PRODUCT DEVELOPMENT

DESIGN, TESTING, AND VALIDATION

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Introduction

24 years of product development experience

- Bose (19 years)
- Motorola (5 years)
- Pratt & Whitney (3 summers)

Electrical, Acoustical, Project Leadership, and Management roles

BSEE University of Miami, Audio Engineering Program

A Few Product Examples

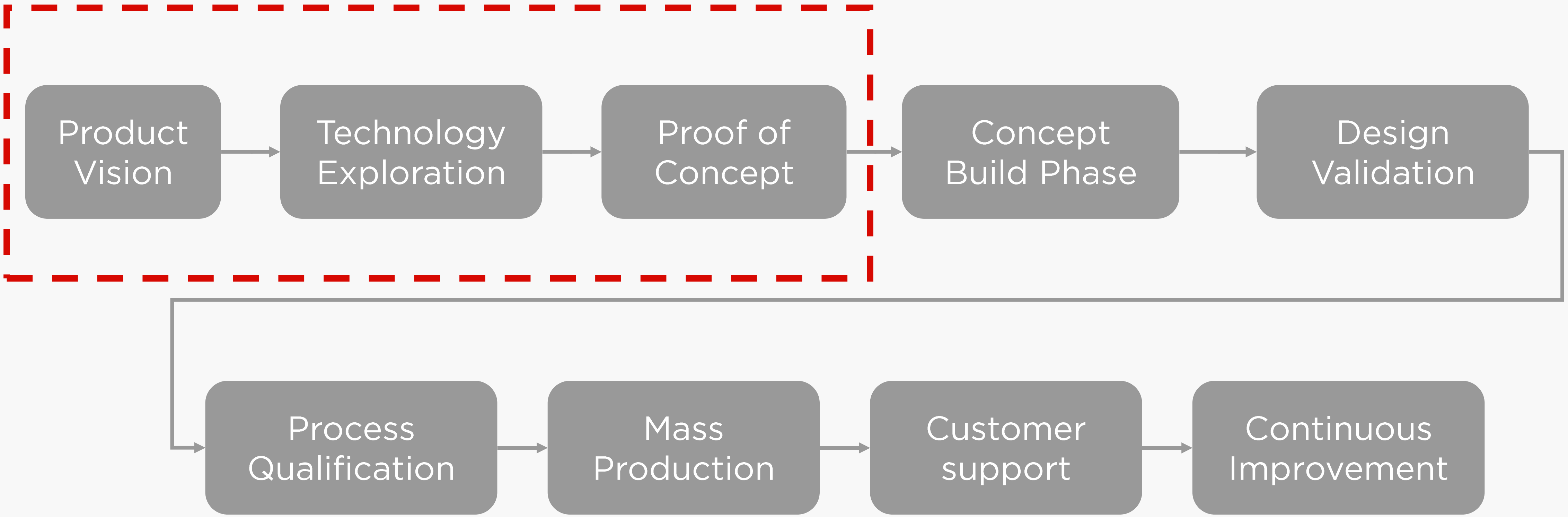
Banded Headphones

In Ear Headphones

Mobile Phone Handsets

And this one too...

Basic Development Process – Review



Product Definition

01 | Product Mission
Primary use case. What is the purpose for this product to exist? What problem is it trying to address for the customer?

02 | Key Differentiators
Required features and functions to realize product vision. These distinguish this product from competitive set.

03 | Core Functionality
Basic functions that must be included, but do not differentiate the product

04 | Other Desirable Features
Wanted, but willing to sacrifice if necessary

Product Requirements

01 | Functional
Design fundamentals, key functions, performance drivers.

02 | User Experience
How the customer will interact with the product. Includes user interface, physical features.

03 | Manufacturability
Materials, process, factory capabilities, supply chain considerations

04 | Reliability
Define use profile, expected product life.

05 | Regulatory
Legal requirements, necessary certifications, safety.

06 | Business Case
Project cost, unit cost, projected sales volumes, delivery costs, market value

Creating a Project Plan

Define design maturity phases and development milestones

Plan development activities and boundaries for each phase

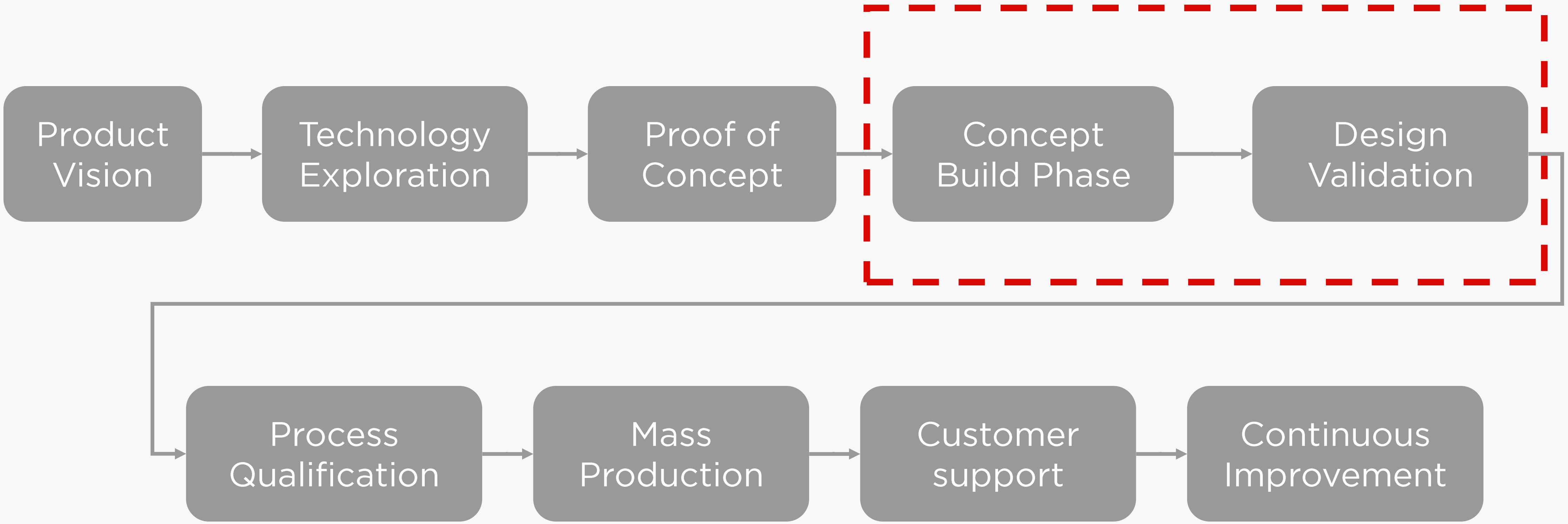
- Break work down into definable tasks
- Calculate the time required for each task and note interdependencies
- Tailor testing plan to align with phase objectives

Allow contingency time for discovered work

- Understand known unknowns
- Expect unexpected surprises
- Anticipate risks and likely problems so you can be proactive in mitigating them

Write down your plan!

Basic Development Process – Focus for Today



Concept Build Phase

A structured, iterative, phased approach to mature a design from Proof-of-Concept to Manufacturing Readiness

Goal: Verify that the design meets all functional and performance requirements, and that the design has a viable path to production

Increasing maturity and functionality as C Builds advance
Reduced risk and uncertainty over time - growing confidence in the outcome

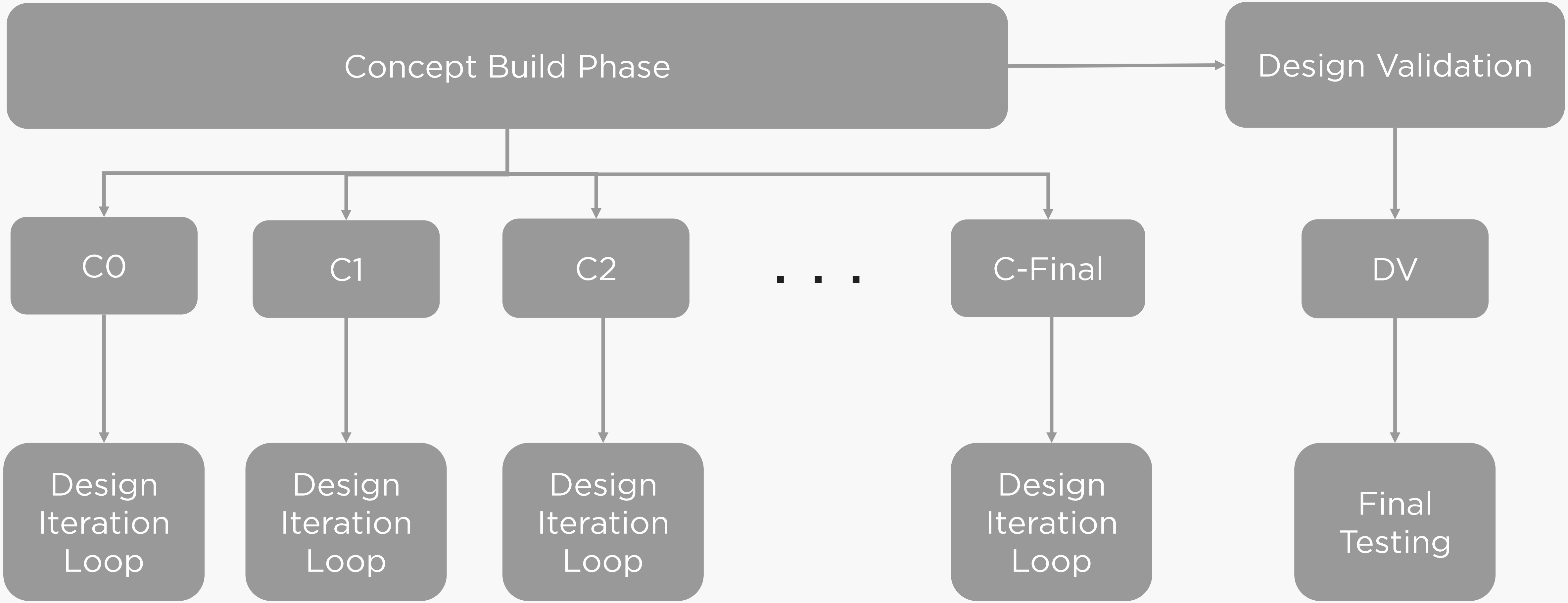
Design Validation Phase

Final validation of all engineering functions and product requirements.

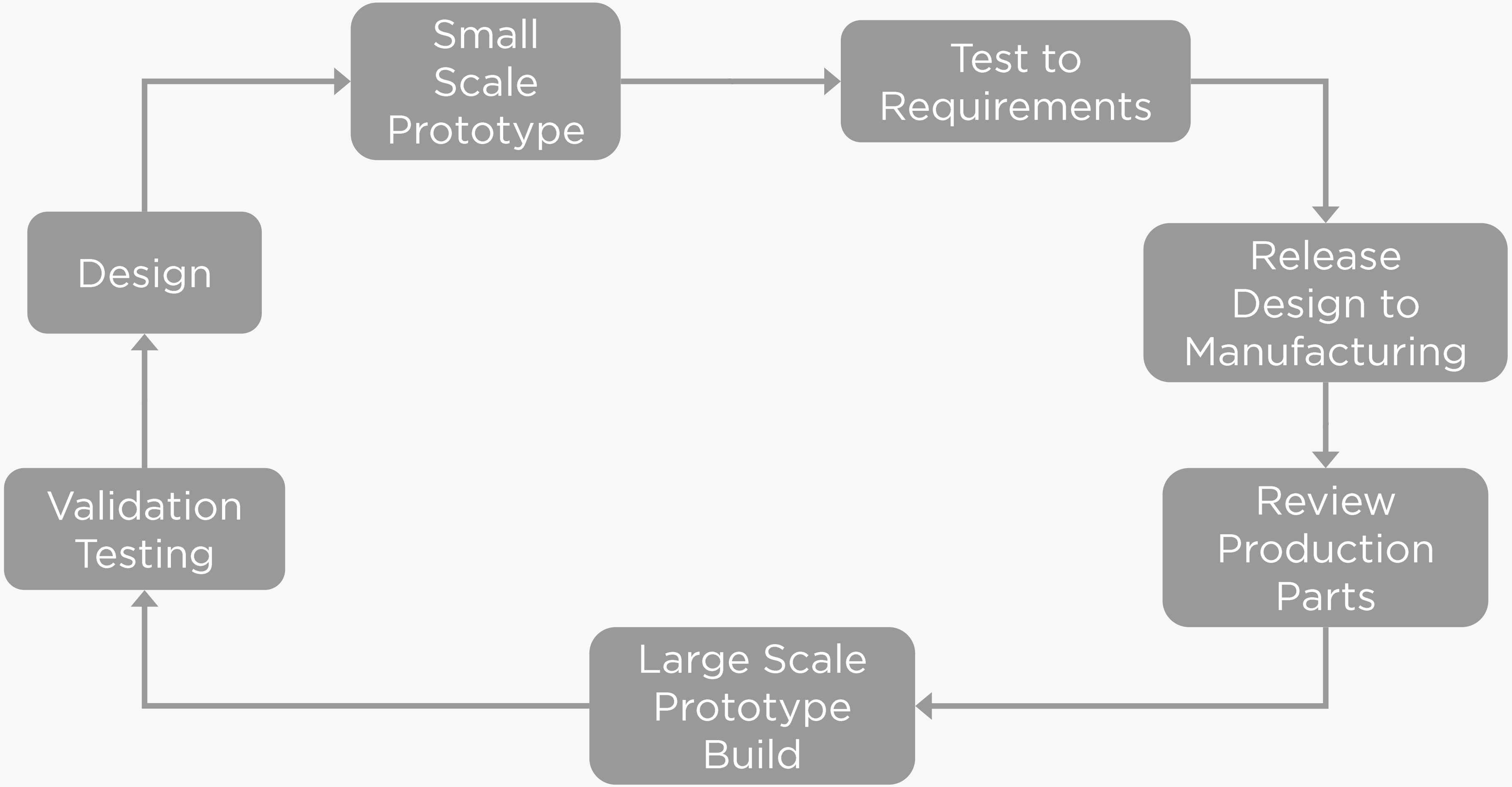
Goal: Ensure the product design meets all requirements and is ready to begin mass production

Finalize the design, incorporating all necessary changes from the Concept Build phase.
Produce prototypes using production-intent processes and materials.
Conduct comprehensive testing, including environmental, durability, and regulatory compliance tests.

Concept Build Phase and Design Validation – Detail



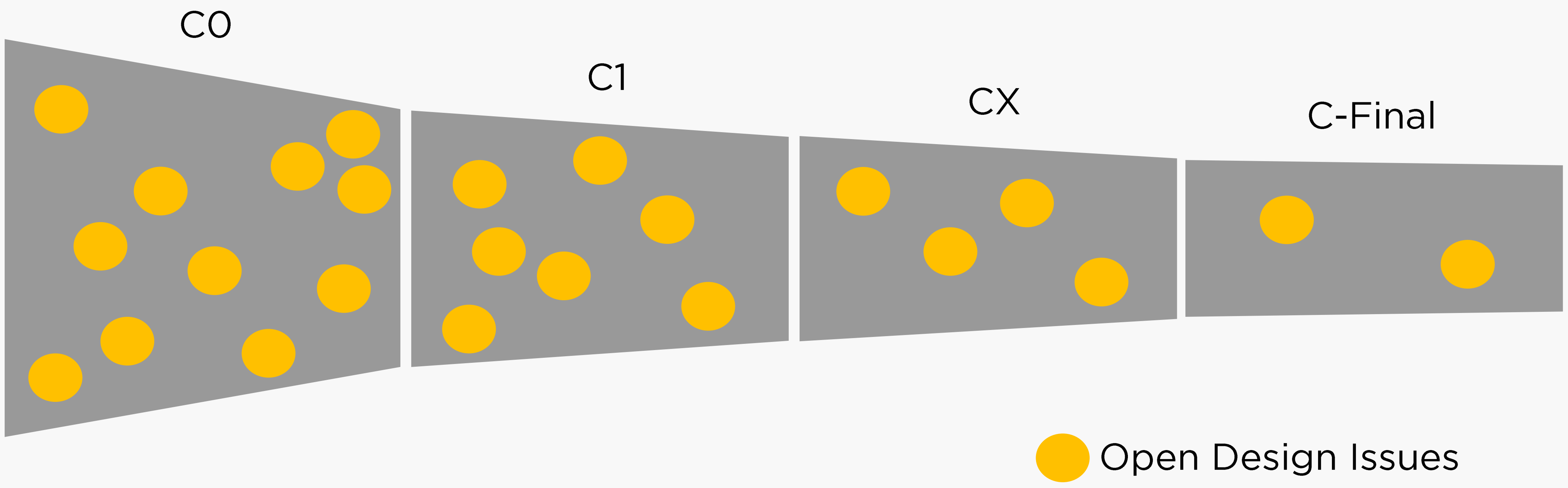
Concept Build Phase –Design Iteration Loop



Concept Build Phase – Driving Design Maturity

Each design cycle is scoped to meet project plan goals for maturity and functionality

By C-Final, all design related questions should be addressed – no known additional open design issues



Product Testing

Q: How do you know what you need to test, and when?

Recall - Product Requirements

01 | Functional
Design fundamentals, key functions, performance drivers.

02 | User Experience
How the customer will interact with the product. Includes user interface, physical features.

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Product Testing – What and When?

A: Consider the following:

- Design Integration
  - Assess the integration and functionality of all components. Have all subsystems been tested individually and in conjunction? Are all functions available? How mature is the physical embodiment of the design?
- Functional Requirements
  - Confirm that the design meets all core functional requirements. Are performance targets being met under all operating conditions?
- Design Phase Goals
  - What are the objectives for the current phase? What must be proven or achieved before moving to the next phase?
- Reliability and Durability
  - Evaluate your design for performance over time. What is the expected product lifecycle? Do tests simulate real-world usage scenarios, include stress testing, and accelerated life testing?

Product Testing – What and When?

A: Consider the following (cont.):

- Regulatory and Compliance Standards
    - What are applicable standards and certifications required to launch your product?
- Resource Utilization
    - Testing costs time and money. Is the value in the testing aligned with program priorities? Has the testing already been completed previously? Is there a need for regression testing?
- User Experience and Field Testing
    - Human factors and interface. How does the product perform in the real world? Have any design changes been made to address specific customer reported issues?
- Risk Assessment
    - Evaluate risks associated with each design element and test. What are the high-risk areas that need focused testing? What are the consequences of a test failure at this stage?
- Pass/Fail vs. Evaluation Only Testing
    - Understanding margin to failure

Developing a Test Plan

01 | Cast a Wide Net
Capture all tests required to prove attainment of project goals. Define test procedures and pass/fail criteria to align with product requirements.

02 | Plan Testing Strategy
Identify the relevant tests for each development phase. Document **what** is to be done and **when**.

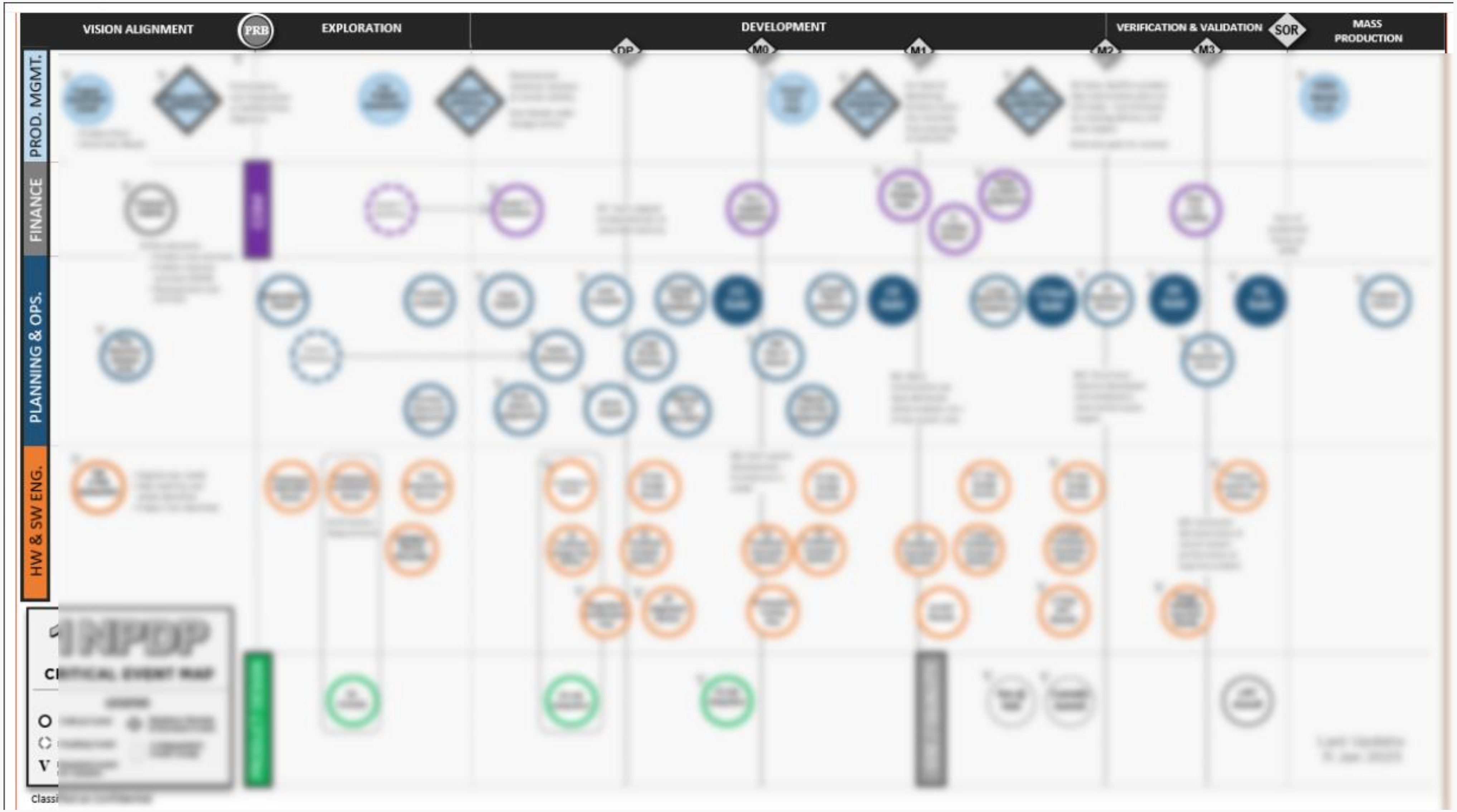
03 | Establish Ownership
Assign owners for each test to drive accountability.

Consider:
Where is there potential overlap? What are opportunities for parallel or sequential testing?

Integrated Test Plan Example (Live Walkthrough)

1	**Nautilus EVP**										
2	**Updated 07.11.13**			**Color Key**	**SRD Test**	**Test Not Required**					
3											
4	**Test**	**Category**	**QTY**	**Tester**	**Test Description**	**Procedure and Criteria**	**Due Dat**	**Status**	**Result**	**Test Result Notes**	**Priorit**
61	57	Cable	2	NRT	Cable jacket bunching	conductors, or movement along conductor length	Beta	DV I	Eval Only	No concerns at DV 1. Compare to Edwin issues	2
62	58	Cable	30	Merry	Cable/earbud alignment	Stripe alignment and earbud rotational alignment	Beta	Complete	Pass	DV 1 results good. Monitor.	1
63	59	Cable	1	NRT	Cable noise/microphonics	Eval only. Compare vs WL prototype	Beta	Complete	Pass	No concerns. Monitor.	2
64	60	Cable	4	Merry	Audio Plug Rotational Intermittency	rotate audio connector while inserted, evaluate loss of audio and mic signal over 720 deg rotation	Beta	Complete	Pass	No concerns at DV 1. Monitor	2
65	61	Cable	4	Merry	Intermittent cable testing	Look for intermittent audio while exercising strain reliefs.	Beta	Complete	Pass	No concerns at DV 1. Monitor	1
66	62	Cable	4	Reliability	Force vs Displacement insert/removal of source plug	Instron measurements; 1.5-3lbs target		C3	Pass	Using new (gold) plug for C3	2
67	63	Cable	3	NRT	Plug backout tolerance before audio loss	Evaluate when loss of audio occurs		C3	Pass	Completed at C3. Monitor.	3
68	64	Cable	30	Merry	Cable insertion/removal force	Measured with force gauge and iPod jack.		C3	Pass	Completed at C3. Monitor.	2
69	65	Mechanical	10	Merry	Earbud grille push out force	Measure push out force of metal grille weld assembly. Compare to existing products with field history.	Beta	Complete	Pass	Agreed to min limit of 1.5kg	1
70	66	Mechanical	4	Merry	Earbud glue strength	Pull apart force		Complete	Eval Only	Right is lower than left, will reevaluate	1
71	67	Mechanical	4	Merry	Earbud nozzle screen push in strength	Force to push the screen in from the outside	Beta	Complete	Pass	Still some variation, but control limit agreed to be 150g	1
72	68	Mechanical	4	Merry	LSR Bonding to Control box	Evaluate peeling of LSR. Before and after high temp.	Beta	Complete	Pass	Should evaluate parts made from Nitroflon coated tools in high temp storage test	1
73	69	Mechanical	8	Merry	Control module weld strengtth	Pull apart force	Beta	Complete	Eval Only	Process improvements continuing during DV 2	1
74	70	Mechanical	4	NRT	Battery abuse protection	Step-on, module impacts by objects. Battery safety (not function) if run over by car etc.		DV II	Pass	All battery safetly tesing completed by DCE without issue. Certification passed.	2
75	71	Reliability	4	Reliability	Dynamic Tensile Cable Test	Performed with instron, attached iPod drop simulation 9.5kg/54ms impulse load. Minimum 144 cycles.		Complete	Eval Only	Test not required. Use results of iPod drop test #54	1
76	72	Reliability	4	Reliability	Static Tensile Cable Test	Performed with instron, static loading - Pull Test @ 1/2" per min rate. Min 8kg for product, 10kg for source plug.	Beta	Complete	Pass	Pre-Beta results improved with added ribs ("belt") to min 12kg. Result with final SR design ("suspenders") pending	1
77	73	Reliability	4	Merry	Audio cable connector insertion cycling (3.5mm plug)	Automated test to 10950 Cycles. Remark: Check every 1000 cycles.		C3	Pass	Tested at C3	2
78	74	Reliability	4	Merry	Case zipper cycling	Test to 21900 cycles. Evaluate for issues with function/feel.		C2.5	Pass	Tested previously	2
79	75	Reliability	2	Merry	USB Cable insertion- normal environment, manual cycling	Insert/remove cable by hand 1095 cycles.		DV I	Pass	Retest w/ hard tooled parts	1
80	76	Reliability	2	Reliability	Accidental USB cable removal	Yank Bose charging cable out at various angles and evaluate damage		Complete	Pass	Retest w/ hard tooled parts	2

Product Development Process - Formalized



PROTOTYPING A COMPLEX SYSTEM

MATURING A DESIGN THROUGH THE CONCEPT BUILD PHASE

Protyping – Phased Approach with Increasing Complexity

01 | Targeted Breadboard
Simplified prototype designed to answer a specific question

02 | Full System Mockup
First crack at a full, usable system. Basic functionality. Not user friendly.

03 | Fully Integrated Prototype
Form factor integration of all components. Some allowances for test interface remain. Product is generally usable but may not be feature complete.

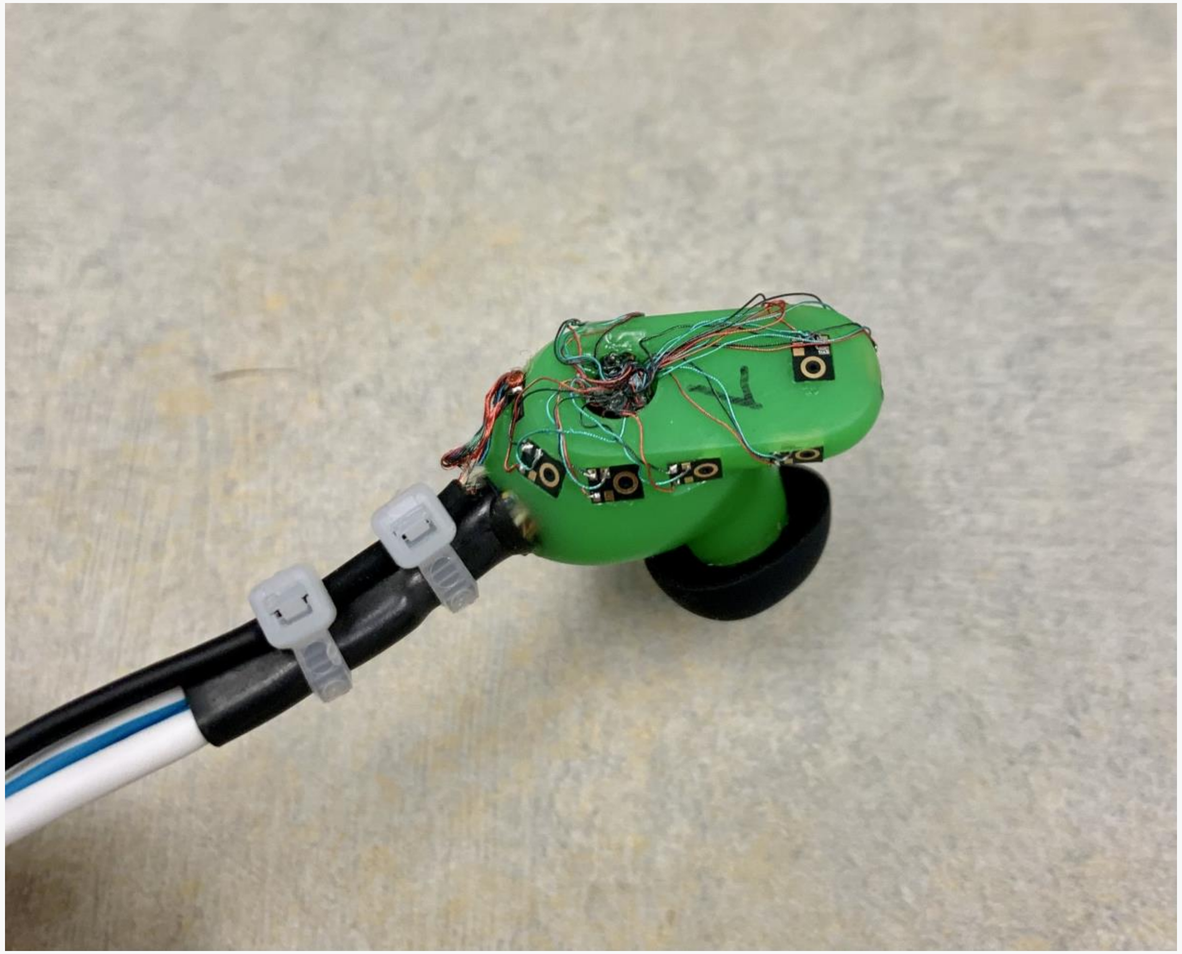
04 | Final Product
Fully realized product, with full functionality. Intended user experience.

QC Earbuds II Example

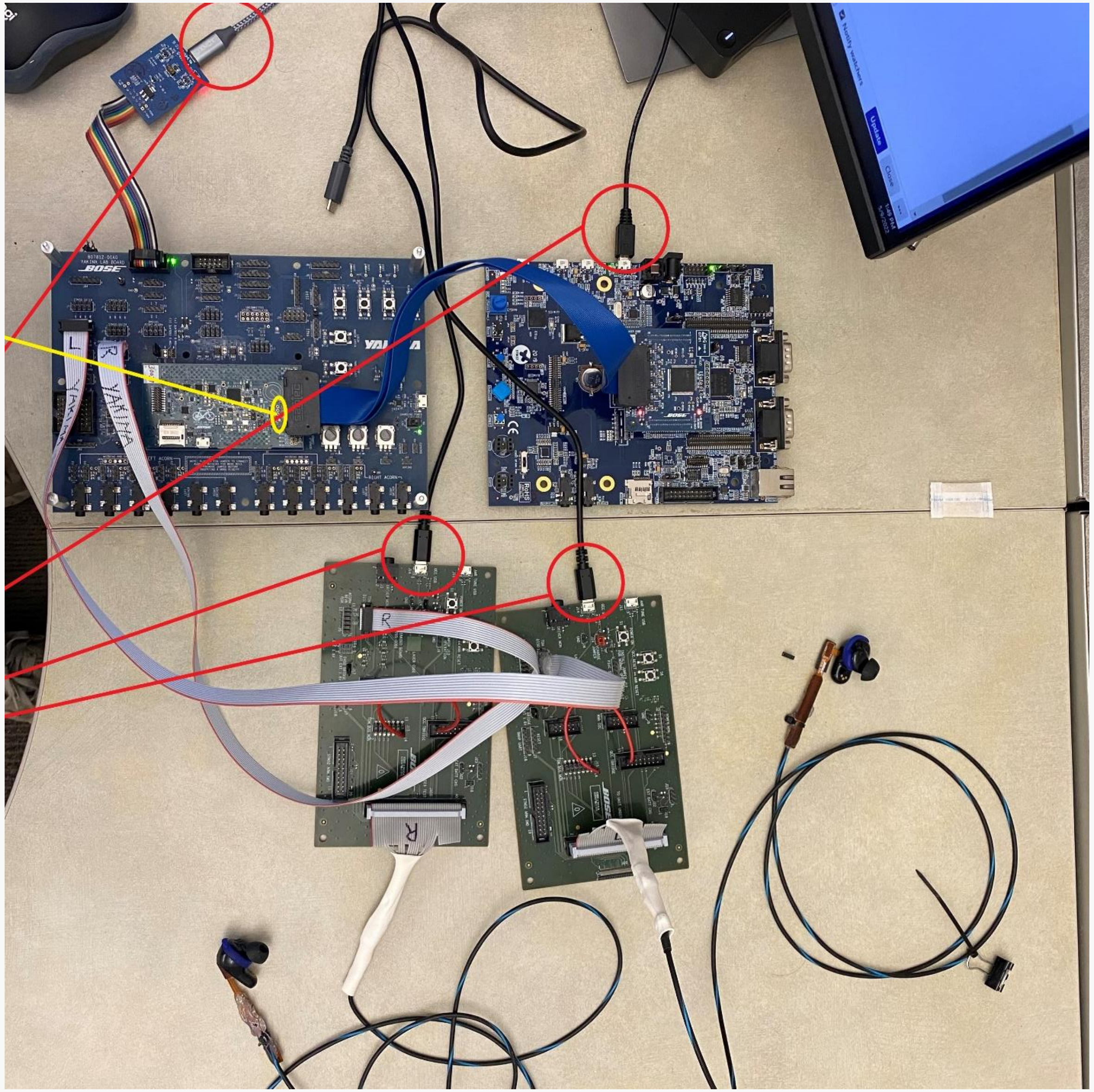
01 | Targeted Breadboard

Simplified prototype designed to answer a specific question

Ex: Where should we put the microphones? How many should we use?



QC Earbuds II Example



02 | Full System Mockup

First crack at a full, usable system. Prototype parts. Basic functionality. Not user friendly.

QC Earbuds II Example

03 | Fully Integrated Prototype

Form factor integration of all components. Mix of some prototype and some manufactured parts. Some allowances for test interface remain. Product is generally usable but may not be feature complete.

FW functionality is maturing.

QC Earbuds II Example

04 | Final Product

Fully realized product, with full functionality. Production parts and assembly processes. Intended user experience.

UNEXPECTED DEVELOPMENT CHALLENGES

REAL WORLD TESTING EXAMPLES

OE1 Headphones

Product Overview

Wired, passive audio playback headphone

New on-ear form factor and acoustic design

Decided to use a new supplier for acoustic mesh

New manufacturing partner building the product

OE1 Headphones

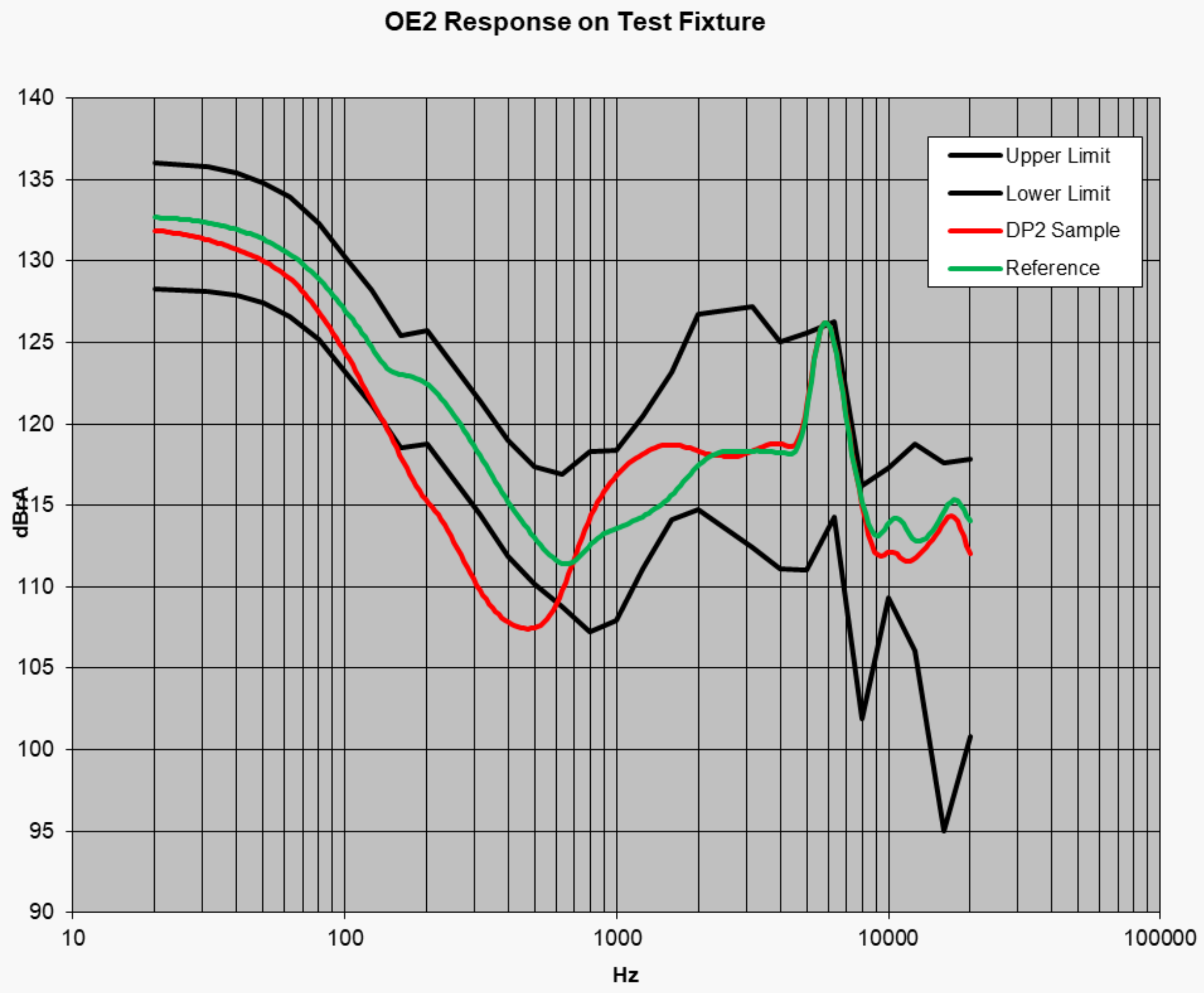
C1 Build - Acoustic Response Issue

First build at factory

Acoustic output not meeting design spec

Root caused to port impedance – too high, caused by acoustic mesh resistance out of spec

Decision: Provide qualified mesh material with known characteristics from known supplier for next build



Acoustic Mesh – OE1 Headphones

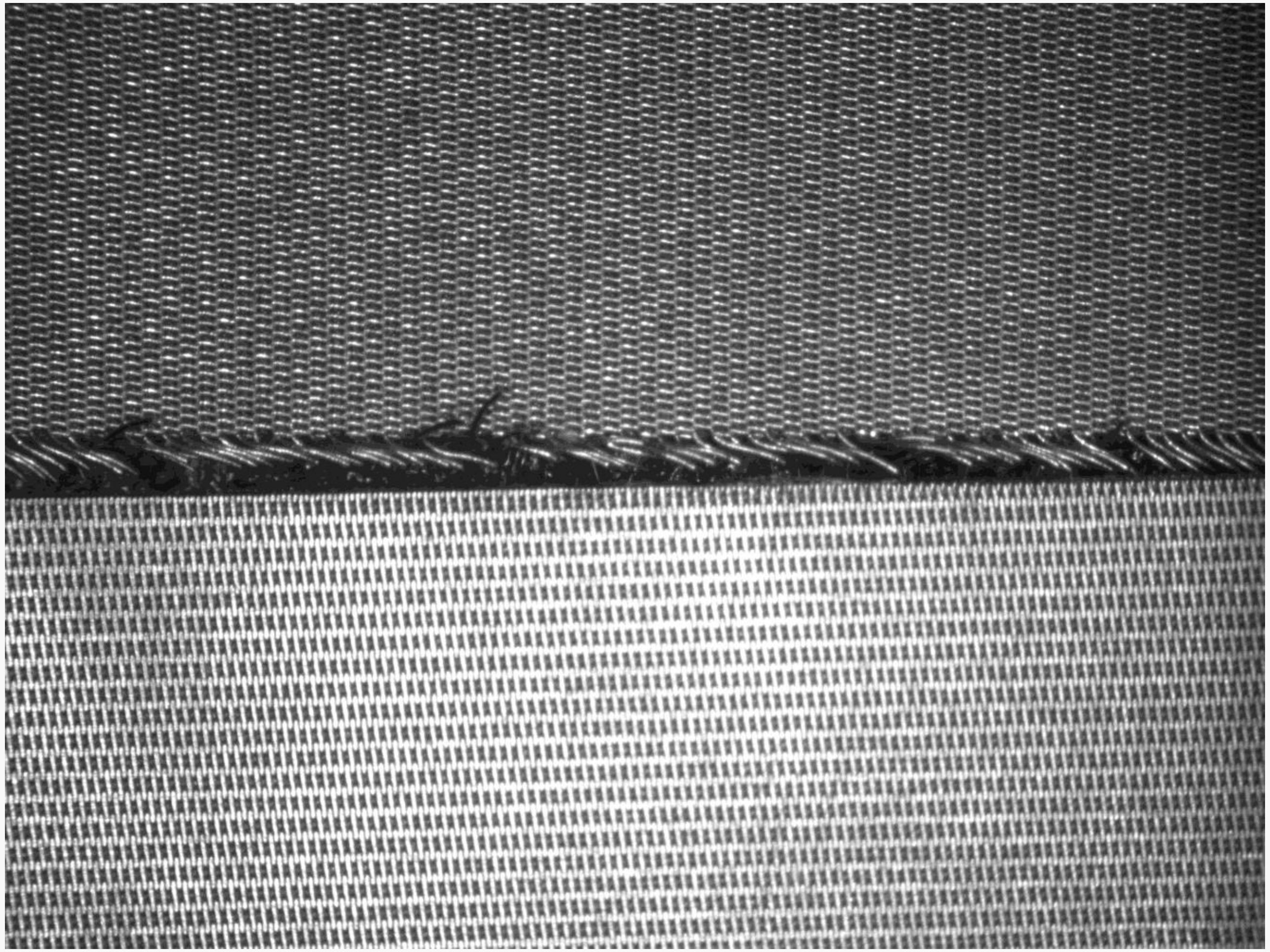
C2 Build - The Problem Persists

Bose tested and shipped new material

At the following build: problem recurred

Mesh appeared to be visually different than what was supplied

Bose Supplied Material



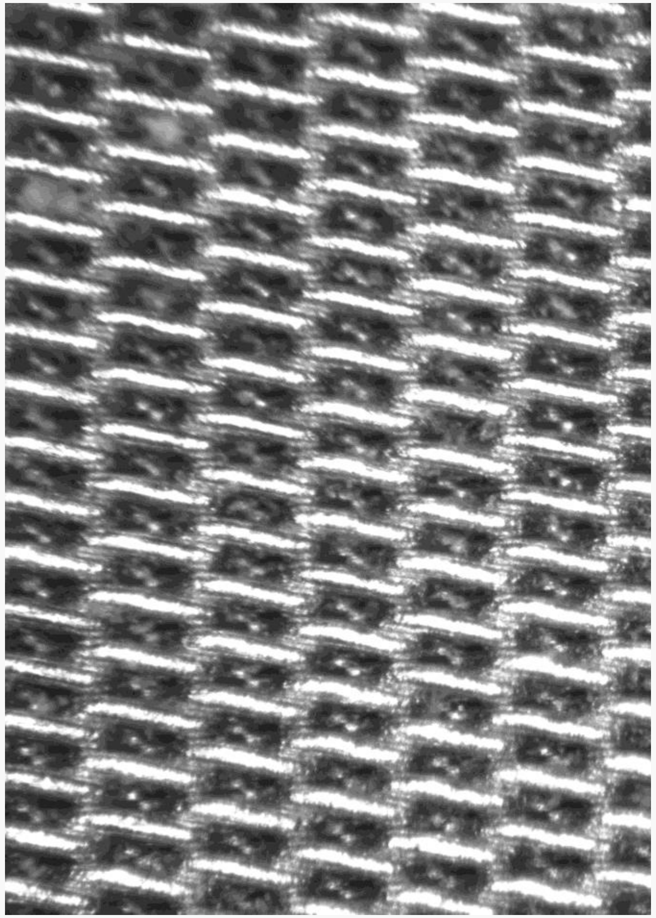
Material at Build

Acoustic Mesh – OE1 Headphones

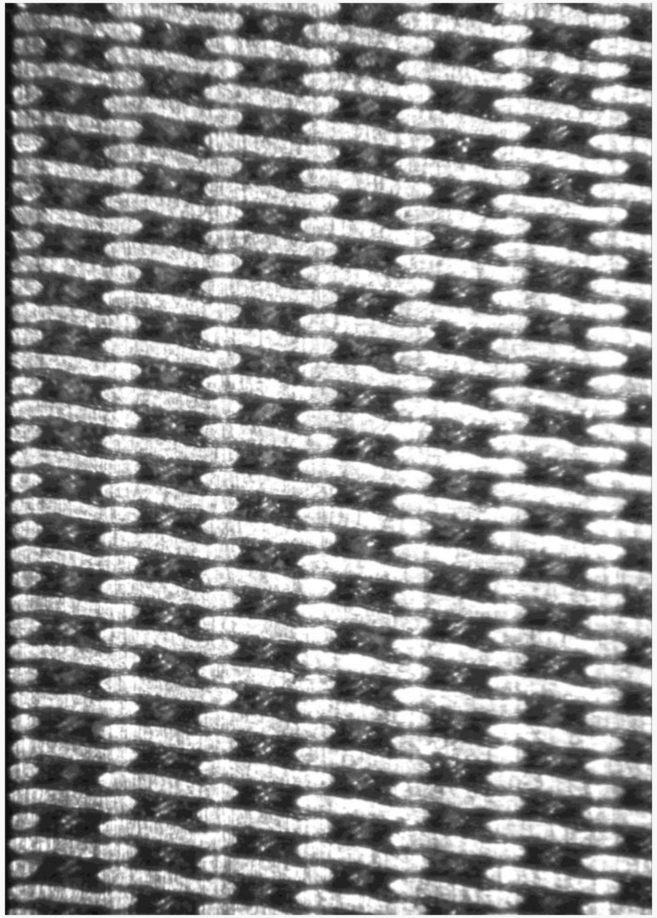
Analysis

Look at mesh under microscope

Wire weave patterns appear similar, but material clearly has been modified



Bose Supplied Material



Material at Build

Acoustic Mesh – OE1 Headphones

Further Investigation

Decided to visit the wire mesh cutting factory

Confirmed: mesh used was indeed Bose supplied material

So what happened??

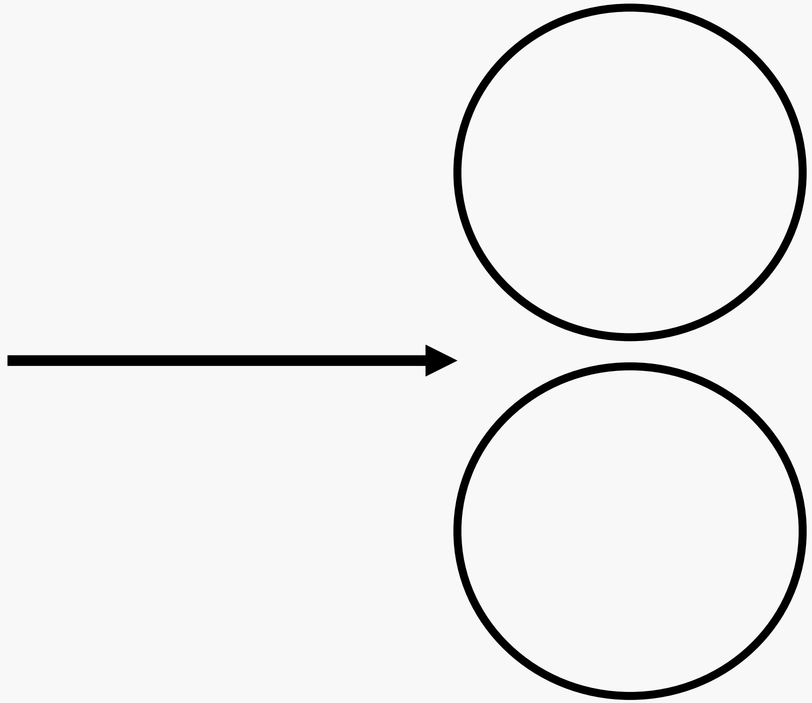
Acoustic Mesh – OE1 Headphones

Finding

Mesh cutting vendor was crushing the mesh between metal rollers prior to cutting

This was to improve the cosmetics of the cut edges

No awareness of the acoustical function of the part



Acoustic Mesh – OE1 Headphones

Outcome

Eliminated crushing operation on mesh

Since all Bose supplied material was already crushed, we decided to use the locally supplied alternative material which was immediately available in raw form for C2 onwards

This was the mesh we had decided to use in the first place!

IE1 Headphones

Product Overview

Wired, passive audio playback headset

First in-ear headphone developed at Bose

IE1 Headphones

Problem

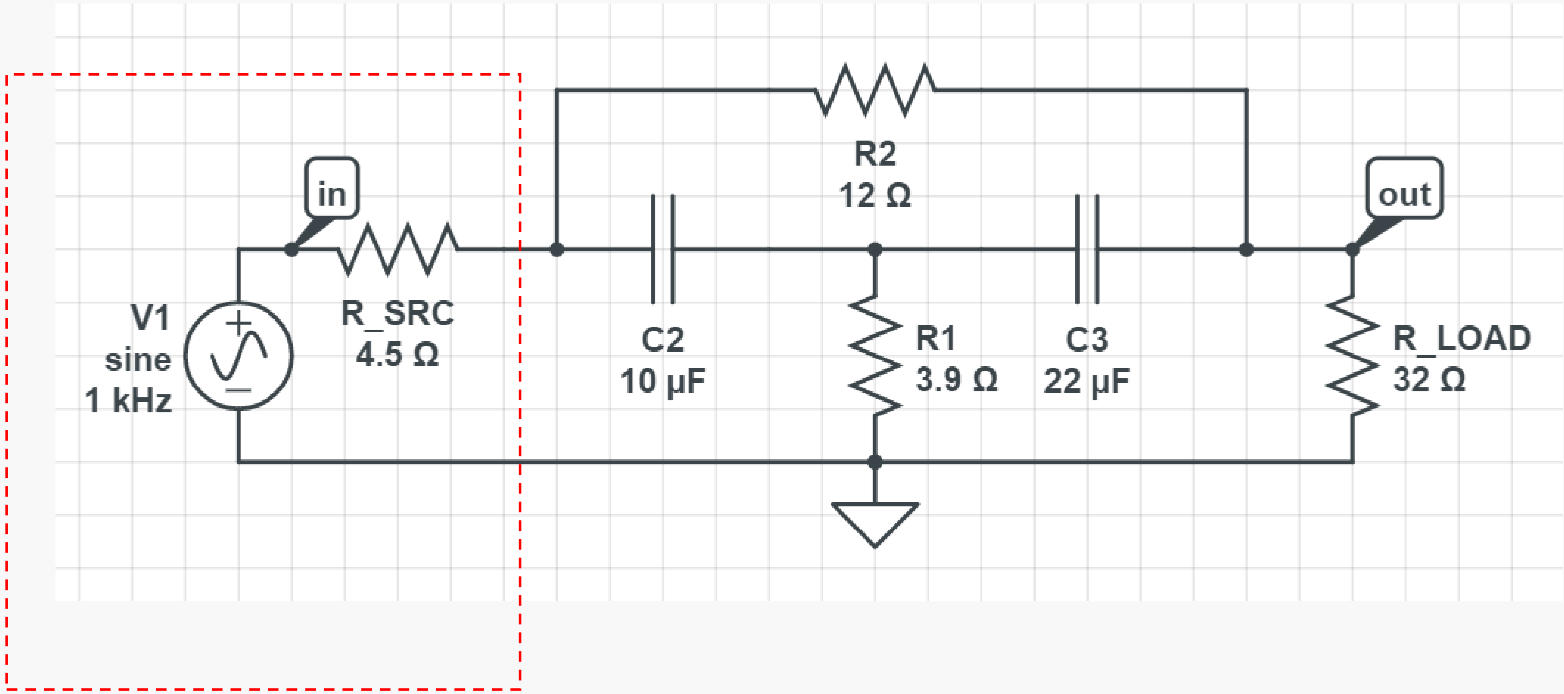
IE1 included a passive EQ circuit to adjust the audio response of the headset to match a target.

Observation: Audio performance with some music players was poor.

IE1 Headphones - Audio Performance Variation

Problem

Circuit design made assumptions about the electrical characteristics of the audio source device



Source Device

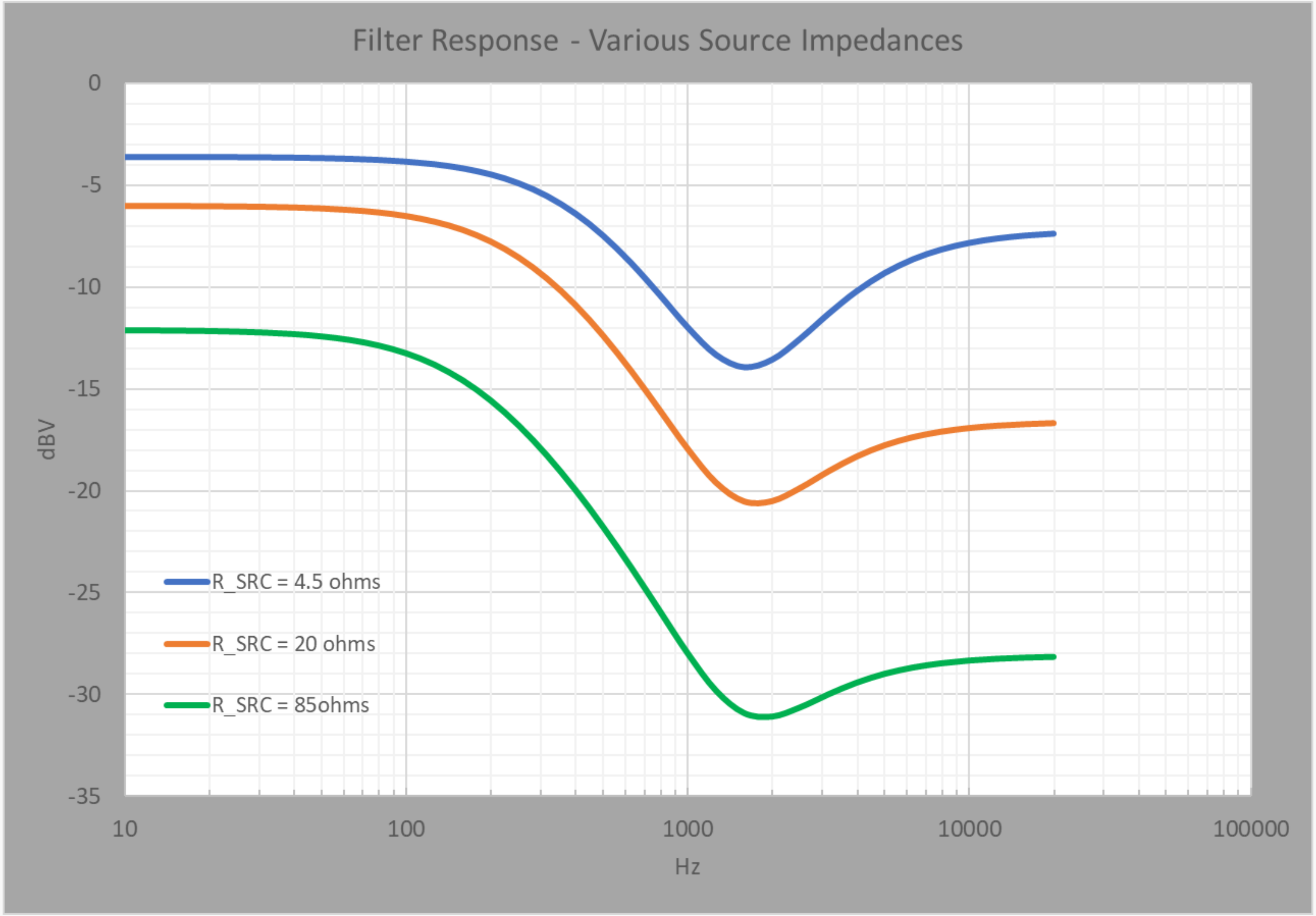
IE1 Headphones - Audio Performance Variation

Problem

Most portable players had an internal source impedance of about 4.5 ohms.

But devices varied considerably. Upon completing a survey of a wide variety of players, some were as high as 85 ohms!

This had significant impact on both output volume as well as EQ shape



IE1 Headphones - Audio Performance Variation

Outcome

Possible solutions included modified filter circuit (increased cost, physical size) or modifications to physical acoustics (long lead time, expensive to re-tool parts)

Decision not to make any design changes

Requirements placed clear focus on functionality with most common portable players (iPod), which did not have this issue

Defer improvements to circuit topology, acoustic architecture to future products

IE2 Headphones

Product Overview

2nd generation of wired, passive in-ear headphones

Included a new passive EQ circuit immune to source impedance induced variation

IE2 Headphones

A Shocking Problem

During user testing of C1 units, participants reported sensation of electrical shocks to their ears while plugging headset into a treadmill and running.

Root cause: static buildup dissipating from ear to ground through the earbud itself (plugged into ground via treadmill).

IE2 Headphones - ESD On Treadmill

Does This Need to be Fixed?

No regulatory concerns

No specific requirement in product definition that addresses this use case

But… customer experience impact was judged to be meaningful

IE2 Headphones - ESD On Treadmill

Outcome

Problem was corrected

Changed plastic resin to include metal powder content

This reduced the impedance of skin contact with the bud housing, allowing the ESD to discharge unnoticeably at a lower voltage.

QC20 Headphones

Product Overview

Wired, in-ear headphone with noise cancellation

Utilizes both Feedback and Feedforward systems for noise reducion

Bose’s first product of this type

QC20 Headphones – “Tic” Sound

Audible Artifact with Overpressure

Noticed late in program (C3 Buld) during normal use testing

Audible “tic” sound could be heard under certain conditions in some units
- Noticeable with high impulse, low frequency stimuli
- Noticeable when putting the buds into your ears while powered on, pushing on buds in ears
- Did not occur when unpowered

Small percentage of units exhibited behavior, so few samples to analyze (~3 units)

QC20 Headphones - “Tic” Sound

Troubleshooting Process

Prioritize nondestructive testing first

Check design for clearance in front acoustic volume, including driver max excursion and mechanical stack up tolerances

Measure electrical output at driver during event

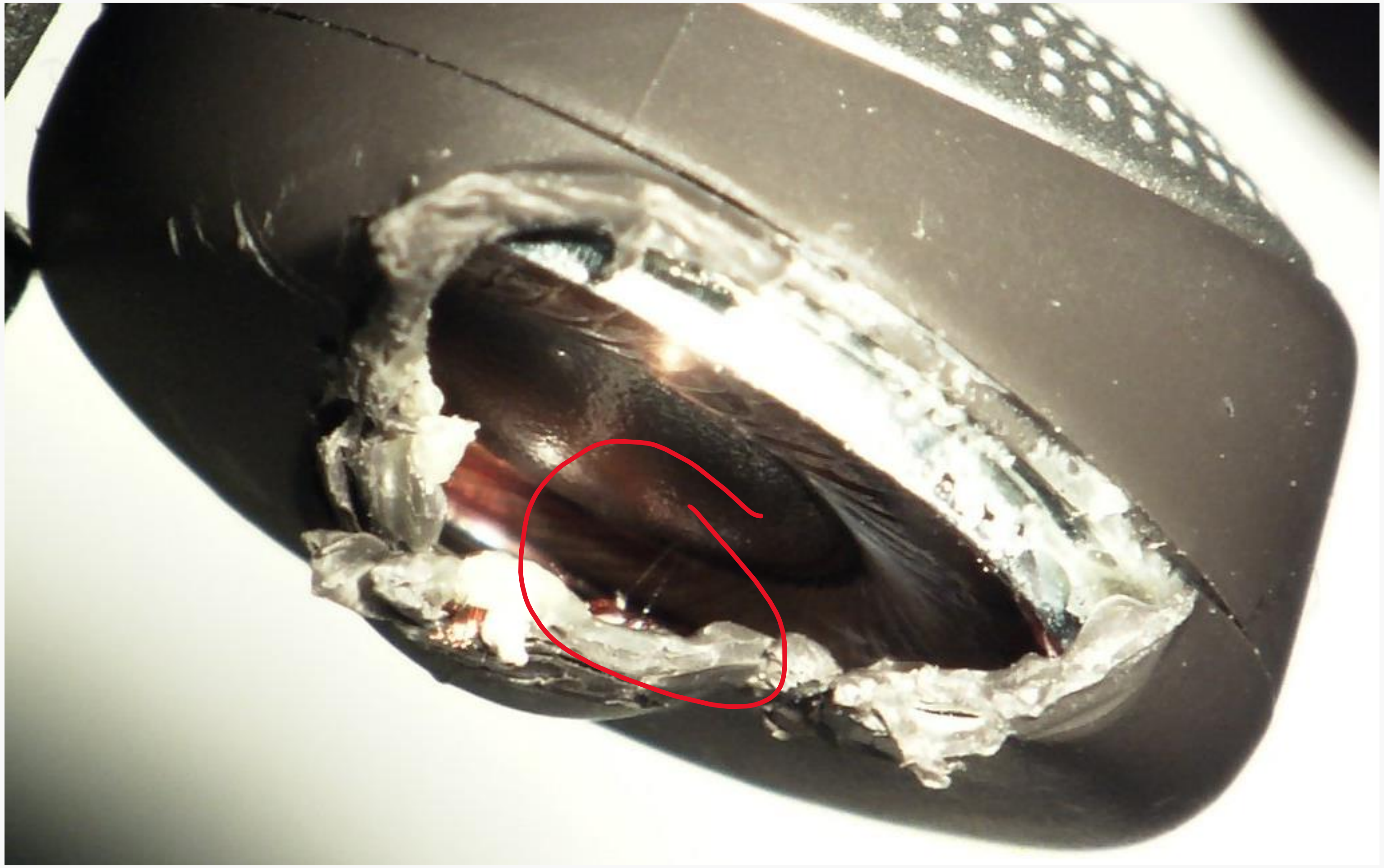
Drive driver with high system voltage, measure response at feedback microphone

Tear down analysis, recognizing risk of losing evidence

QC20 Headphones - “Tic” Sound

Finding 1

Glue strands from feedback microphone in front acoustic volume could be contacted by driver

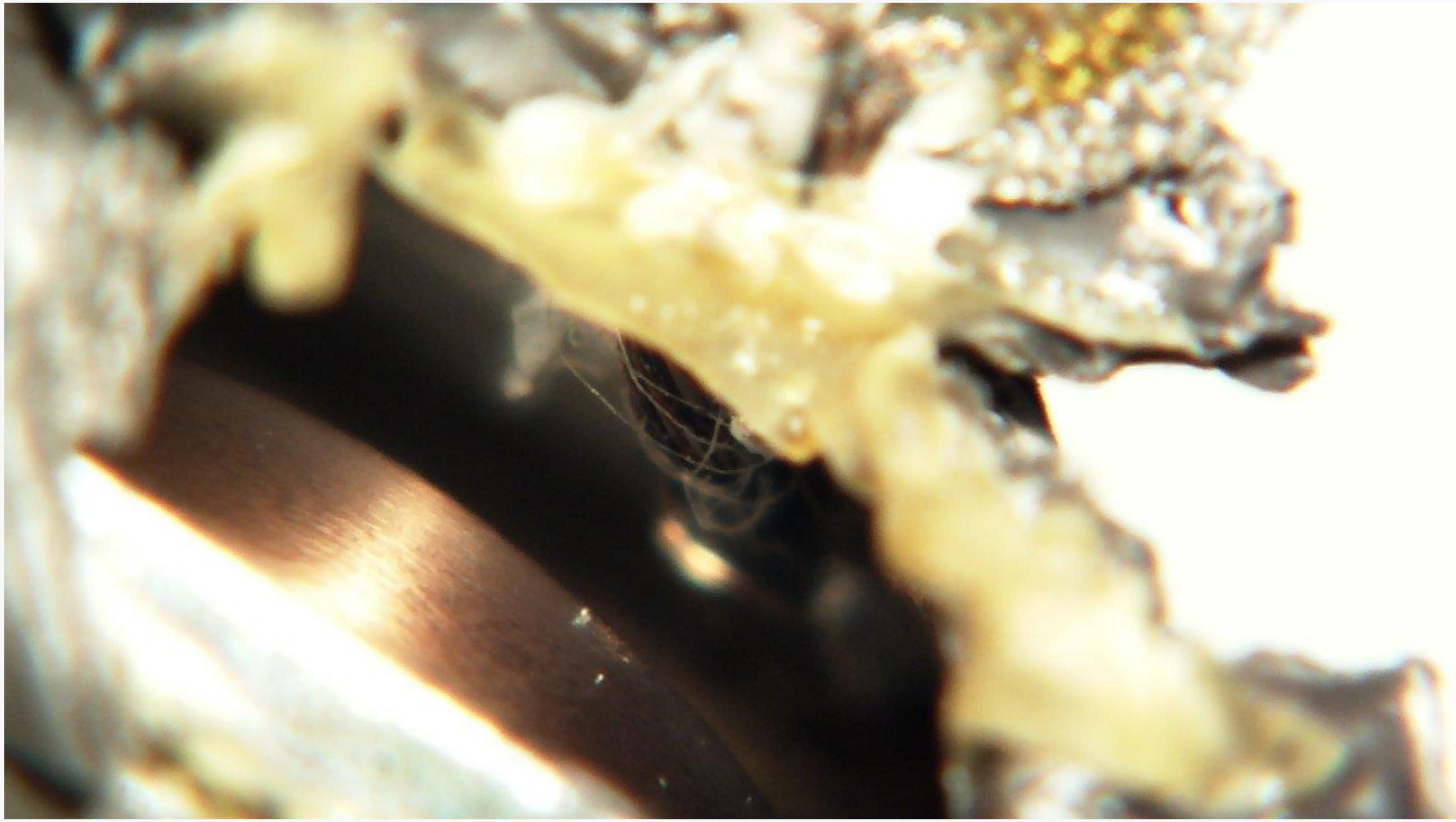


Bud nozzle cut away to expose inside of assembly

QC20 Headphones - “Tic” Sound

Finding 2

Loose fibers from mic wire bundle inside front acoustic volume could contact driver



QC20 Headphones - “Tic” Sound

Video

600mV @ 8Hz

Driver diaphragm hits fiber strands

QC20 Headphones - “Tic” Sound

Solution

Assembly process improvements introduced to prevent these problems

Develop and introduce “Tic test” to production line to detect problem units and prevent escapes

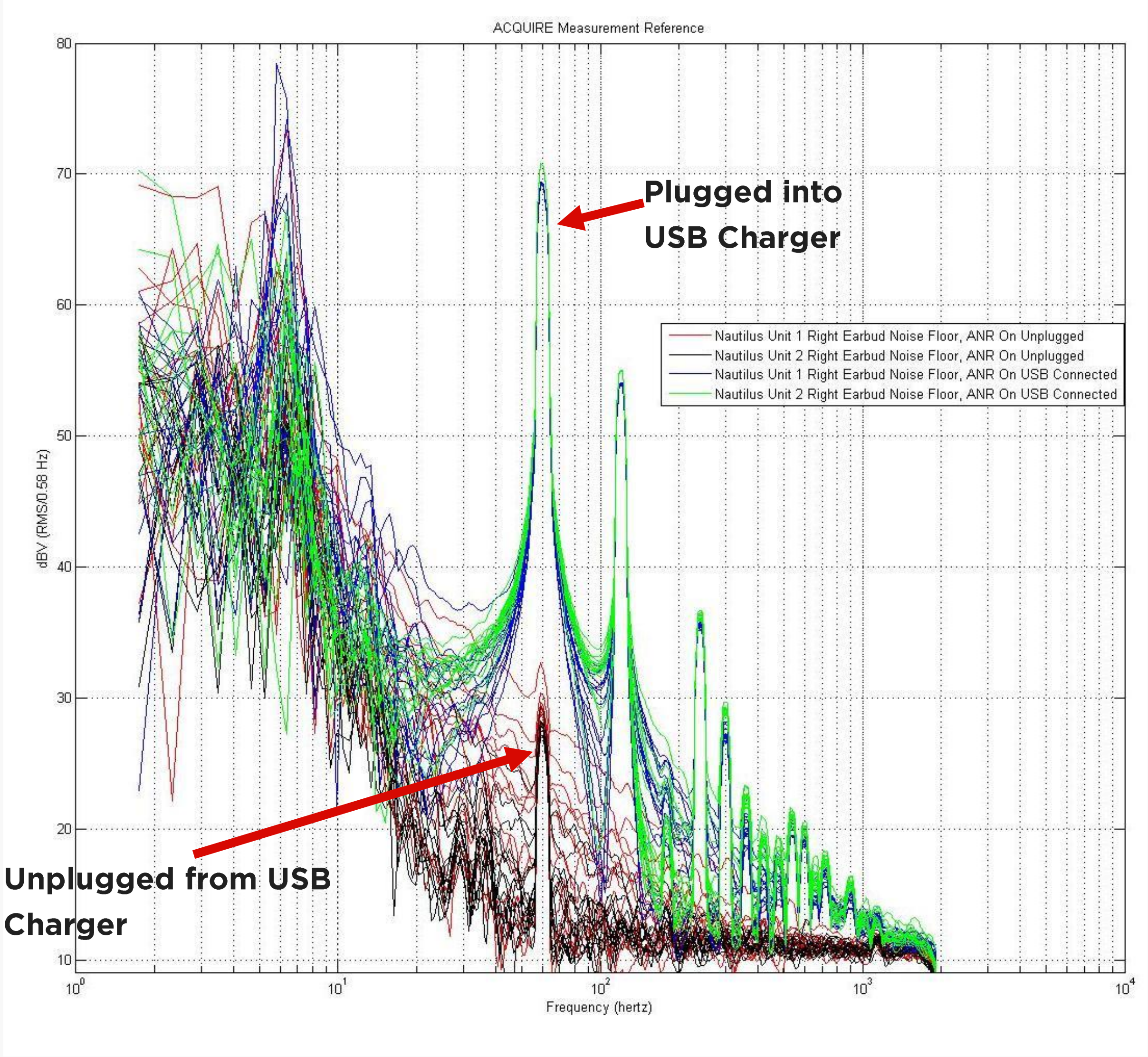
QC20 Headphones – 60Hz Hum

Problem

Detected during normal use testing during C1 Build phase. Headset had audible hum under specific set of operating conditions:

- plugged into a source device that was plugged into wall power (ie a laptop, or smartphone plugged in to charge)
- Source device had a 2 prong plug (ungrounded)
- Headset was plugged into USB for charging
- Device is powered on

Hum was reasonably loud and obviously noticeable

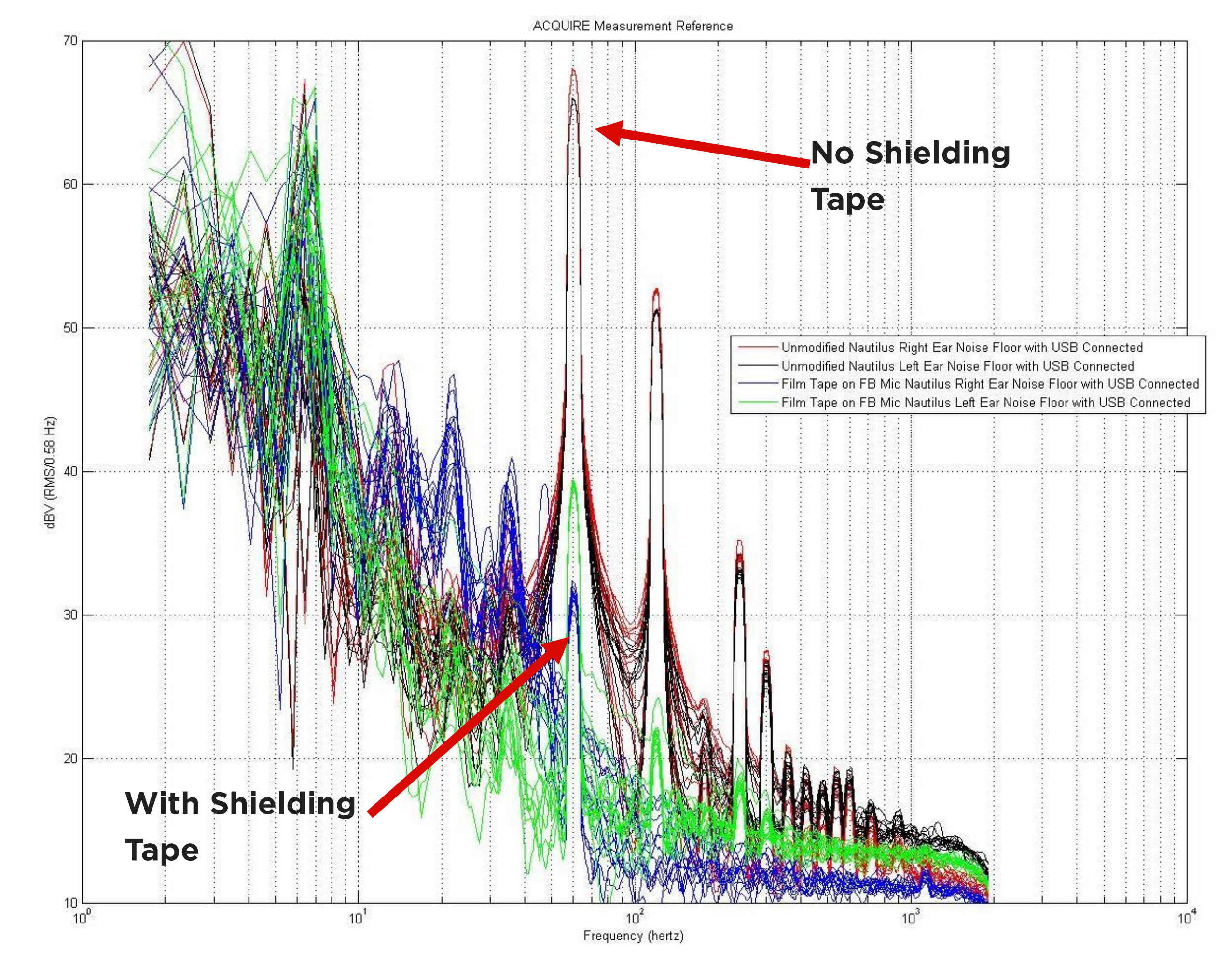


QC20 Headphones – 60Hz Hum

Analysis

Microphone path was suspected due to being a high gain path within the system

Disconnecting microphones eliminated the noise pickup



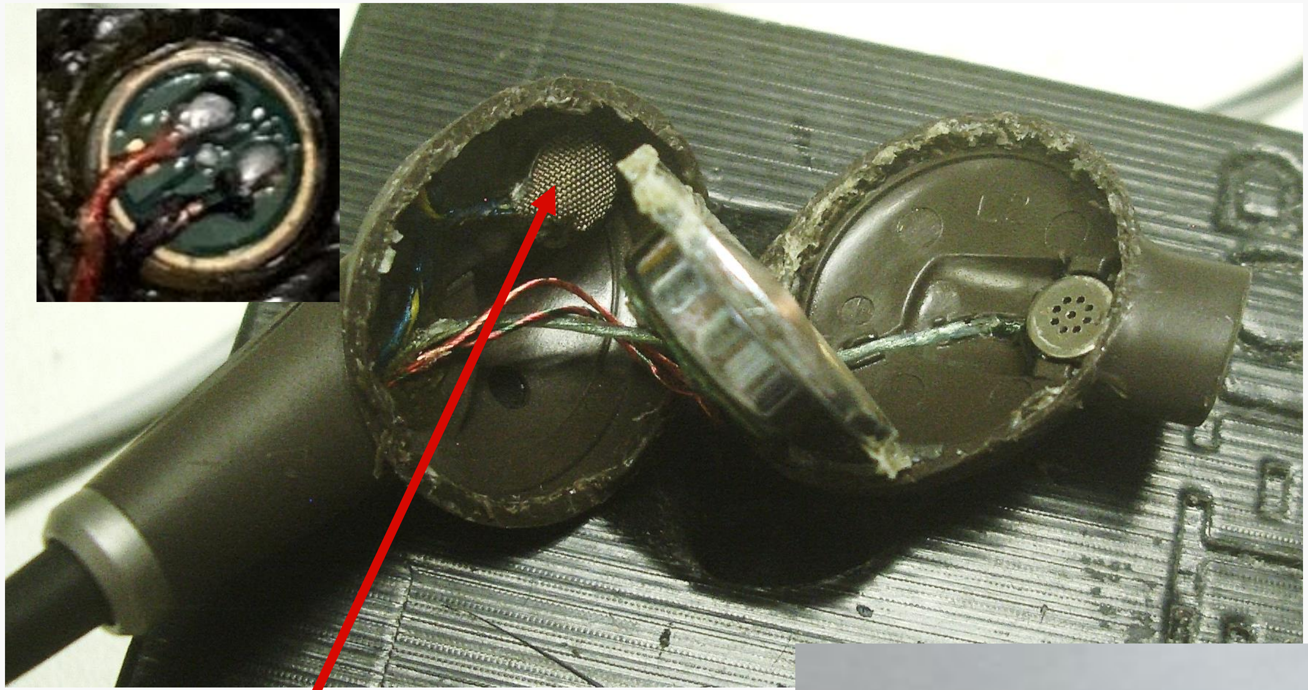
QC20 Headphones – 60Hz Hum

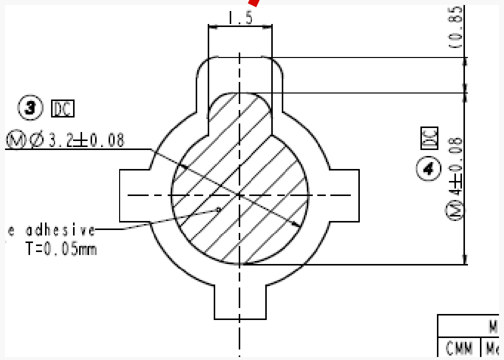
Solution

Shield back of microphones with conductive fabric (metal mesh).

Ensure shield is grounded to mic housing with conductive adhesive

Use Kapton tape to prevent shorting of mic solder pads.





QC Earbuds

Product Overview

True Wireless In-Ear (TWIE) headphones
with noise cancellation

First product of this type for Bose

QC Earbuds - Unexplained Noise Coupling

“Weird Noises” in Some Conference Rooms

Detected with C2 buds under normal use testing.

Buds were sometimes making tonal, narrowband sounding noises, but only sometimes and in some physical locations

First noticed in a particular conference room

QC Earbuds - Unexplained Noise Coupling

Some Clues to Root Cause

Frequency and loudness would modulate with movement, head position

Noise would get noticeably louder when standing in certain places

Covering the bud with your hand would stop the noise

Covering just the microphones with a finger would stop the noise

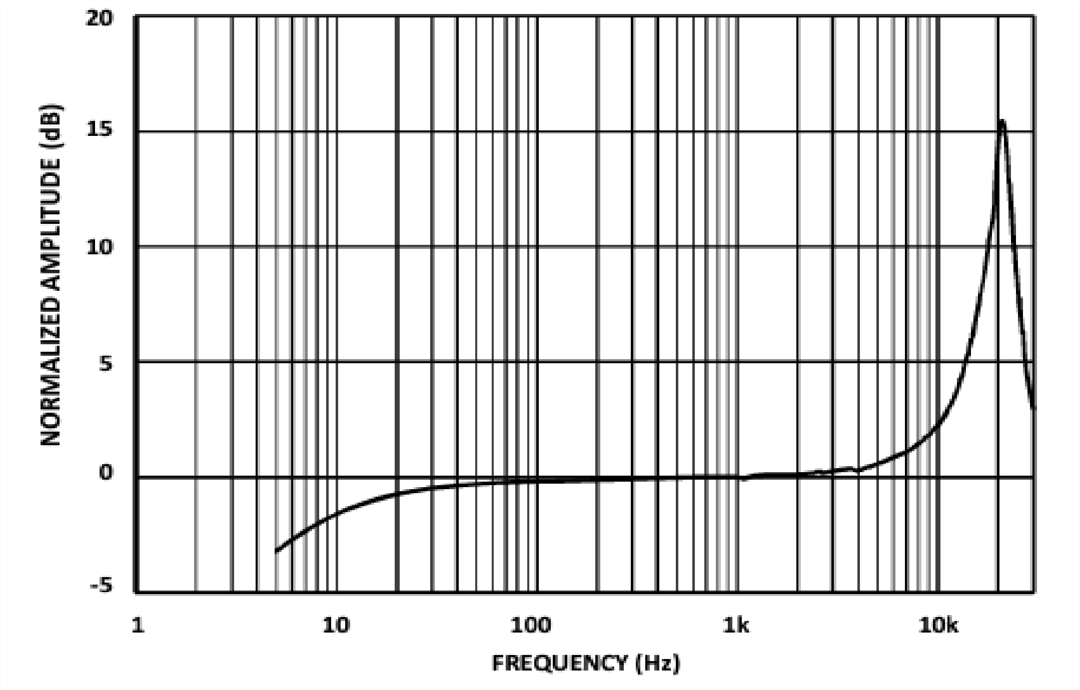
QC Earbuds - Unexplained Noise Coupling

Microphone Frequency Response

This product utilized MEMS microphones

MEMS mics typically have a resonant peak of sensitivity between 20-30kHz

What could excite the microphone in this frequency range?

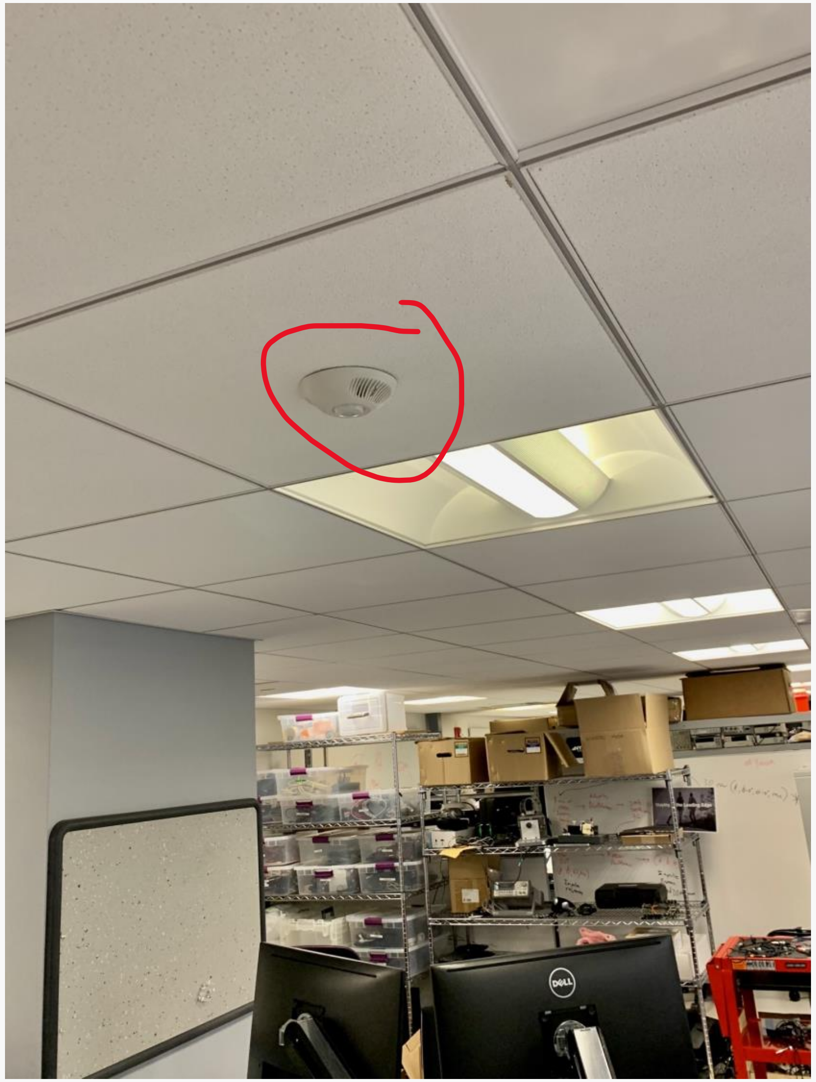


QC Earbuds - Unexplained Noise Coupling

The Answer

Some motion detectors utilize sensors that emit ultrasonic sound energy in the 30-50kHz range.

High output levels are enough to saturate or clip the microphone input, causing unpredictable overload behaviors.



QC Earbuds - Unexplained Noise Coupling

Outcome

Worked with mic manufacturer to understand root cause and potential fixes.

Root cause: Mic ASIC clock frequency was aligned with ultrasonic output of sensor.
Nonlinear mixing of ultrasonic noise contaminated the internal clock signals.

Clock change proposed to ASIC to move away from ultrasonic frequency peak.

Note: A recurrence of this same problem happened with the next gen product.
Different mic, different root cause, different fix!

QC Earbuds II

Product Overview

2nd generation TWIE earbuds with noise cancellation

Better performance, smaller form factor

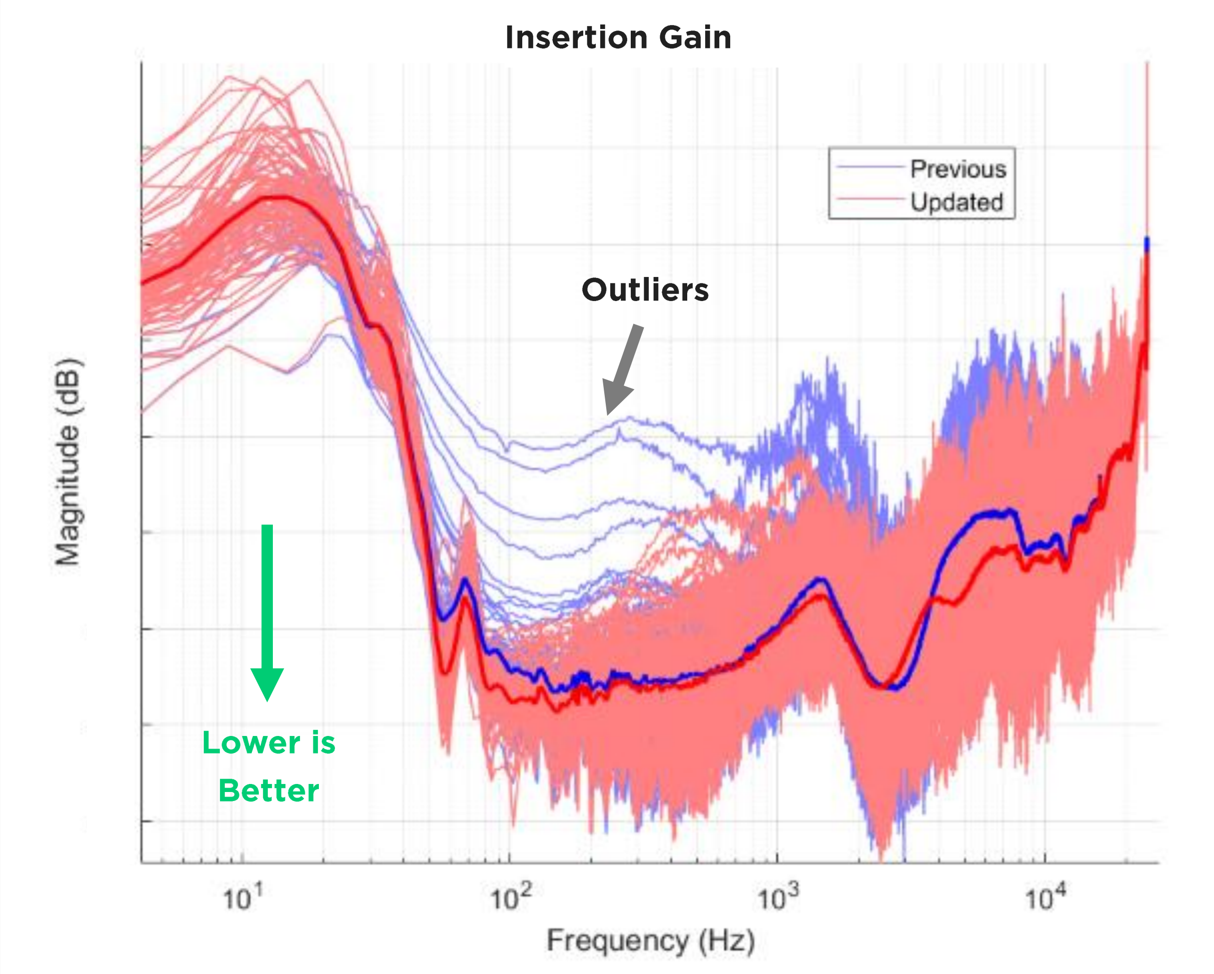
QC Earbuds II – Loss of Noise Cancellation

Problem

For some users, noise reduction performance was degraded

Detected with C0 Build units during functional performance testing

Could be many reasons why this could occur



QC Earbuds II – Loss of Noise Cancellation

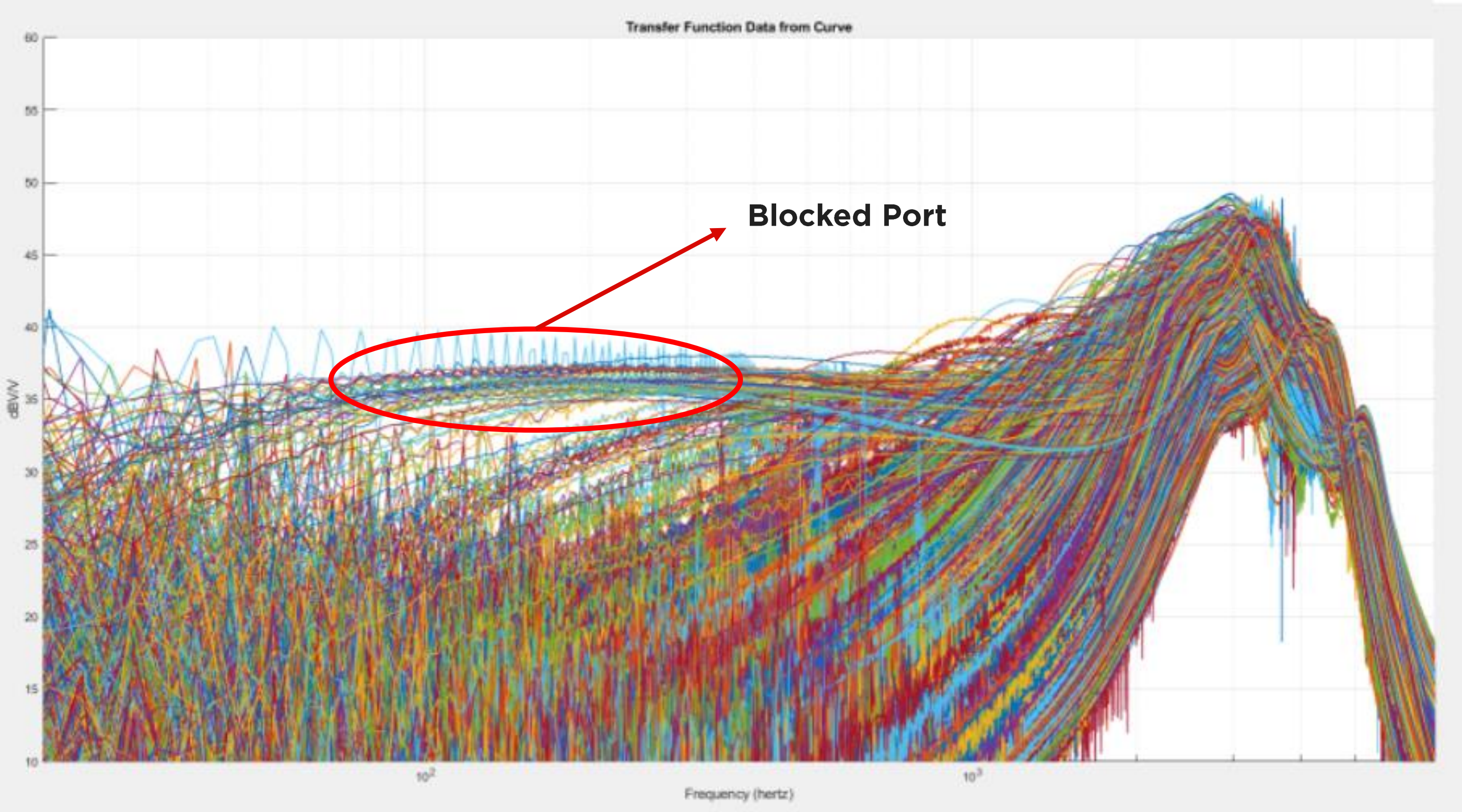
Port Block Experiment

Prototype devised to evaluate potential to block acoustic port

Measurements conducted on large group of human subjects

High output = blocked

Low output = open



QC Earbuds II – Loss of Noise Cancellation

Solution

Relocate port exit to prevent occlusion

No perfect solution, but had to choose best compromise

Old New

Quiet Comfort Ultra Headphones

Product Overview

New headphone using new microprocessor

New processor is variant of part used in existing products – "it should just work"

Product has self test capabilities, can stream PCM digital audio data out via I2S

Quiet Comfort Ultra Headphones

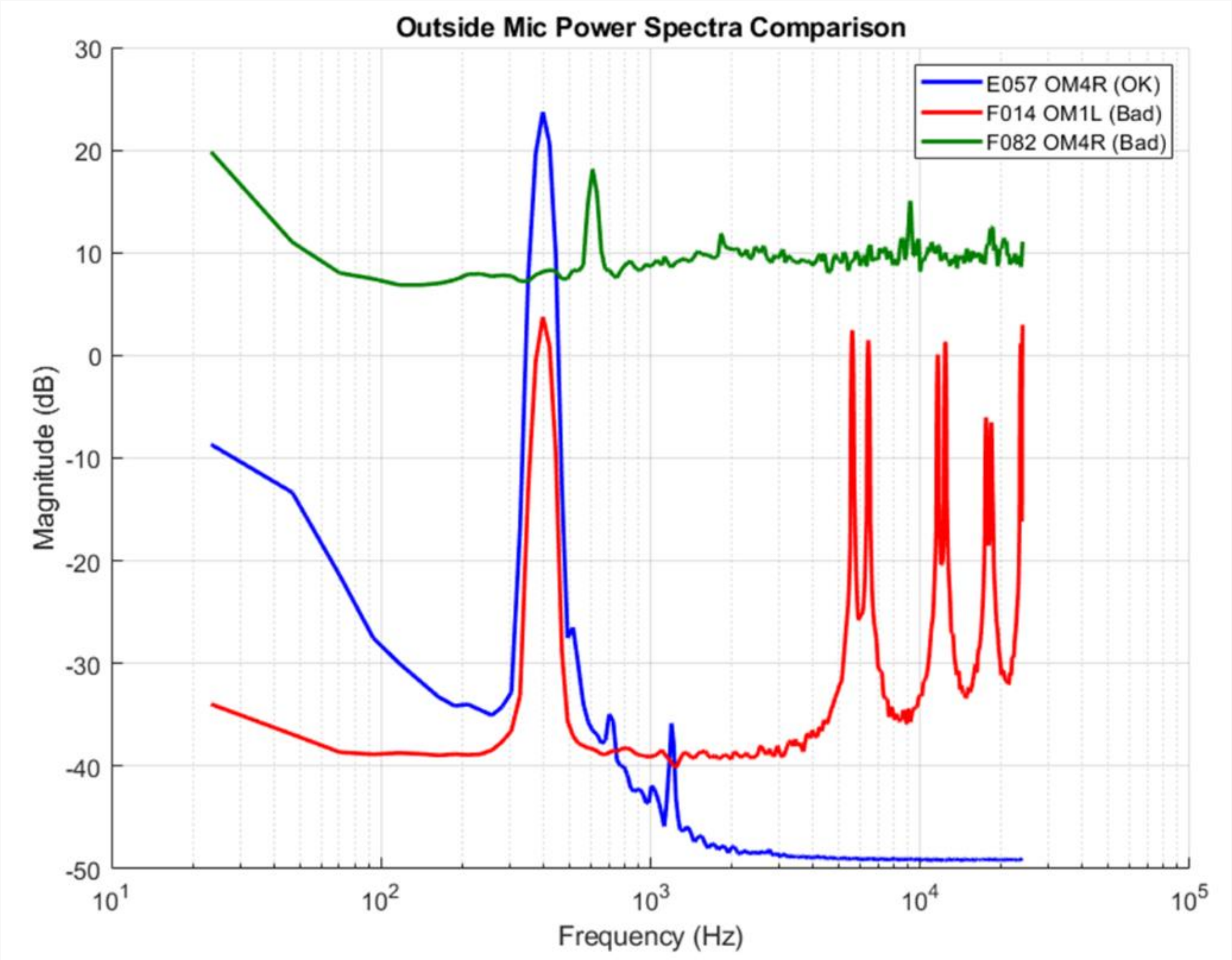
Problem

Detected during engineering process development work with C2 Build units.

Acoustic calibration response data from I2S was attenuated, and contained high frequency noise on about 40% of units

Acoustic fixture evaluation showed that there was no true acoustic difference. Therefore, the I2S data was incorrect.

But why?

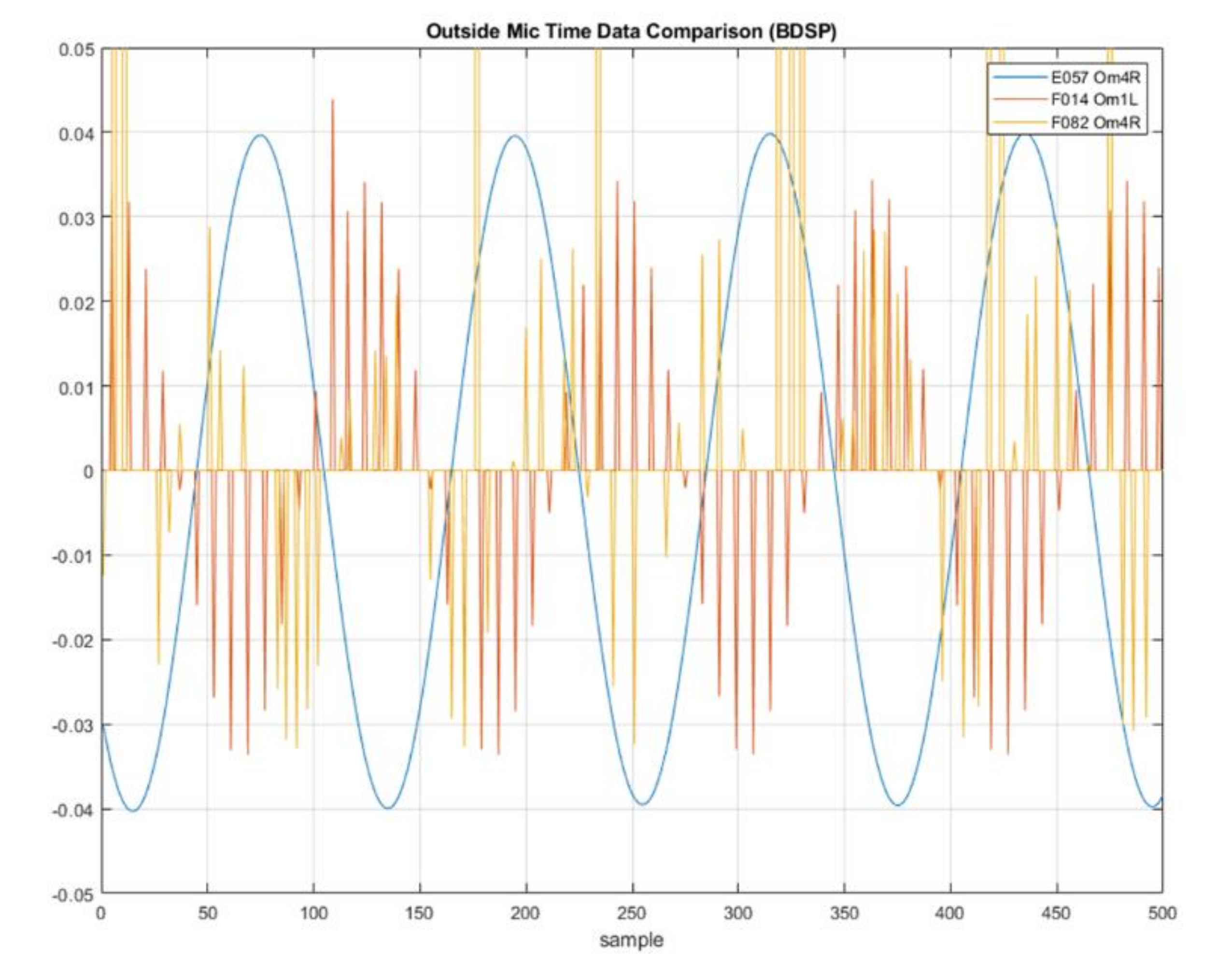


Quiet Comfort Ultra Headphones

Analysis

Check time series data

Noticed many samples were zeroed out on bad units



Quiet Comfort Ultra Headphones

I2S Line (for Measurement Data)

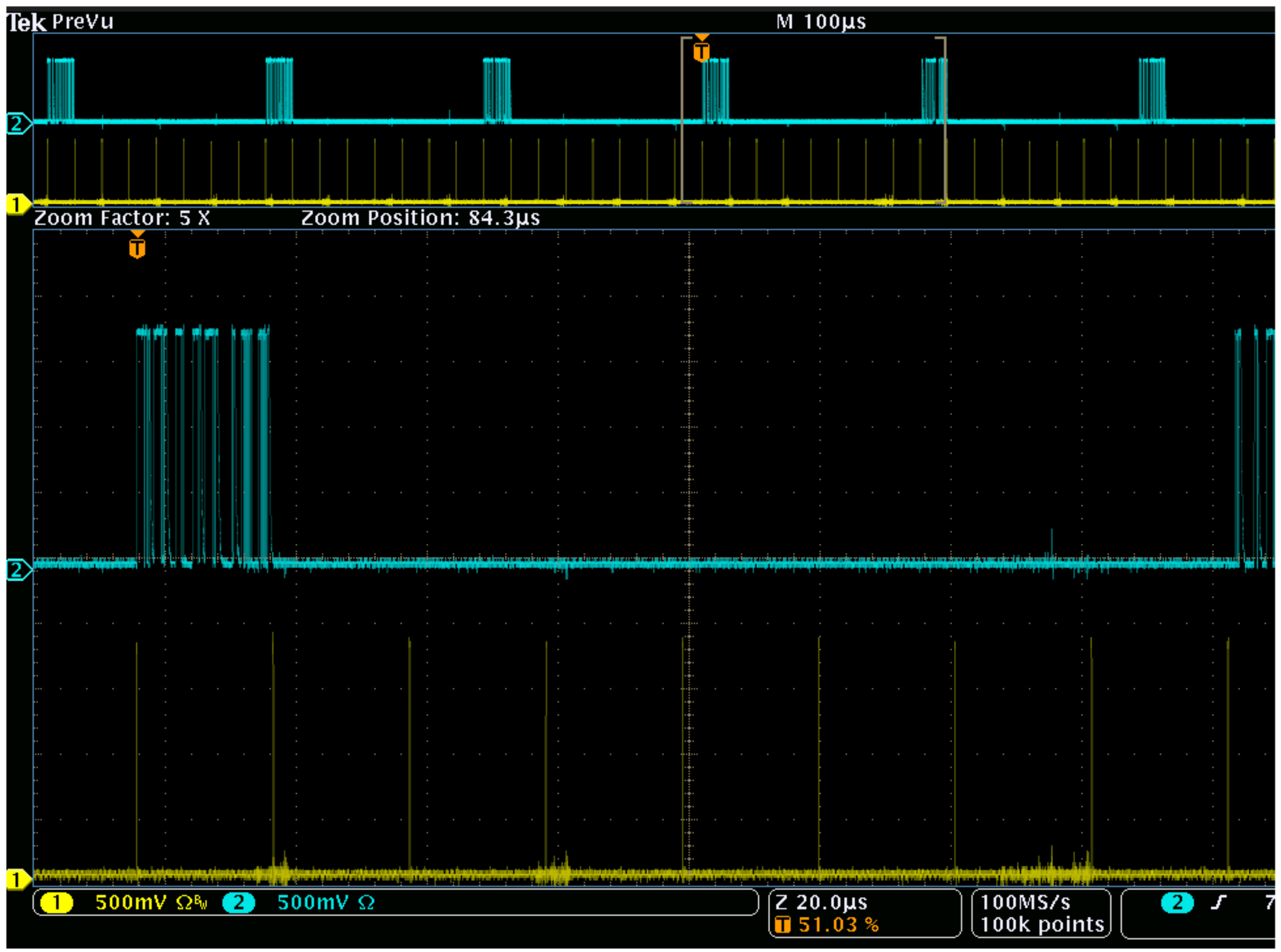
Analysis

Check digital sample data

Only 1 of every 8 frames contained data

Serial Data

Frame Sync



Quiet Comfort Ultra Headphones

Root Cause and Solution

Frame sync was triggering incorrectly on the rising edge of the clock signal.

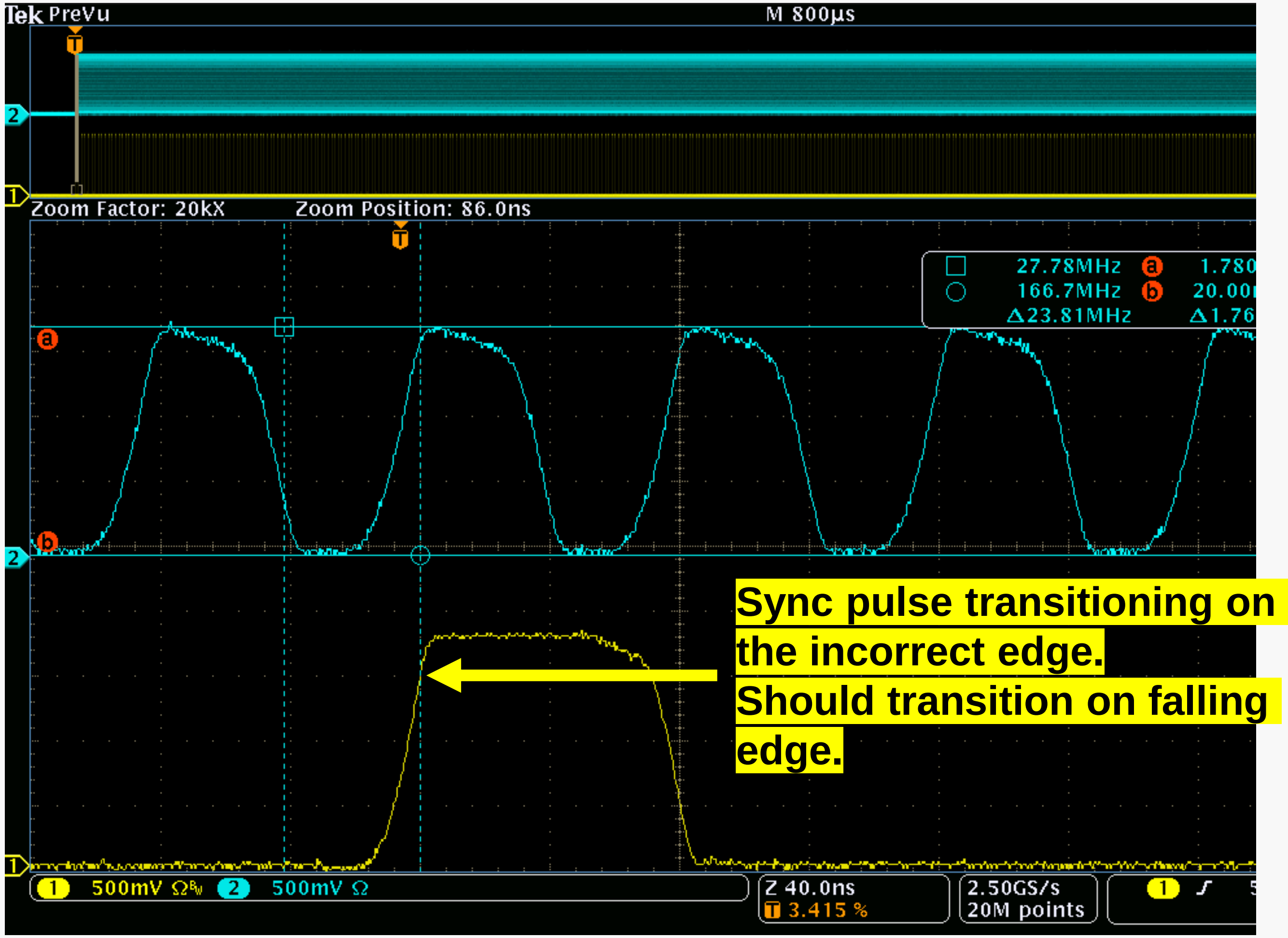
Notice the clock signal is not a perfect square wave – this shape is influenced by the variations in passive component values. This explains the unit to unit variation for this issue.

Adjusting the device Firmware setting to trigger on the falling edge restored functionality to all devices.

I2S Line (for Measurement Data)

Bit Clock

Frame Sync



Summary of Issues

Many sources of root cause and corrective action

Note that all of these issues have audio performance related symptoms, but the root causes span a variety of functional disciplines

Product	Issue	Root Cause	Solution Type
OE1	Acoustic mesh too resistive	Material	Process
IE1	Source impedance causes audio performance variation	EE Design	Requirements
IE2	Electric shock to users running on treadmill	Electro-Mechanical	Material
QC20	Tic sound under high driver excursion	Mechanical	Process
QC20	60 Hz hum	EMC	EE Design
QCE1	Ultrasonic noise coupling	Electro-Acoustic	Component
QCE2	Acoustic port blockage	Human Factors	ME Design
QCUH	Audio data digital communications	Electro-Acoustic	Firmware

Key Takeaways

Expect and plan for unexpected, discovered work to emerge along the way

Understand: Requirements and use case are the referees keeping you on the field

- Does the problem need to be solved?
- What constitutes a sufficient solution?

Root Cause Analysis can sometimes be tricky

- Cross-functional, system thinking required to identify and solve complex issues

Key Takeaways

Solutions can come from a variety of places

- Mechanical design
- Components
- Materials
- Manufacturing process
- Firmware
- Requirements change

Tradeoffs are inevitable

- Between functional disciplines
- Product requirements
- Schedule
- Cost


Q&A