

A sample calculation is provided below:

$sk10od4 := 4.5in$	outer diameter of inner pipe
$th_{MLI} := .28947in$	MLI thickness
$k_{MLI} := 1.6776 \times 10^{-5} \frac{mBTU}{hr \cdot ft \cdot R}$	MLI thermal conductivity
$l_{pipe} := 1ft$	pipe length
$R_{mli} := \frac{\ln\left[\frac{(sk10od4 + 2th_{MLI})}{sk10od4}\right]}{2\pi \cdot l_{pipe} \cdot k_{MLI}}$	thermal resistance through MLI
$Q_{mlik} := \frac{(T_{hot} - T_{cold})}{R_{mli}}$	conduction heat transfer through MLI
$Q_{mlik} = 0.506 \frac{mBTU}{hr}$	

Radiation heat transfer between layers of MLI uses the infinite concentric cylinder relation as defined in Incropera and DeWitt.

$$q_{12} = \frac{\sigma A_1 (T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1 - \varepsilon_2}{\varepsilon_2}\left(\frac{r_1}{r_2}\right)} \qquad \text{Eq. 2}$$

A sample calculation is provided below:

$sk10id6 := 6.357in$	inner diameter of outer pipe
$A_1 := \pi \cdot sk10od4 \cdot l_{pipe}$	inner pipe outer surface area
$\varepsilon_1 := 0.04$	emissivity of aluminized mylar
$\sigma := 5.67 \cdot 10^{-8} \frac{W}{m^2 \cdot K^4}$	Stefan-Boltzmann constant
$Q_{mlir} := \frac{\left[\sigma \cdot A_1 \cdot \left(T_{hot}{}^4 - T_{cold}{}^4\right)\right]}{\left[\left(\frac{1}{\varepsilon_1}\right) + \left[\frac{(1 - \varepsilon_1)}{\varepsilon_1}\right] \cdot \left(\frac{sk10od4}{sk10id6}\right)\right]}$	radiation heat transfer through MLI
$Q_{mlir} = 7.002 \frac{mBTU}{hr}$	

Free molecular gas conduction between layers of MLI must be considered when the Knudsen number is greater than 10. The Knudsen number is defined by dividing the mean free path, defined for helium by Green as

$$\lambda(T_g) = 1.23\frac{\mu(T_g)}{P}\left(\frac{RT}{M}\right)^{0.5} \qquad \text{Eq. 3}$$

$$\mu(T_g) = 5.03 \times 10^{-7} \quad T_g^{0.65} \qquad \text{Eq. 1a}$$

by the spacing between the aluminized polyester film or plastic sheet. If this value is greater than 10, then free molecular conduction is taking place. It should be noted that Equation 3 is an empirical correlation using metric units. The heat transfer rate for this condition is defined by

$$Q = F_a G p A_1 (T_2 - T_1) \qquad \text{Eq. 4}$$

$$G = \frac{\gamma + 1}{\gamma - 1}\left(\frac{g_c R}{8\pi T}\right)^{1/2} \qquad \text{Eq. 4a}$$

$$\frac{1}{F_a} = \frac{1}{\alpha_1} + \left(\frac{1}{\alpha_2} - 1\right) \qquad \text{Eq. 4b}$$

$$\alpha(T) = 1.23e^{-T/20} + 8.34 \times 10^{-4} T \qquad \text{Eq. 4c}$$

Equation 4c is the temperature-dependent accommodation coefficient of helium to an aluminum plate as defined by Green, and is an empirical correlation in metric units. The remaining equations are from Barron. A sample calculation is provided below:

$T_{warm} := 79.4R$	MLI layer temperature
$R_{gas} := 1545ft\cdot\frac{lbf}{mol\cdot R}$	universal gas constant
$P_{int} := 1\cdot 10^{-8} torr$	interstitial pressure
$MW_{He} := 4.003\frac{lbm}{mol}$	helium molecular weight
$T_{avg} := \frac{(T_{warm} + T_{cold})}{2}$	average temperature between layers
$hevisc := 5.03\cdot 10^{-7}\frac{kg}{m\cdot s\cdot K^{0.65}}\cdot T_{avg}^{\;0.65}$	helium viscosity
$hemfp := 1.23\left(\frac{hevisc}{P_{int}}\right)\cdot\left(R_{gas}\cdot\frac{300K}{MW_{He}}\right)^{0.5}$	helium mean free path

$$\mathrm{Knud} := \frac{\mathrm{hemfp}}{\frac{\mathrm{th}_{\mathrm{MLI}}}{22}}$$

Knudsen number

$$\mathrm{Knud} = 1.05 \times 10^{7}$$

$$\alpha_{\mathrm{hot}} := 1.23e^{\frac{-T_{\mathrm{warm}}}{20K}} + 8.34 \cdot 10^{-4} \cdot T_{\mathrm{warm}} \cdot \frac{1}{1K}$$

accommodation coefficient

$$\alpha_{\mathrm{hot}} = 0.172$$

$$\alpha_{\mathrm{cold}} := 1.23e^{\frac{-T_{\mathrm{cold}}}{20K}} + 8.34 \cdot 10^{-4} \cdot T_{\mathrm{cold}} \cdot \frac{1}{1K}$$

accommodation coefficient

$$\alpha_{\mathrm{cold}} = 0.457$$

$$A_2 := \pi \cdot \left(\mathrm{sk10od4} + \frac{2 \cdot \mathrm{th}_{\mathrm{MLI}}}{22} \right) \cdot l_{\mathrm{pipe}}$$

surface area of first layer of MLI

$$F_a := \frac{1}{\left[\left(\frac{1}{\alpha_{\mathrm{cold}}} \right) + \left(\frac{A_1}{A_2} \right) \cdot \left(\frac{1}{\alpha_{\mathrm{hot}}} \right) - 1 \right]}$$

accommodation coefficient factor

$$\gamma_{\mathrm{He}} := 1.67$$

helium specific heat ratio

$$g_c := 32.174 \mathrm{lbm} \cdot \frac{\mathrm{ft}}{\mathrm{lbf} \cdot s^2}$$

gravitational coefficient

$$G_{ee} := \left[\frac{(\gamma_{\mathrm{He}} + 1)}{(\gamma_{\mathrm{He}} - 1)} \right] \cdot \left(g_c \cdot \frac{R_{\mathrm{gas}}}{8 \cdot \pi \cdot MW_{\mathrm{He}} \cdot T_{\mathrm{avg}}} \right)^{0.5}$$

$$Q_{\mathrm{MLIgc}} := F_a \cdot G_{ee} \cdot P_{\mathrm{int}} \cdot A_1 \cdot (T_{\mathrm{warm}} - T_{\mathrm{cold}})$$

gas conduction heat transfer rate

$$Q_{\mathrm{MLIgc}} = 1.073 \times 10^{-5} \, \frac{\mathrm{mBTU}}{\mathrm{hr}}$$

Finally, the cone closures are simple conduction. When discretizing the nodes for use in SINDA, care must be taken to properly size the aspect ratio and node volume. This is done by treating the cone closure segments as successive frusta of right circular cones.

References:

Barron, R.F. 1999. *Cryogenic Heat Transfer*. New York: Taylor & Francis.

Green, M.A. 1994. "Radiation and Gas Conduction Heat Transport Across a Helium Dewar Multilayer Insulation System." Berkeley, California: Lawrence Berkeley Laboratory.

Incropera, F.P., and D.P. DeWitt. 2002. *Introduction to Heat Transfer,* 4th ed. New York: John Wiley and Sons.

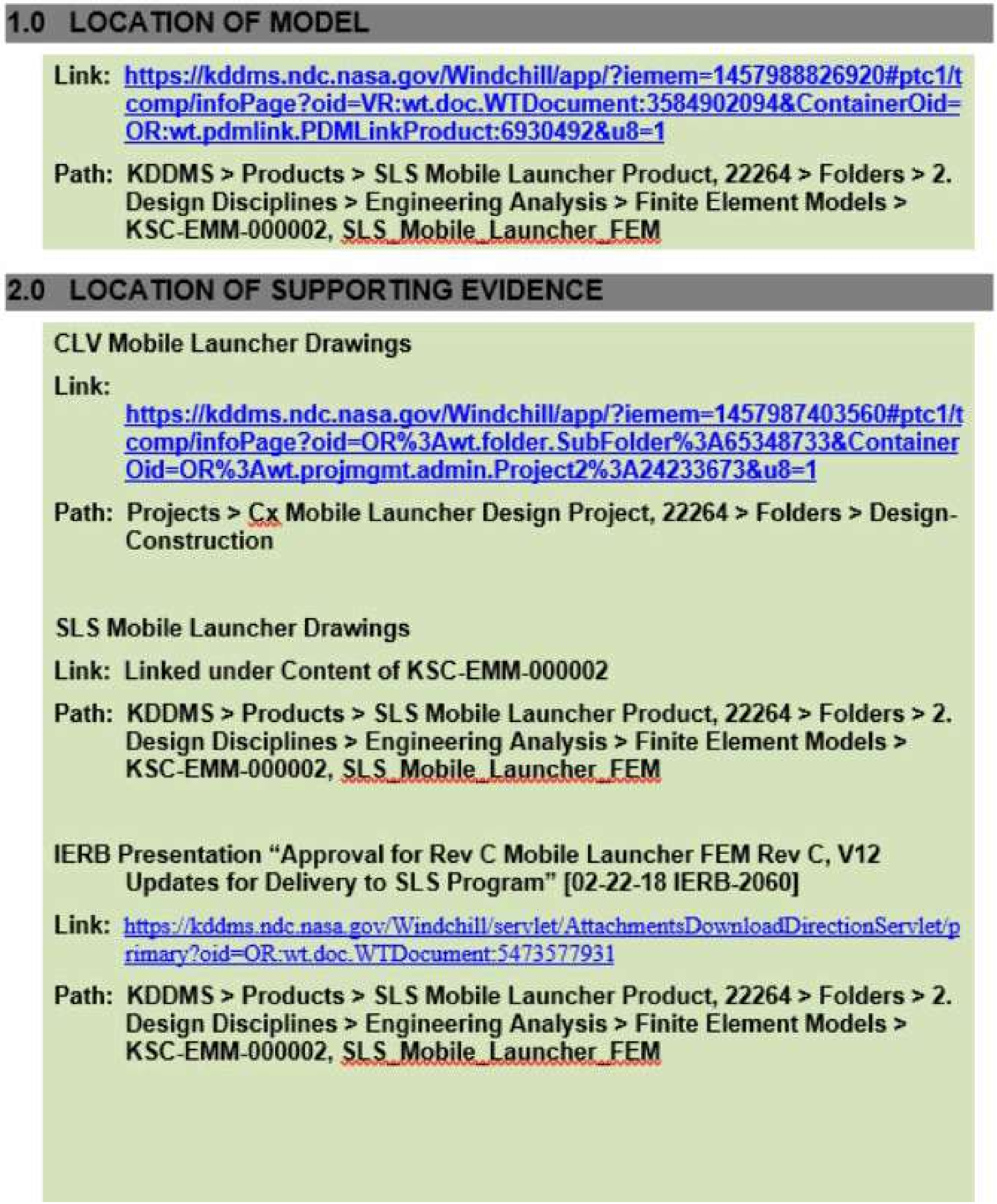
APPENDIX E. CRITICALITY ASSESSMENT EXAMPLE

EMM Unique Identifier:	**KSC-EMM-000002**
Model Title:	**SLS Mobile Launcher (ML) Finite Element Model (FEM)**
Associated EGS Element/Subsystem(s):	**Mobile Launcher 1**
Model Technique POC:	**Christopher J. Brown**
Lead Analyst:	**Christopher J. Brown**
Engineering Analysis Chief:	**Craig Fortier**
Developing Organization:	**KSC-NE-XY**

Critical Requirement & Rationale:	This model is provided as a cross-program data delivery and is a critical input with significant impact to the overall integrated vehicle coupled loads analysis results mainly in the prelaunch and launch operations.
Statement of Intended Use:	This Finite Element Model is a "loads and dynamics model". As such, the model contains detail that adequately represents the stiffness, mass, and primary low frequency modes of the mobile launcher base and tower. This model provides the SLS Mobile Launcher dynamics models rollout, on-pad stay, prelaunch, and liftoff. These models are required input to the vehicle level coupled loads analysis which produces vehicle loads during those regimes.
Technical Description of Model:	The SLS Mobile Launcher Finite-Element Model (FEM) includes the Base and Tower structure as well as Crew Access Arm (CAA) and Interim Cryogenic Propulsion Stage Umbilical (ICPSU). The model may be applied in multiple configurations with different states of launch accessory deployment. Currently, these include Vehicle Assembly Building (VAB), Rollout, and On-pad Stay. In the VAB the CAA is in the 166 degree position. For rollout, the CAA is retracted. The on-pad stay configuration has the CAA in the deployed position. Note that for liftoff the CAA is again retracted. Model delivery in in compliance with and requirements are specified in the Cross Program Integrated Vehicle Loads Control Plan (SLS-PLAN-062). Model is saved in Siemens NX assembly fem (.afm) format with NASA Structural Analysis (NASTRAN) bulk format attached in ascii file within KDDMS. Model is provided to SLS Program as NASTRAN bulk data. The analysis associated with KSC-EMM-000002 is performed in NX NASTRAN version 9.0. SLS performs a 100 Hz Craig-Bampton reduction on model, and then reformats it into Matlab Mass, Stiffness, and Applied Load Matrices before utilizing it in response analyses.
EMM SME Assessed Consequence Level:	The consequence to human safety or mission success if a design decision is based on flawed model outputs is Catastrophic
Consequence Level Rationale:	An incorrect model could lead to invalid prediction of design-to loads, the prediction of expected vehicle hardware capability, and decisions to fly a mission.

<table>
<tr><td>EMM SME Assessed Influence Level:</td><td colspan="5">The degree to which this model’s results influence an EGS design decision is Significant</td></tr>
<tr><td>Influence Level Rationale:</td><td colspan="5">This model has significant influence on predicted loads during ground operations and when the launch vehicle is sitting on the pad before launch. This model also impacts the initial flexibility sensed by the vehicle at liftoff and influences the ability to ensure vehicle liftoff clearance.</td></tr>
<tr><td colspan="6">EMM SME Recommendations</td></tr>
<tr><td>Consequence Level:</td><td>5</td><td>Influence Level:</td><td>4</td><td>Resulting Color Code:</td><td>Red</td></tr>
<tr><td colspan="3">EMM SME Recommendation to Include Model in EMMI Log:</td><td colspan="3">Yes – Add to EMM Model Log</td></tr>
<tr><td>EMM SME Rationale:</td><td colspan="5">This model is provided as a cross-program data delivery and is a critical input with significant impact to the overall integrated vehicle coupled loads analysis results mainly in the prelaunch and launch operations.</td></tr>
<tr><td colspan="6">Do Model Technical POC, Developer and User Concur with Description, Consequence and Influence?</td></tr>
<tr><td>Technical POC:</td><td>Concur</td><td>Rationale:</td><td colspan="3"></td></tr>
<tr><td>Lead Analyst:</td><td>Concur</td><td>Rationale:</td><td colspan="3"></td></tr>
<tr><td>Engineering Analysis Chief:</td><td>Concur</td><td>Rationale:</td><td colspan="3">Agree with initial assessment. This must be a maintained critical math model, and will be reassessed once more data for the real world system (RWS) is available.</td></tr>
<tr><td colspan="6">Technical Authority Decision</td></tr>
<tr><td>Consequence Level:</td><td>5</td><td>Influence Level:</td><td>4</td><td>Resulting Color Code:</td><td>Red</td></tr>
<tr><td>Technical Authority Concurrence/Rationale:</td><td colspan="5">Patrick Maloney concurs with the assessment (via email, 5/2/2019)</td></tr>
<tr><td colspan="6">Program Decision</td></tr>
<tr><td>Consequence Level:</td><td>5</td><td>Influence Level:</td><td>4</td><td>Resulting Color Code:</td><td>Red</td></tr>
<tr><td>Technical Authority Concurrence/Rationale:</td><td colspan="5">Keith Braun concurs with assessment (via email, 5/14/2019)</td></tr>
</table>

APPENDIX F. METADATA EXAMPLE



1.0 LOCATION OF MODEL

Link: https://kddms.ndc.nasa.gov/Windchill/app/?iemem=1457988826920#ptc1/tcomp/infoPage?oid=VR:wt.doc.WTDocument:3584902094&ContainerOid=OR:wt.pdmlink.PDMLinkProduct:6930492&u8=1

Path: KDDMS > Products > SLS Mobile Launcher Product, 22264 > Folders > 2. Design Disciplines > Engineering Analysis > Finite Element Models > KSC-EMM-000002, SLS_Mobile_Launcher_FEM

2.0 LOCATION OF SUPPORTING EVIDENCE

CLV Mobile Launcher Drawings

Link: https://kddms.ndc.nasa.gov/Windchill/app/?iemem=1457987403560#ptc1/tcomp/infoPage?oid=OR%3Awt.folder.SubFolder%3A65348733&ContainerOid=OR%3Awt.projmgmt.admin.Project2%3A24233673&u8=1

Path: Projects > Cx Mobile Launcher Design Project, 22264 > Folders > Design-Construction

SLS Mobile Launcher Drawings

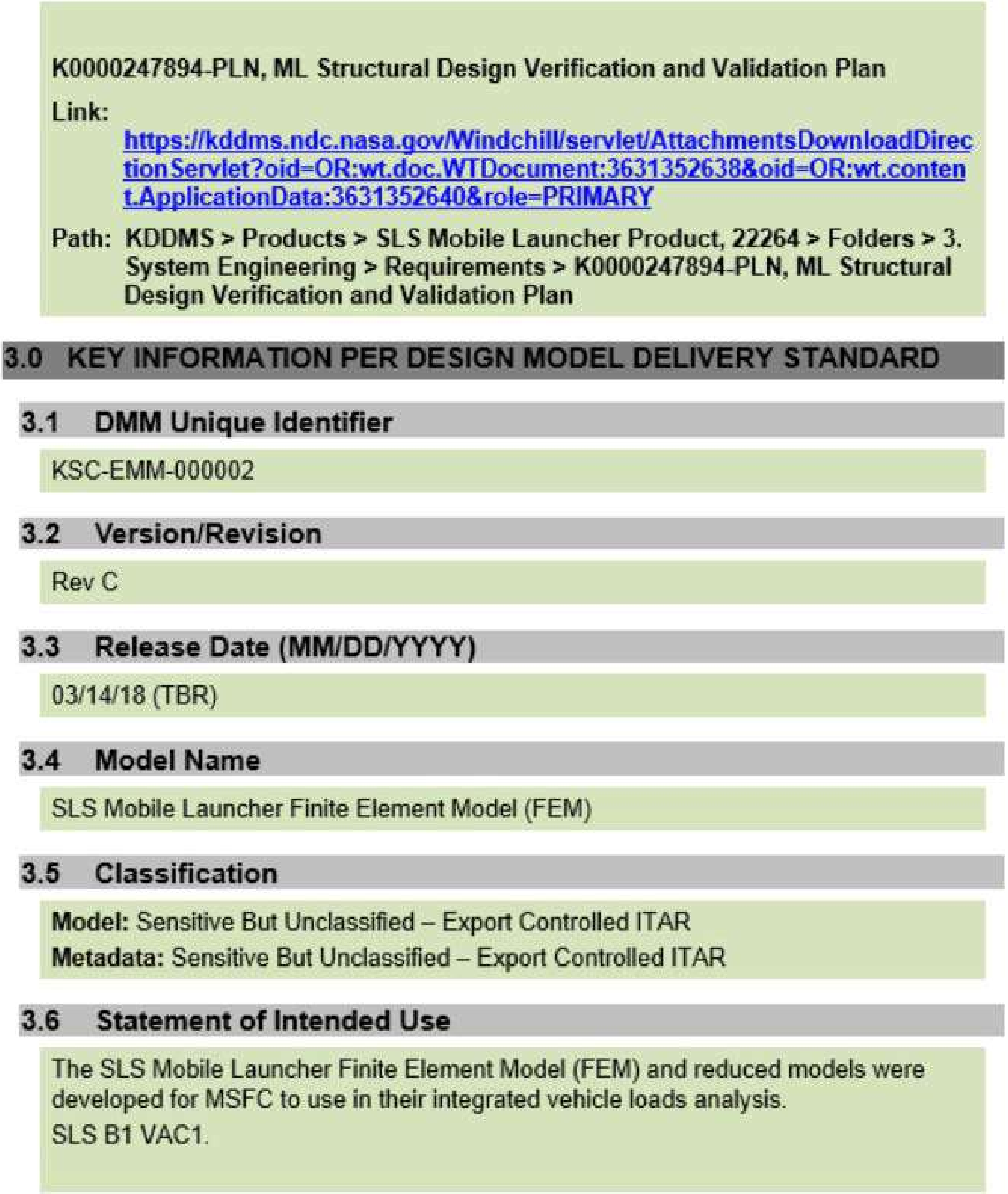
Link: Linked under Content of KSC-EMM-000002

Path: KDDMS > Products > SLS Mobile Launcher Product, 22264 > Folders > 2. Design Disciplines > Engineering Analysis > Finite Element Models > KSC-EMM-000002, SLS_Mobile_Launcher_FEM

IERB Presentation “Approval for Rev C Mobile Launcher FEM Rev C, V12 Updates for Delivery to SLS Program” [02-22-18 IERB-2060]

Link: https://kddms.ndc.nasa.gov/Windchill/servlet/AttachmentsDownloadDirectionServlet/primary?oid=OR:wt.doc.WTDocument:5473577931

Path: KDDMS > Products > SLS Mobile Launcher Product, 22264 > Folders > 2. Design Disciplines > Engineering Analysis > Finite Element Models > KSC-EMM-000002, SLS_Mobile_Launcher_FEM



K0000247894-PLN, ML Structural Design Verification and Validation Plan

Link: https://kddms.ndc.nasa.gov/Windchill/servlet/AttachmentsDownloadDirectionServlet?oid=OR:wt.doc.WTDocument:3631352638&oid=OR:wt.content.ApplicationData:3631352640&role=PRIMARY

Path: **KDDMS > Products > SLS Mobile Launcher Product, 22264 > Folders > 3. System Engineering > Requirements > K0000247894-PLN, ML Structural Design Verification and Validation Plan**

3.0 KEY INFORMATION PER DESIGN MODEL DELIVERY STANDARD

3.1 DMM Unique Identifier

KSC-EMM-000002

3.2 Version/Revision

Rev C

3.3 Release Date (MM/DD/YYYY)

03/14/18 (TBR)

3.4 Model Name

SLS Mobile Launcher Finite Element Model (FEM)

3.5 Classification

Model: Sensitive But Unclassified – Export Controlled ITAR

Metadata: Sensitive But Unclassified – Export Controlled ITAR

3.6 Statement of Intended Use

The SLS Mobile Launcher Finite Element Model (FEM) and reduced models were developed for MSFC to use in their integrated vehicle loads analysis.

SLS B1 VAC1.

The model is also used by SLS Vehicle Management (VM) Separation and Clearance Analysis and the Dynamic Test and Modal Sensitivity Study (DTaMSS)

The IMT/PSMT, & DRT models

3.7 SLSP Element/Subsystem

GSDO Mobile Launcher

3.8 Scope/Milestone

GSDO CDR

Task Team Review Comments:

3.9 Model Point of Contact

Element/Organization Representative: Christopher Brown
Location/Org. Code: KSC/NE-XY
Telephone #: 321-867-7584
Email: christopher.j.brown@nasa.gov

Technical Representative: Christopher Brown
Location/Org. Code: KSC/NE-XY
Telephone #: 321-867-7584
Email: christopher.j.brown@nasa.gov

3.10 Dependencies

The results of KSC-EMM-000002 are used in integrated vehicle loads analyses through DMM-STE-0104. As an input model into DMM-STE-0105 Integrated Vehicle Loads FE Models, this model will be used in all analyses that employ DMM-STE-0104 that include the Mobile Launcher. It is also used in STE-DMM-105-5 which is utilized in the VM Sep analysis CLVTOPS DMM-VM-0002.

Task Team Review Comments:

3.11 Technical Description of Model

This model provides the SLS Mobile Launcher dynamics models rollout, on-pad stay, prelaunch, and liftoff. These models are required input to the vehicle level coupled loads analysis which produces vehicle loads during those regimes.

The SLS Mobile Launcher Finite-Element Model (FEM) includes the Base and Tower structure as well as Crew Access Arm (CAA) and Interim Cryogenic Propulsion Stage Umbilical (ICPSU).

Model delivery requirements are specified in the SLSP Integrated Vehicle Loads Control Plan, SLS-PLAN-062.

The analysis associated with KSC-EMM-000002 is performed in NX NASTRAN version 9.1.

The model may be applied in multiple configurations with different states of launch accessory deployment. Currently, these include VAB, Rollout, and On-pad Stay. In the VAB the CAA is in the 166 degree position. For rollout, the CAA is retracted. The on-pad stay configuration has the CAA in the deployed position. Note that for liftoff the CAA is again retracted.

Task Team Review Comments:

3.12 Assumptions

The modeling approach was consistent with generally accepted practices for developing dynamics finite element models. Simplifying assumptions were used where appropriate.

There are numerous assumptions that are typical of dynamic finite element models. These assumptions include such things as using shell elements at the mid-plane of skin sections, using rigid elements and lumped masses to model most components, neglecting nonlinearities in joints, and addition of nonstructural mass. These approaches are standard practice in dynamic analysis.

Task Team Review Comments:

3.13 Operational Phase

Model is applicable for all phases of operation from rollout through lift-off by using the appropriately configured model.

Task Team Review Comments:

3.14 Verification

The verification of KSC-EMM-000002 is supported by peer reviews within the KSC engineering organization as well as coordinated reviews with the NASA MSFC loads & environments community (EV31). The following reviews were performed:

- Internal review of component models
- Space and Weight check by internal review
- Combined Joint Loads Task Team w/MSFC
- SE&I Working Group
- MSFC check of reduced models (planned to be documented in SLS-RPT-233-1)

Further verification of KSC-EMM-000002 has been accomplished through successful integration and implementation into the NASA MSFC coupled loads analyses.

The following people signed:

Christopher Brown – Preparer

Confidence that the model provides output that truly represents the system is based on the fact that the majority of the structural modeling is consistent with standard design practices and finite element representations thereof. The joints modeled are predominately welded or, if bolted, secondary in nature to the modal dynamics of the overall structure. As a large portion of the Mobile Launcher is already constructed, the member sizes and connections are readily verifiable.

Task Team Review Comments:

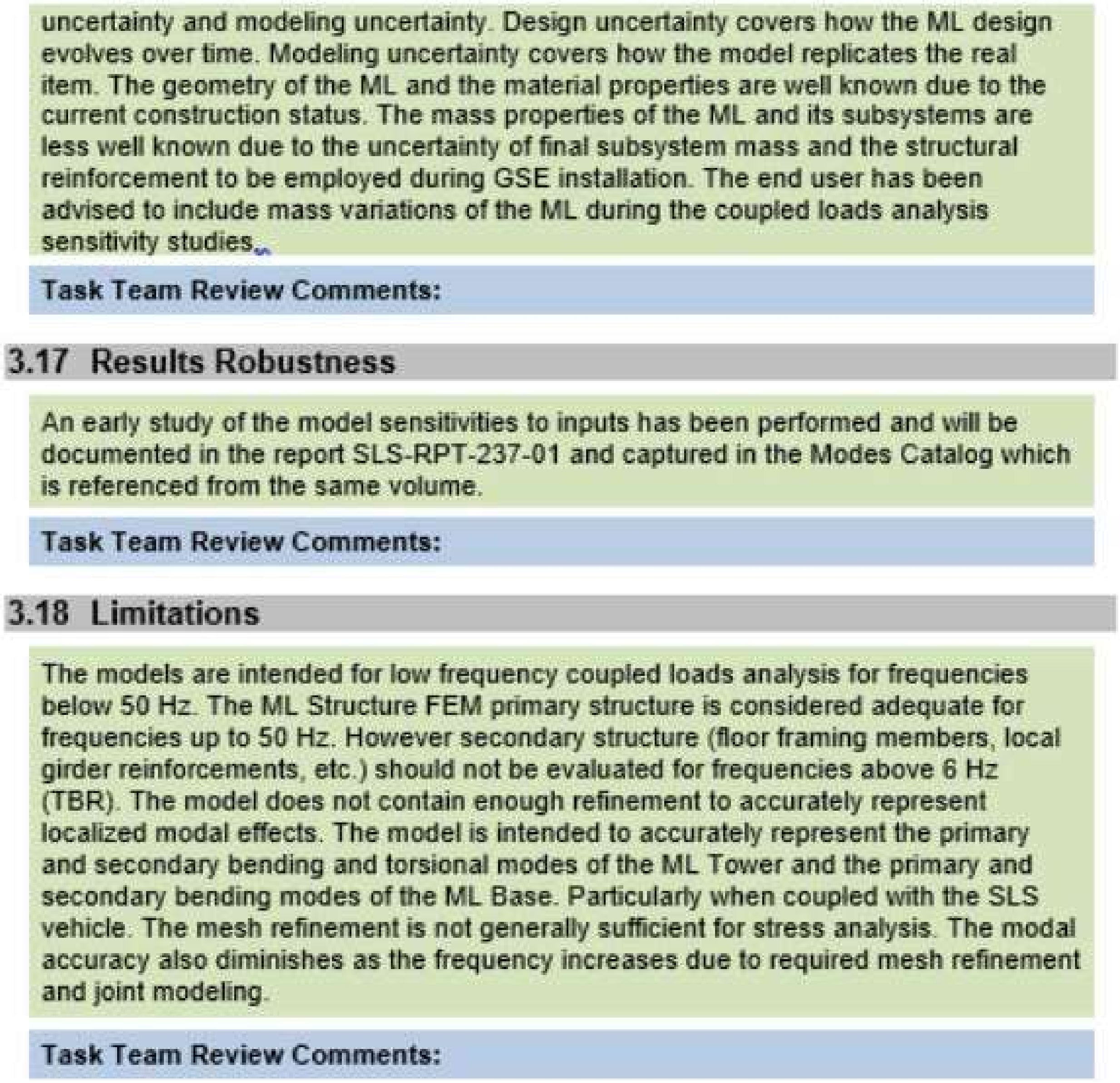
3.15 Validation

This validation work will be detailed in K0000247894-PLN, ML Structural Design Verification and Validation Plan (currently not baselined). This document describes the data acquisition opportunities that include ML rollout and fit check at pad, PSMT, IMT, DRT, and WDR. During these acquisition activities modal and static deflection data will be collected to validate the math model and demonstrate that the tuned model can accurately predict modal frequencies and structural stiffness.

Task Team Review Comments:

3.16 Results Uncertainty

The statistical confidence of the model has not been defined. As an input model into Integrated Vehicle Loads Models (DMM-STE-0104), this model will be used in all analyses that employ DMM-STE-0104 up to and including Liftoff. Uncertainty Factors associated with the Integrated Vehicle Loads Models are applied within the end-user analyses. For the FE Model uncertainty, there are two main factors; design



uncertainty and modeling uncertainty. Design uncertainty covers how the ML design evolves over time. Modeling uncertainty covers how the model replicates the real item. The geometry of the ML and the material properties are well known due to the current construction status. The mass properties of the ML and its subsystems are less well known due to the uncertainty of final subsystem mass and the structural reinforcement to be employed during GSE installation. The end user has been advised to include mass variations of the ML during the coupled loads analysis sensitivity studies.

Task Team Review Comments:

3.17 Results Robustness

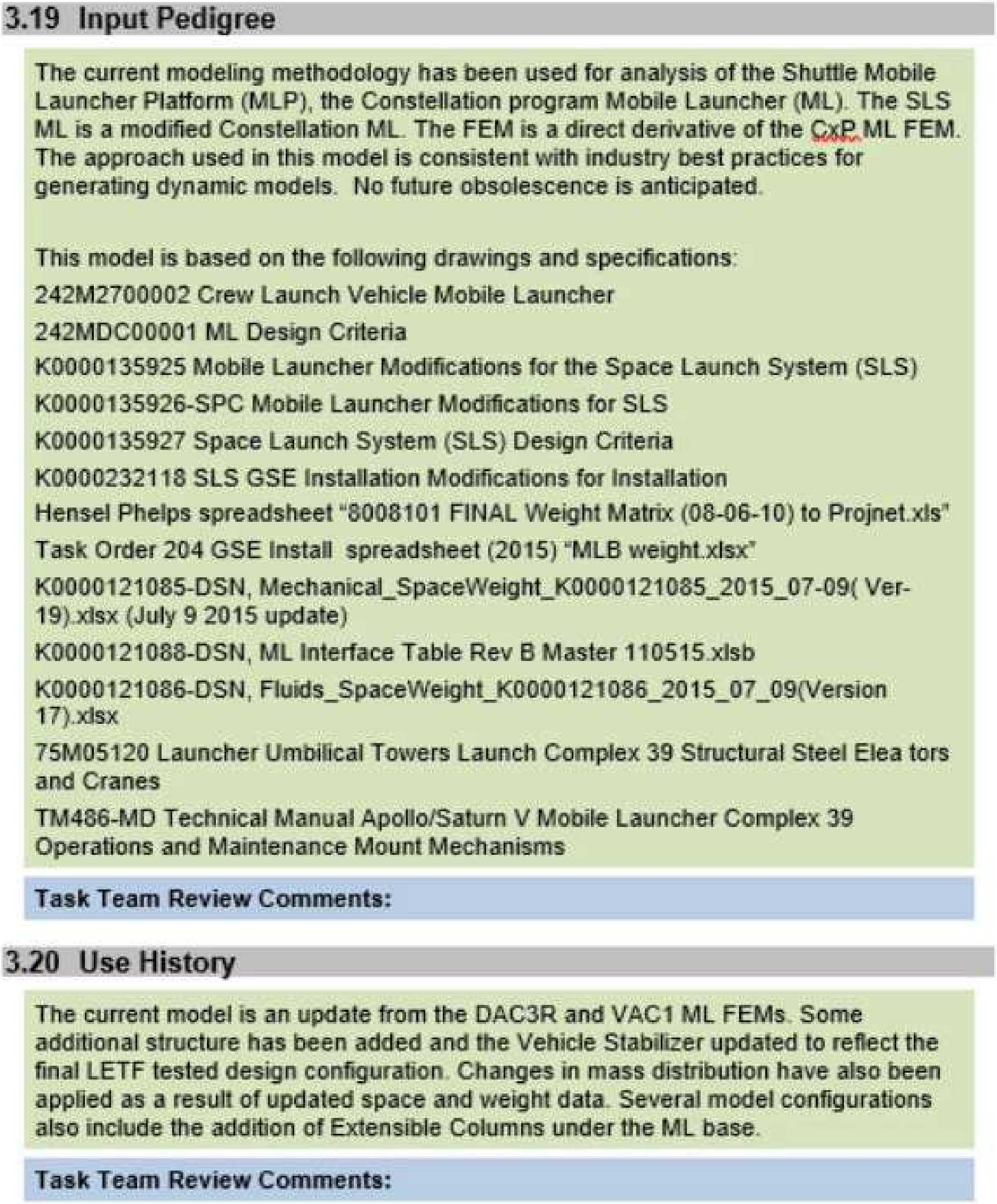
An early study of the model sensitivities to inputs has been performed and will be documented in the report SLS-RPT-237-01 and captured in the Modes Catalog which is referenced from the same volume.

Task Team Review Comments:

3.18 Limitations

The models are intended for low frequency coupled loads analysis for frequencies below 50 Hz. The ML Structure FEM primary structure is considered adequate for frequencies up to 50 Hz. However secondary structure (floor framing members, local girder reinforcements, etc.) should not be evaluated for frequencies above 6 Hz (TBR). The model does not contain enough refinement to accurately represent localized modal effects. The model is intended to accurately represent the primary and secondary bending and torsional modes of the ML Tower and the primary and secondary bending modes of the ML Base. Particularly when coupled with the SLS vehicle. The mesh refinement is not generally sufficient for stress analysis. The modal accuracy also diminishes as the frequency increases due to required mesh refinement and joint modeling.

Task Team Review Comments:



3.19 Input Pedigree

The current modeling methodology has been used for analysis of the Shuttle Mobile Launcher Platform (MLP), the Constellation program Mobile Launcher (ML). The SLS ML is a modified Constellation ML. The FEM is a direct derivative of the CxP ML FEM. The approach used in this model is consistent with industry best practices for generating dynamic models. No future obsolescence is anticipated.

This model is based on the following drawings and specifications:

242M2700002 Crew Launch Vehicle Mobile Launcher

242MDC00001 ML Design Criteria

K0000135925 Mobile Launcher Modifications for the Space Launch System (SLS)

K0000135926-SPC Mobile Launcher Modifications for SLS

K0000135927 Space Launch System (SLS) Design Criteria

K0000232118 SLS GSE Installation Modifications for Installation

Hensel Phelps spreadsheet "8008101 FINAL Weight Matrix (08-06-10) to Projnet.xls"

Task Order 204 GSE Install spreadsheet (2015) "MLB weight.xlsx"

K0000121085-DSN, Mechanical_SpaceWeight_K0000121085_2015_07-09(Ver-19).xlsx (July 9 2015 update)

K0000121088-DSN, ML Interface Table Rev B Master 110515.xlsb

K0000121086-DSN, Fluids_SpaceWeight_K0000121086_2015_07_09(Version 17).xlsx

75M05120 Launcher Umbilical Towers Launch Complex 39 Structural Steel Elea tors and Cranes

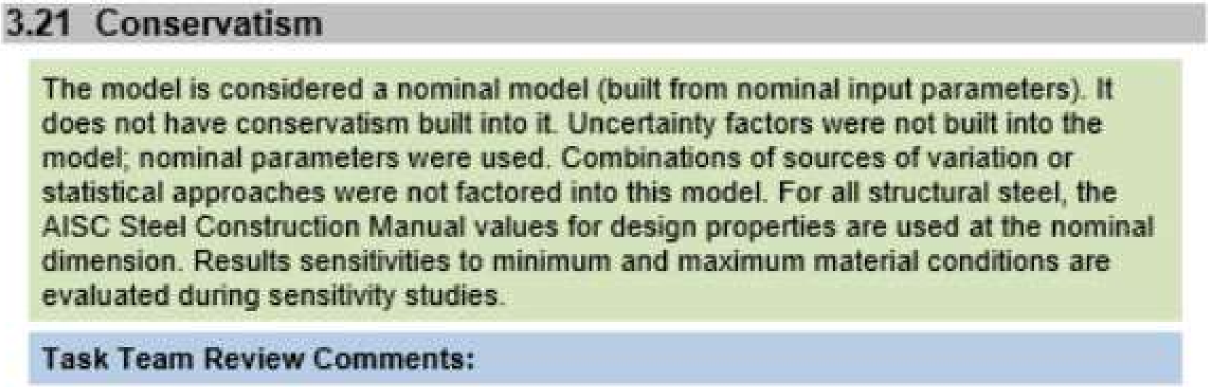
TM486-MD Technical Manual Apollo/Saturn V Mobile Launcher Complex 39 Operations and Maintenance Mount Mechanisms

Task Team Review Comments:

3.20 Use History

The current model is an update from the DAC3R and VAC1 ML FEMs. Some additional structure has been added and the Vehicle Stabilizer updated to reflect the final LETF tested design configuration. Changes in mass distribution have also been applied as a result of updated space and weight data. Several model configurations also include the addition of Extensible Columns under the ML base.

Task Team Review Comments:



3.21 Conservatism

The model is considered a nominal model (built from nominal input parameters). It does not have conservatism built into it. Uncertainty factors were not built into the model; nominal parameters were used. Combinations of sources of variation or statistical approaches were not factored into this model. For all structural steel, the AISC Steel Construction Manual values for design properties are used at the nominal dimension. Results sensitivities to minimum and maximum material conditions are evaluated during sensitivity studies.

Task Team Review Comments:

APPENDIX G. SUPPLEMENTAL PUBLICATIONS

NASA

NASA-HDBK-1001	Terrestrial Environment (Climatic) Criteria Handbook for use in Aerospace Vehicle Development
NASA-HDBK-4002	Mitigating In-Space Charging Effects, A Guideline
NASA-HDBK-4006	Low Earth Orbit Spacecraft Charging Design Handbook
NASA-HDBK-7009	NASA Handbook for Models and Simulations: An Implementation Guide for NASA-STD-7009
NASA-HDBK-8739.19-2	Measuring and Test Equipment Specifications, NASA Measurement Quality Assurance Handbook – ANNEX 2
NASA-HDBK-8739.19-4	Estimation and Evaluation of Measurement Decision Risk, NASA Measurement Quality Assurance Handbook – ANNEX 4
NASA-STD-8719.17	NASA Requirements for Ground-Based Pressure Vessels and Pressurized Systems (PVS)
ESD 10015	Exploration Systems Development Design Specification for Natural Environments (DSNE)

Robert H. Goddard Space Flight Center (GSFC)

545-PG-8700.2.1	Procedures and Guidelines: Requirements for Thermal Design, Analysis, and Development, NASA GSFC
GD-AP-2301	Earth Orbit Environmental Heating

Kennedy Space Center (KSC)

GP-425	Fluid Fitting Engineering Standards
KSC-DE-512-SM	Facility, System, and Equipment General Design Requirements

Kennedy Space Center (KSC)

KSC-SPEC-P-0027	Tubing, Superaustenitic Steel, Corrosion Resistant, UNS N08367 and UNS S31254, Seamed, Bright Annealed, Passivated, Specification for
KSC-SPEC-Z-0007	Tubing, Steel, Corrosion Resistant, Types 304 and 316, Seamless, Annealed, Specification for
KSC-SPEC-Z-0008	Flared Tube Assemblies and Installation of Fittings and Fitting Assemblies, Fabrication and Installation of, Specification for
KSC-STD-Z-0005	Pneumatic Ground Support Equipment, Design of, Standard for
KSC-STD-Z-0006	Hypergolic Propellants Ground Support Equipment, Design of, Standard for
KSC-STD-Z-0007	Hydrocarbon Fuel Ground Support Equipment, Design of, Standard for
KSC-STD-Z-0008	Ground Life Support Systems and Equipment, Design of, Standard for
KSC-STD-Z-0009	Cryogenic Ground Support Equipment, Design of, Standard for
KSC-STD-Z-0010	Environmental Control Systems, Ground Coolant Systems, Coolant Servicing Systems and Ground Support Equipment, Design of, Standard for

George C. Marshall Space Flight Center (MSFC)

MSFC-DWG-20M02540	Assessment of Flexible Lines for Flow Induced Vibration

Non-Governmental

	Aluminum Design Manual
ANSI/ISA-75.01.01	Flow Equations for Sizing Control Valves
ANSI/ISA-75.02.01	Control Valve Capacity Test Procedures
ASME B16.9	Factory-Made Wrought Buttwelding Fittings

Non-Governmental

ASME B31.12	Hydrogen Piping and Pipelines
ASME B31.3	Process Piping Guide
ASME B36.10M	Welded and Seamless Wrought Steel Pipe
ASME MFC-3M-2004	Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi
ASME MFC-3Ma-2007	Addenda A to ASME MFC-3M-2004
ASME Section VIII, Div. I	Rules for Construction of Pressure Vessels
ASME Section VIII, Div. II	Alternative Rules for Construction of Pressure Vessels
ASME V&V 20	Standard for Verification and Validation in Computational Fluid Dynamics and Heat Transfer
ASTM G88	Standard Guide for Designing Systems for Oxygen Service
ASTM MNL 36	Safe Use of Oxygen and Oxygen Systems: Handbook for Design, Operation , and Maintenance
IEC 60534-1	Industrial-Process Control Valves Part 1: Control Valve Terminology and General Considerations
ISO 21011	Cryogenic vessels -- Valves for cryogenic service