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A perfect model is the enemy of a good enough model	System Architecture Analysis - Modeling	Joe Fragola	The perfect is the worst enemy of the good-enough. ESAS was successful because we were willing to use models that were not perfect in giving us THE risks. They gave us enough discrimination between options to make decisions. Deep simulation models are not needed at this stage.	ESAS Video; Time marker: 23:15	13

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Carefully consider redundancy, cross-strapping, and component reliability in deep space mission design	On-orbit matted interfaces and required EVA support	Gregg Baumer	That's one of the things that I think I've learned most about the Russians and the Russians' approach to hardware: we do a lot by analysis - they do a lot by test, mostly by test. They have redundancies. In one particular case, we were looking at a system and they only had an A Side and a B Side to do a particular function, and we said 'No, if this function is lost, it's catastrophic to this Station.' This was on their propulsion system. They said 'That's not an issue because the A Side is really single-failure tolerant and the B Side is single-failure tolerant; and not only that, the individual components within that ORU [Orbital Replaceable Unit] are cross-strapped; actually, we could probably withstand about seven failures on the A Side and about seven different failures on the B Side and still be fully functional.' Redundancy, cross-strapping, and reliability [are some things] that have to be stressed in a long-term vehicle that's interplanetary. That's beyond the two-failure tolerance requirements that we levied for ISS [International Space Station] safety - because there, they're not going to have the luxury of bringing up spares and fixing something, it's going to have to work and have to continue to work.	KBR 2650 Failures of On–Orbit Mated Interfaces last clip	13

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Define and communicate success criteria up-front to all stakeholders	Ares 1-X Project Management - Requirements - Success Criteria	Dan Dumbacher	We had to work through a culture change to define what success is for a development flight test. Initially there were many different views on the definition of success.	Ares 1-X Clip: Senior Leadership Part Two	13
Develop a clear strategy for technology development and technology incorporation within each architectural option	System Architecture Analysis - Technology Management	Jay Falker	There is an issue in NASA of how to deal with technology, because there are two cultures. We have development & flight, and we have research & technology. There is mistrust and there are some barriers that need to be broken down. There are two kinds of research projects. One is on the critical path, and others are looking further out. We need communictions on which type you are.	ESAS Video; Time marker: 32:00	13
Develop capability to do apple-to-apple trade studies	System Architecture Analysis - Trade Studies	Doug Stanley	Have integrated analysis capabilities with apples-to-apples comparison, using the best methods available.	ESAS Video; Time marker: 1:30	13

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Establish the acceptable level of mission risk up front.	Ares 1-X Risk Management	Stephan Davis	If you're going to do a flight test program, understand up front what the level of risk is that you're willing to accept in the mission. For example, would an 80% probability of meeting a mission objective be OK?	Ares 1-X Clip: Plan Then Do	13
Implement logistics, maintenance, reliability trades up-front	Design / Logistics / Reliability	Anthony Butina	We really didn't come on board until the CD phase. By that time, the design had solidified enough that any ability to influence it for maintenance and for repair was gone .... you need to be up there early in the program and considered from the first time a piece of paper hits a pencil ... it takes that engineer to have that in the back of his head as he designs it so that we can get to these things and get them repaired as fast as we can	ISS Video Dashboard Anthony Butina Clip 1	13
Pay attention to infrastructure required to support architecture	System Architecture Analysis - Infrastructure and Facilities	Bill Claybaugh	Give attention to infrastructure. Every buidling comes with people in it, and fixed overhead costs. You have to knock down buildings in order to have lower infrastructure costs.	ESAS Video; Time marker: 28:30	13

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Prioritize!	People, Communication	Jonathan Krezel	the great thing about priorities is, even if you're last on the priority list, it's better to know that you're at the bottom than to have any ambiguity about where you stand.	Space Shuttle Transition and Retirement LessonsClip: 2 Start Up Transients: Time Marker 5:23	13
Set a baseline of mission objectives	Defining spacecraft objections	Chris Calfee	One of the other issues early-on as proposed was really a limited set of mission objectives. We were trying to accomplish in the 'prox ops' phase—in other words, as the DART spacecraft approached the target—what kind of operations were we going to demonstrate?	DART Video Case Study:	13
Start early to develop test data and models to support design activities.	Composite Overwrap Pressure Vessels (COPVs) in service now (SSP, ISS, spacecraft, EELVs) and will be used in future space systems (CxP, Lunar)	Multiple Subject Matter Experts	The most important thing that we have learned from this test, analysis and risk assessment program is to generate your data set and your models early in the planning phase for risk assessment. We have really been challenged in this program because we are developing our models for risk assessment after the programs have already selected vessels and are already buying components. It has been very difficult for us provide decision makers an accurate assessment of what the risks are.	KBR 7084 Last Clip : Lessons Learned	13

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Understand acceptable uncertainty in modeling	System Architecture Analysis - Modeling	Joe Fragola	There always is some uncertainty. We use the concept of Expected Value of Perfect Information, i.e. if you reduce the uncertainty, would it change your decision? In many cases it doesn't, so the investment is not useful. Let's not strive for better models just for the sake of having better models. The type of model you need to discriminate is different from the type of model you need for an actual design.	ESAS Video; Time marker: 24:00	13
Understand and communicated constraints imposed on the architecture	System Architecture Analysis - Constraint Requirements	Doug Stanley	We cut the new technology budget in half because the administrator wants to accelerate the CEV program and he likes the proven and the Keep It Simple Stupied (KISS) approach.	ESAS Video; Time marker: 20:15	13
Use architecture-level risk modeling tools	System Architecture Analysis - Risk Management	Joe Fragola	The risks in the ESAS report are not real risks but coherent sets that allow us to discriminate between designs. We build the risk analysis modeling tool over time, module by module, as funds were avaible, based on the 1995 Shuttle PRA. If we would not have had this tool, we would not have been able to do this study.	ESAS Video; Time marker: 16:00	13

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Use simple over complex tools in system architecture development	System Architecture Analysis - Modeling and Analysis	ESAS Team	I rather have simple tools that eveyone knows how to use, than complex tools and nobody knowing how inputs turn into outputs. I rather have a simple model now that gives me some type of top-down understanding of the overall system behavior, than spend two years developing a integrated platform, webbased, etc., and then be two years too late finding out what I needed to know.	ESAS Video; Time marker: 12:30	13
"Unexpected things are going to happen"	Design robustness / ECLSS	Robyn Gatens	We learned some things once we launched our ECLSS system to the space station on orbit that we didn't anticipate when we designed it.	ISS Video Dashboard Robyn Gatens Clip 3 (all - esp 2:40)	23

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Always perform an integrated test - known unknowns will emerge.	ISS integration testing in a cost constrained environment	Timothy R. Honeycutt	So these types of problems, we learned from them as far as finding them on the ground, resolving them prior to launching into orbit. If we would have had these types of problems on orbit, we would have had major cost and schedule delays. It would have caused increased safety issues for the crew. We could have had a loss of mission objectives and loss of flight hardware. It would have driven unplanned EVAs. So for future programs I would take all of this information under consideration from what we learned from MEIT not only that we need to look at what type of integrated testing we need at the launch site but also the planning that it takes to put one of these tests together providing all the correct GSE, the right personnel, the right involvement of other organizations and companies, down to the manufacturers level. To plan that up front is a great cost savings as well as to catch these problems that we find and resolve on the ground prior to getting in orbit. So some specific lessons from MEIT, one is the fact that we do know that we will come across unknowns when we integrate hardware together. There is no way of understanding all of the scenarios involved with large-scale integration of space hardware until you put the actual hardware together. You can simulate that, you can emulate that to the best that you can but there are some unknowns that you will come across when you actually perform that final integration.	KBR 10440 ISS: Multi-Element Integration Testing (MEIT)last clip	23

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Always perform an integrated test for critical systems - always.	ISS integration testing in a cost constrained environment	Stephanie Sowards	Using risk-based analysis to determine if we should conduct integrated test is a nice idea and it looks good on paper. However, given the complexity and the tightly coupled configurations of elements that span geographical and international boundaries that could result in catastrophic outcomes, the right thing to do is to always perform the actual integrated test. MEIT was designed to test mechanical, data, electrical, fluids every subsystem across those elements.	KBR 10440 ISS: Multi-Element Integration Testing (MEIT)second clip	23
Balance safety v complexity	Safe Design - complexity / ECLSS	Robyn Gatens	So I think as we go forward, yes safety is very critical but we need to find a balance between making something so safe that it is too complex and therefore not as reliable and where is that balance.	Robyn Gatens Clip 5	23
Be Flexible	TRL Levels may need back up plans	William Yuknis	I think the number one thing when encountering new technology, especially with a great unknown, the best thing that you can do in my opinion, is to be flexible. In other words be prepared to change the course and have a backup plan ready to go. In others word, we call it the "Plan B".	KBR 11397Parallel Pathways to Mission Success Command & Data Handling,(C&DH) Lessons Learned	23

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Be weary of obvious answers	Risk Management	Richard Williams	Just because a part has been reliable and something that we have used for a very long time here, doesn't necessarily mean that it doesn't have an inherent flaw within it and don't just accept that part the way it is.	KBR 11365- Lunar Reconnaissance Orbiter Project (LRO) - Defect in Socket Contacts (Lessons Learned)	23
Carefully Evaluate Heritage parts with used in extreme thermal environments	Thermal	Charles Baker	The word heritage only applies to thermal if the actual environment that the instrument was used in last was more severe than the environment that it's being baselined for. If it is less severe than there needs to be resources put in to and early model exchanges and early technical exchanges to help develop the thermal subsystems so that it can handle the more severe environment.	KBR 11377 - LRO Heritage Instruments Still Require Significant Design Efforts (Lessons Learned)	23
Check heritage hardware drawings in case something changed in the interim.	Ares 1-X Heritage Hardware	Mike Stelzer	Don’t trust the drawings of heritage hawrdware. Do those additional surveys to verify that your drawings- your models- are accurate and up to date in case something changed in the interim.	ARES 1-X Clip: Caution! Heritage Systems	23

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Conduct end-to-end testing - absolutely essential	Integration testing and verification ECLSS	Robyn Gatens	It is important to note that this end to end testing is absolutely critical before we fly future exploration missions. Not only was it the first time in some cases that the flight hardware met the flight software but just everything integrated together is critical before you fly that element	ISS Video DashboardRobyn Gatens Clip 2 (all - especially 5:20)	23
Consider a Skunk Works approach when facing technology challenges	SLWT Project - Design & Development	Mike Pessin	And we managed this like a Skunk Works. This technique gives you a certain amount of risk because you don't get the multiple levels of review, but it gives you a virtually immediate response; and if you have the right people – and you've got to make sure you get the right people involved – it gives you a very efficient and streamlined program.	SLWT Exercise 5: Production Verification Risks; video clip/transcript	23
Design with integration and operability in mind	Ares 1-X Design and Integration	Jim Bolton	Infusing operability early makes a huge difference later. Include design engineers visiting KSC and ground ops people visiting design centers.	Ares 1-X Clip: Operability is Not an Afterthought	23

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Early flight test experience will inform "main line" development project structure	Ares 1-X Project Management - Organization	Jeff Hanley	What Ares I-X taught us is that we could treat the main line program very differently once we got past PDR, we could organizationally lean it out, flatten it, and get the team focused on flight tests, i.e. be test-centric.	Ares 1-X Clip: Senior Leadership Part One	23
Early flight test is important to program growth and stability	Ares 1-X Project Management - Stability	Jeff Hanley	Senior management saw the technical value of 1-X, but also from a team perspective it was good getting an early flight test success.	Ares 1-X Clip: Senior Leadership Part One	23
Employ the latest (ARES I-X) updated acoustical environment prediction models	Ares 1-X Design Modeling	Marshall Smith	This test showed that we under-predicted the vibro-accoustic sound pressure levels for some places by a factor of three or four. This is not ARES 1-X specific but geometry specific. This allowed us to update our models, which now can be used for other vehicles as well.	Ares 1-X Clip: Systems Engineering and Integration	23

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Evaluate the end-to-end (design to launch) impact of heritage hardware before deciding on the use.	Ares 1-X Heritage Hardware	Robert Ess	If you think through the integrated end to end from design all the way to launch day impacts of a heritage change then you can understand whether it's really a good trade for you or not.	ARES 1-X Clip: Caution! Heritage Systems	23
Except to run loads and environments analysis up to the time of launch	Ares 1-X Design, Development & Test	Marshall Smith	Any time you build a new vehicle you're going to be doing loads and environments until the time you launch and after. I'm very convinced that this is never going to get better. It's always going to be uncertain. People are always going to be running loads. You're always just going to be saying, well, what if we did this, what if we did that. You've got to understand it, you've got to accept, and you need to set people's expectations so they don't freak out about it.	Ares 1-X Clip: Systems Engineering and Integration	23
Expect that heritage hardware will require the same integration level of effort as new flight hardware	Ares 1-X Heritage Hardware	Robert Ess	With heritage hardware, the physical integration and technical integration is as much work as if you started off from scratch and sometimes it's more work.	ARES 1-X Clip: Caution! Heritage Systems	23

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Expect that heritage hardware will require the same system-level verification as new flight hardware	Ares 1-X Heritage Hardware	Jon Cowart	Heritage is great, I recommend you go use it, but make sure you plan up front that down the road it's going to require from you some extra verification and certification time.	ARES 1-X Clip: Caution! Heritage Systems	23
Identify assumptions and uncertainties in using any model and build in margin as necessary.	Uncertainty in the space environmental models	Robert Manning JPL	As a system engineer, you need to be cognizant of the uncertainties in the environment that is being specified for you by environmental specialists, and if you have the ability to do it, you can hedge your bets by adding complexity and systems to try to deal with unexpected environmental conditions or conditions that may be worse than the specified environment that the experts have predicted. Because it turns out you're asking them a very difficult question, and when they give you an answer, you have to be aware of the fact that they may not be certain that that answer is correct.	KBR 1339 High Level of Uncertainty (Environmental Model)second clip	23

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Increase design safety factors when there is higher technical uncertainty.	SLWT Project - Design	N/A; Report	Due to questions about the fidelity of analysis, the goodness of the modeling, synergistic effects and the applicability of component testing data, we increased the safety factor to 2.0 and required independent analysis.	SLWT Exercise 4: 4.1 Introduce Higher Design Safety Factors; PPT	23
Integrate final hardware together before launch to uncover unplanned problems	MEIT - Component Testing and Verification	Tim Honeycutt	There is no way of understanding all of the scenarios involved with large-scale integration of space hardware until you put the actual hardware together. You can simulate that, you can emulate that to the best that you can but there are some unknowns that you will come across when you actually perform that final integration.	KBR 10440	23
Leverage technology - employ RFID for inventory control	Operations / Storage	William Robbins	Leverage technology and get the human out of the loop as much as possible .... using RFI de-tags, ... automated readers that are mounted in various places in your living space such that if an item moves you automatically know about it ... (freeing the crew) to operate the vehicle and do science and explore and do those things rather than being an inventory checker.	ISS Video Dashboard William Robbins Clip 8	23

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Plan for success in multiple ways	parrallel path, mitigation strategies	Lora Bailey	As a project manager I typically always have at least three parallel paths in mind. That is I have a primary path, so that's plan A, and not only do I always have a plan B in my hip pocket but I have a plan C because I want to have at least two layers of redundancies of places to go to in the event that I have a failure with plan A. That's just how I do business and I believe that it the right way to do business, to have at least two backup plans.	KBR 11938 Clip: Context; Parrel path-Time marker: 0:00	23
Recognize that flight test project design verification may differ in complexity from other types of missions	Ares 1-X Design verification testing	Marshall Smith	Doing verification is different for a fast moving one-of-a-kind vehicle development program than for operational environments. The former includes product verification where you actually check each part, whereas the latter uses just spot checks. The ARES 1-X project had people from both those cultures. Some of us had to learn to trust the processes and people and to not check everything on this one-of-a-kind vehicle.	Ares 1-X Clip: Systems Engineering and Integration	23
Recognize the need to address triboelectrifcation risks and requirements	Ares 1-X Requirements Management	Jeff Spaulding	ARES 1-X was not treated or tested for triboelectrification, so we could not fly through any clouds above the minus 10 degrees Celsius level. This was a cost tradeoff decision that ended up delaying the launch one day.	Ares 1-X Clip: Triboelectrification	23

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Reduce Margins Carefully	Margin reductions represent increased risk	Mike Pessin	There are often places were margins can be reduced while maintaining the required FoS. There always represent areas of optimization, built is should be remembered that any form of margin reduction increases overall risk	SLWT Clip: Lessons Learned (4 of 4)	23
Review and renew ones understanding of data underlying any critical design model.	Systems Engineering Design Verification	Robert Manning JPL	The validation process didn't go back far enough into the past to look to ensure that we did the right thing from the original data. We were shocked; and, well, the good news [is] we caught it in time for the MER project.	KBR 1599 Common Mode (Model error) Failures in TechnologyClip: 3:47 + 1:42	23
Scale tests to fit the purpose	Test objectives, test cost, testing	Warren Woodworth	The basic guideline is to do the right test and do the test right. Document the test properly and clearly state the objectives and intended purpose of the test. Conducting a test that does more than is necessary or overly complex for the purpose or objective will add increased cost and schedule.	5045 Orbiter Program	23

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Solicit manufacturing practitioners experience and knowledge in solving tough design problems	SLWT Project - Problem solving in design	Bryan O'Conner	The project manager and his senior folks did not limit their brainstorming to themselves. Invite enough people from enough levels to participate in that. Sometimes you get the best answer by going to the floor and talking to the folks with the wrench in their hand and the torch in their mitt that are actually doing the job.	SLWT Four Important Take-Aways; video clip/transcript	23
Start and end with the same risk posture	Categorizing risk posture for program classification	Chris Calfee	DART was proposed and accepted as a high risk, low cost project. What came with that should have been a high threshold for risk and a reasonable amount of acceptance that there could be a failure here—it was a flight demonstration. So decisions were made early-on with that in mind, with those assumptions firmly in place and thought to be understood by management. As time evolved—and really it wasn't an evolution that it changed, it was like it flipped overnight—DART suddenly went from a 'high risk, low cost' to a 'can't fail, low cost' project.	DART Video Case Study: Page 21, Risk Posture and Verification 0:06	23

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Test integrated avionics and anomaly conditions in a flight-like simulator lab.	Ares 1-X Design verification testing	Kevin Flynn	Use an integrated avionics simulation lab that truly has flight-like hardware, meaning having the same form, fit, and function as the flight boxes, and test all the functions possible. Especially testing things like anomaly condition is worth its weight in gold.	Ares 1-X Clip: Test Like You Fly, Fly Like You Test	23
Test, Test, and Test	Ares 1-X Design verification testing	Marshall Smith	A flight test does not only solves the problems you think you're going to have, but it tells you about a lot of unknowns. You find out things you didn't expect. I highly recommend that you set up a series of test programs, each building on the next, similar to what we did in the past on Mercury, Gemini and Apollo. They had it right and that's the right way to go.	Ares 1-X Clip: Systems Engineering and Integration	23
Verify that your model is valid for the application scenario.	Systems Engineering Design Verification	Rodney Rocha	There's always the opportunity or mis-opportunity to misuse a critical math model and fall into a pitfall of misuse, a flawed recommendation, an inaccurate statement about the usage of such math models.	KBR 11939 Application of Models in Design Verification and Safety Critical Decision Making first & last clip	23

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We must understand COPV failure modes.	Composite Overwrap Pressure Vessels (COPVs) in service now (SSP, ISS, spacecraft, EELVs) and will be used in future space systems (CxP, Lunar)	Multiple Subject Matter Experts	They are integrated throughout all of our vehicles. They are also integrated throughout our international partner's vehicles. Right now we are getting ready to inspect the AMS vessels which we have in our international partner's vehicles and also our payloads. Anything that is trying to save weight, we will put a composite pressure vessel in that application. We must understand the failure modes and be able to mitigate the failure causes so that we have a safe and reliable vessel.	KBR 7084 Composite Overwrap Pressure Vessel Safety Hazards First clip: Intro & background	23
Challenge the requirements	Verification	David McCann	You got to challenge the requirements as you develop hardware. One early requirement that was levied on the SARJ was that we shouldn't have any liquid greases in the system. Many times in the development of the program there were suggestions that they move to a grease and that was always discounted because of this requirement they had to not use liquid greases. What it turned out to be was there was no hard written down requirement like that, it was just always believed that you shouldn't be using liquid lubricants.	KBR- 11825 SARJ Vibrations Pose Risk to ISS Power and Operations	33