Systems Engineering the World's Most Energetic Laser

March 2023

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Chair, Systems Engineering Board, LLNL

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Lawrence Livermore National Laboratory

Robert Plummer

- Chair of LLNL Systems Engineering Board
- Chief Engineer for Advanced Photon Technologies within NIF&PS and Project Engineer for the MEC Rep-Rated Petawatt Laser Upgrade for SLAC LCLS
- Formerly Head of Engineering & Maintenance for NIF Optics
- Technical expertise in structural mechanics, machine design and integration, systems engineering, and optomechanics
- Education
  - Systems Design and Management (SDM) Program, Massachusetts Institute of Technology
  - Masters of Science, Structural Engineering, Stanford University
  - Bachelors of Science, Civil and Environmental Engineering, Rice University

What we are going to talk about

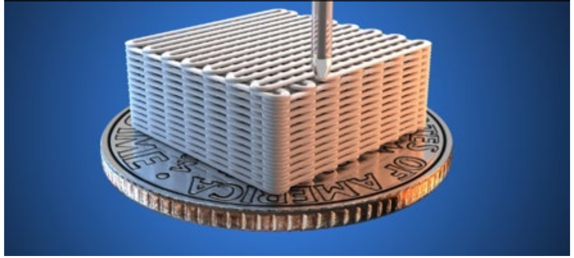
- NIF, the world's largest and most energetic laser
- NIF's evolving history with SE
- SE in practice at NIF/case study

LLNL is a DOE national security laboratory located in SF Bay Area

- Established in 1952
- 1 square mile, >500 facilities
- ~8,300 employees
- Annual budget ~$2.9B

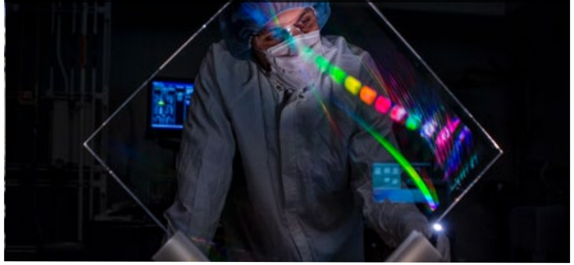
World-class science, technology, and engineering

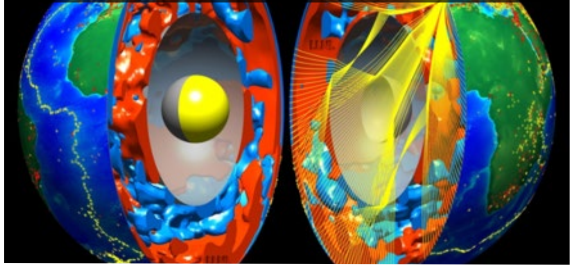
High-Energy-Density Science


Advanced Materials and Manufacturing


Bioscience and Bioengineering

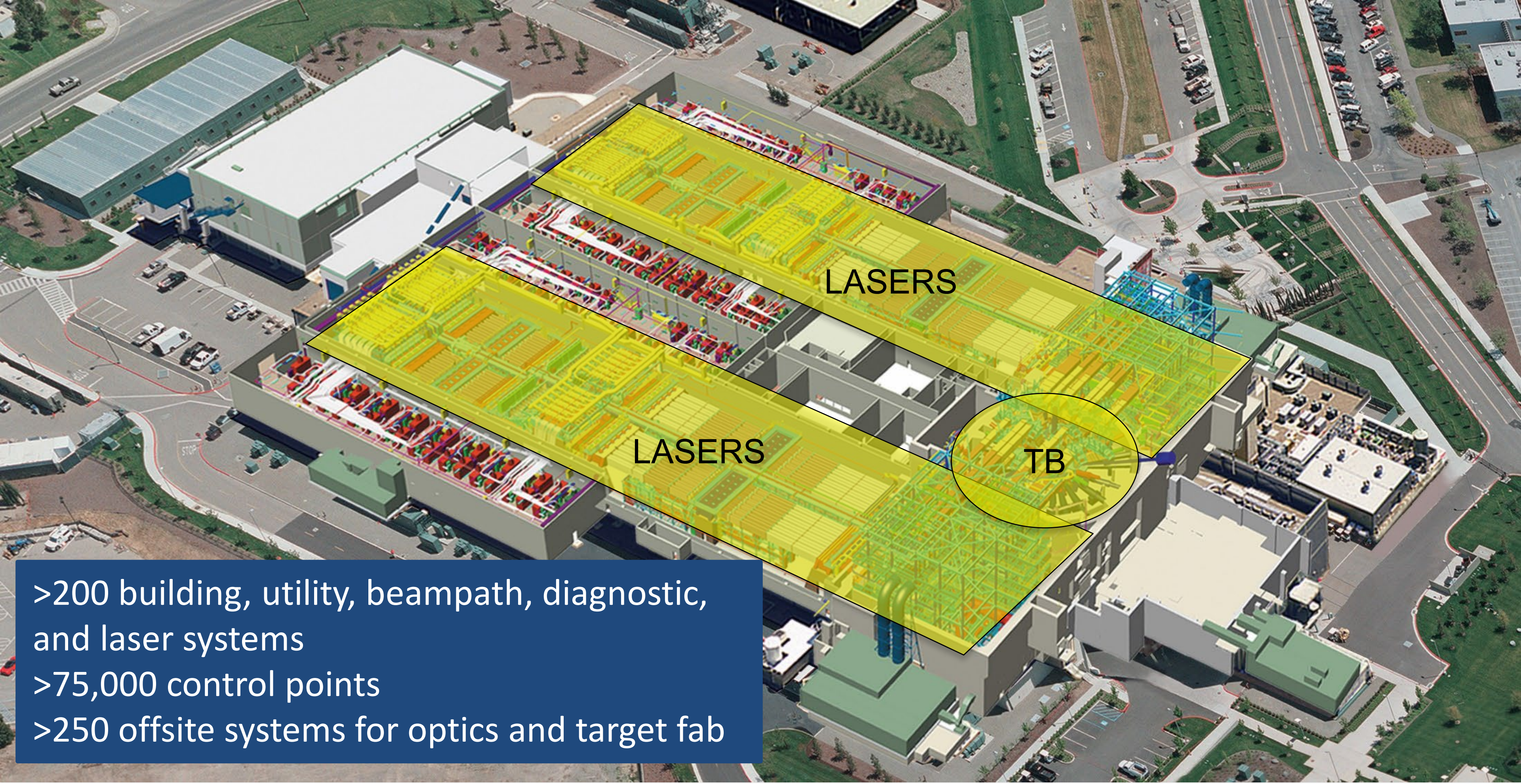

Nuclear, Chemical, and Isotopic S&T


Laser and Optical S&T


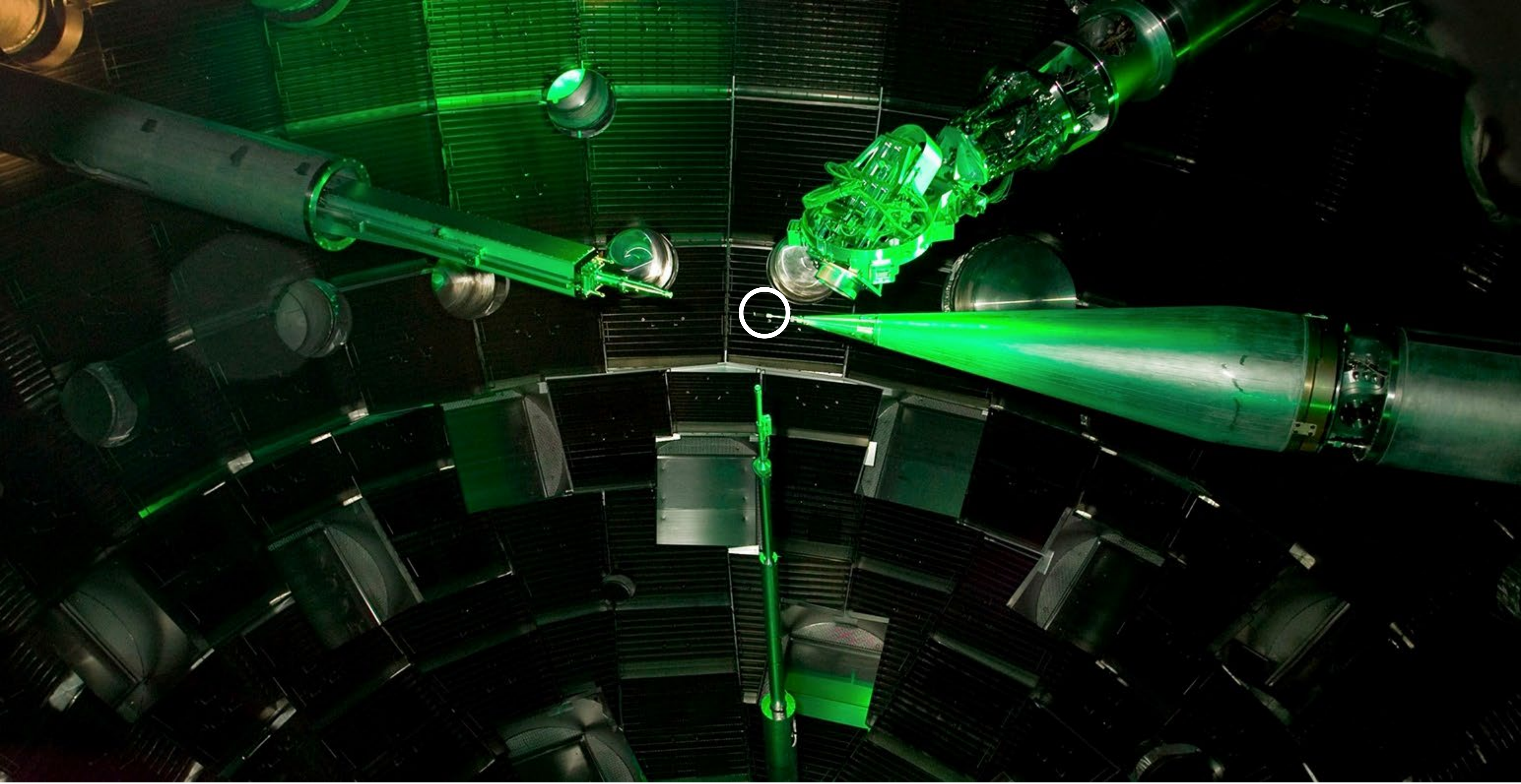
Earth and Atmospheric Science


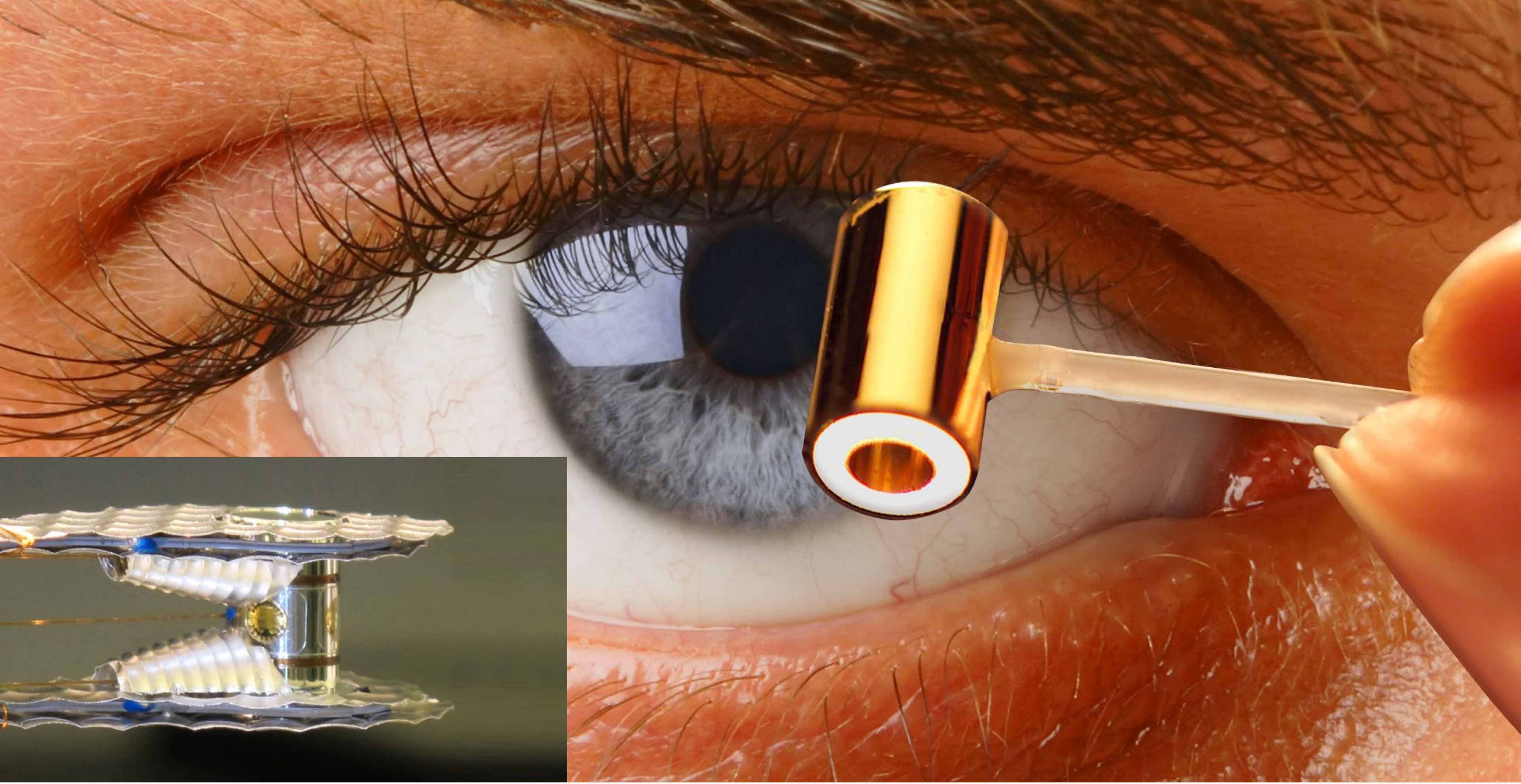
High-Performance Computing, Simulation, and Data Science


National Ignition Facility (NIF) is the world's largest and most energetic laser, delivering >1.8MJ and 500TW to targets



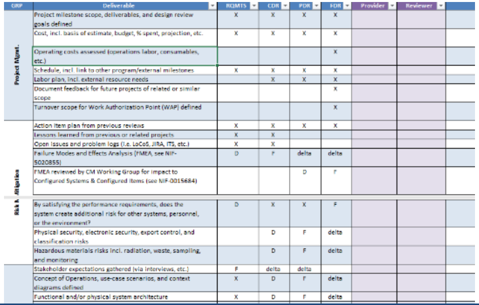
>200 building, utility, beampath, diagnostic, and laser systems
>75,000 control points
>250 offsite systems for optics and target fab



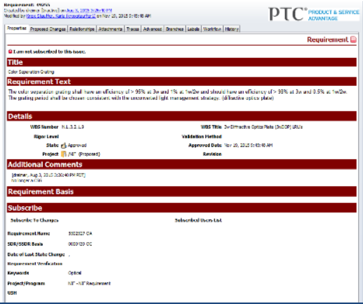


SE at NIF: past and present

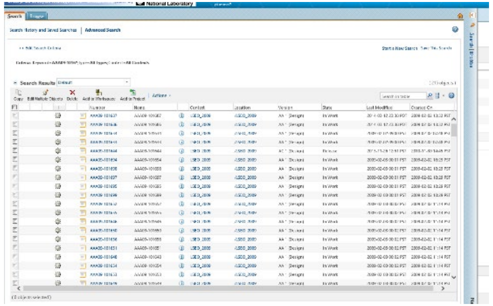
Through engineering best practices and process, SE is built into everything we do at NIF



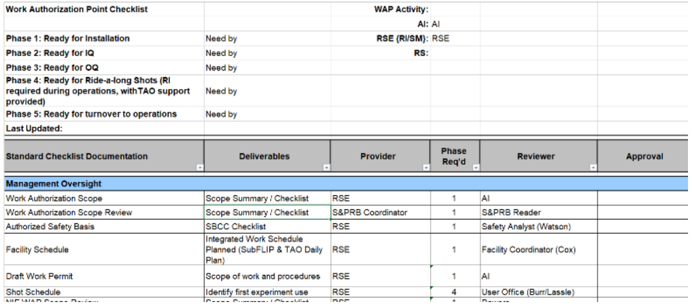
Design Reviews



Requirements Management



Configuration Management



Work Authorization Process

Design reviews are conducted to solicit independent, peer review in order to identify and manage risk

- Checklist-driven process ensures consistency and thoroughness
- Categories
  - Project mgmt.
  - Risk mitigation
  - Requirements
  - Physics basis
  - Procurement
  - Documentation
  - Verification testing

GRP	Deliverable	RQMTS	CDR	PDR	FDR	Provider	Reviewer	
Project Mgmt.	Project milestone scope, deliverables, and design review goals defined	X	X	X	X			
	Cost, incl. basis of estimate, budget, % spent, projection, etc.	X	X	X	X			
	Operating costs assessed (operations labor, consumables, etc.)				X			
	Schedule, incl. link to other program/external milestones	X	X	X	X			
	Labor plan, incl. external resource needs		X	X	X			
	Document feedback for future projects of related or similar scope				X			
	Turnover scope for Work Authorization Point (WAP) defined				X			
Risk Mitigation	Action item plan from previous reviews	X	X	X	X			
	Lessons learned from previous or related projects	X	X					
	Open issues and problem logs (i.e. LoCoS, JIRA, ITS, etc.)	X	X					
	Failure Modes and Effects Analysis (FMEA, see NIF-5020855)	D	F	delta	delta			
	FMEA reviewed by CM Working Group for impact to Configured Systems & Configured Items (see NIF-0015684)			D	F			
	By satisfying the performance requirements, does the system create additional risk for other systems, personnel, or the environment?	D	X	X	F			
	Physical security, electronic security, export control, and classification risks		D	F	delta			
	Hazardous materials risks incl. radiation, waste, sampling, and monitoring		D	F	delta			
	Stakeholder expectations gathered (via interviews, etc.)	F	delta	delta				
	Concept of Operations, use-case scenarios, and context diagrams defined	X	D	F	delta			

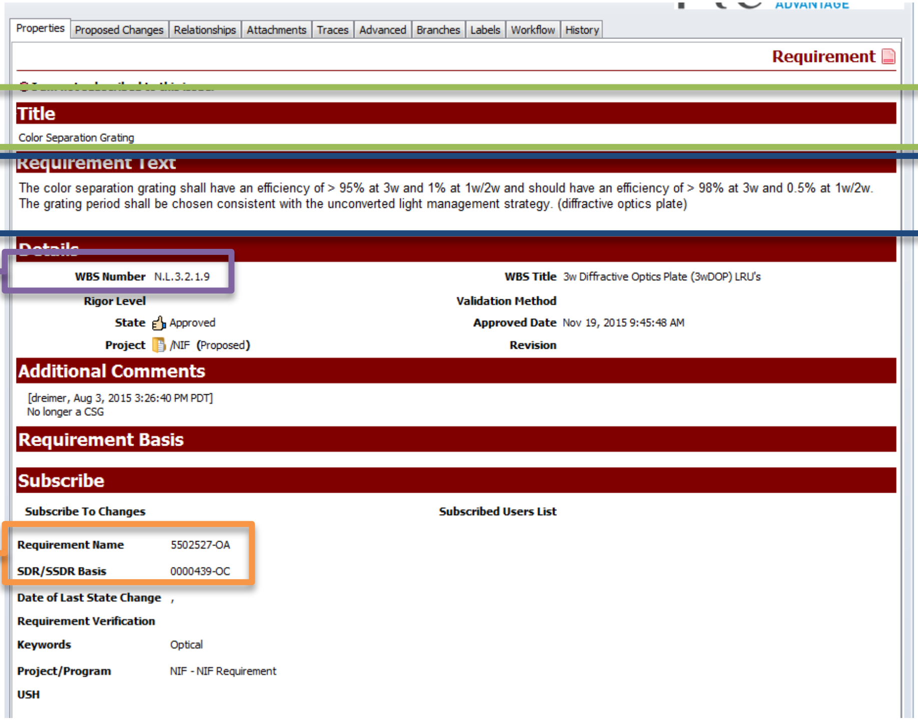
Stakeholder analysis and interface management prevalent; reviews tailored to risk

Single database serves as repository for requirements mgmt.

Title

Product Breakdown Structure (PBS)

Basis & Traceability


Properties | Proposed Changes | Relationships | Attachments | Traces | Advanced | Branches | Labels | Workflow | History

Requirement

Title

Color Separation Grating

Requirement Text

The color separation grating shall have an efficiency of > 95% at 3w and 1% at 1w/2w and should have an efficiency of > 98% at 3w and 0.5% at 1w/2w. The grating period shall be chosen consistent with the unconverted light management strategy. (diffractive optics plate)

Details

WBS Number	N.L.3.2.1.9	WBS Title	3w Diffractive Optics Plate (3wDOP) LRU's
Rigor Level		Validation Method	
State	Approved	Approved Date	Nov 19, 2015 9:45:48 AM
Project	/NIF (Proposed)	Revision	

Additional Comments

[dreimer, Aug 3, 2015 3:26:40 PM PDT]
No longer a CSG

Requirement Basis

Subscribe

Subscribe To Changes | Subscribed Users List

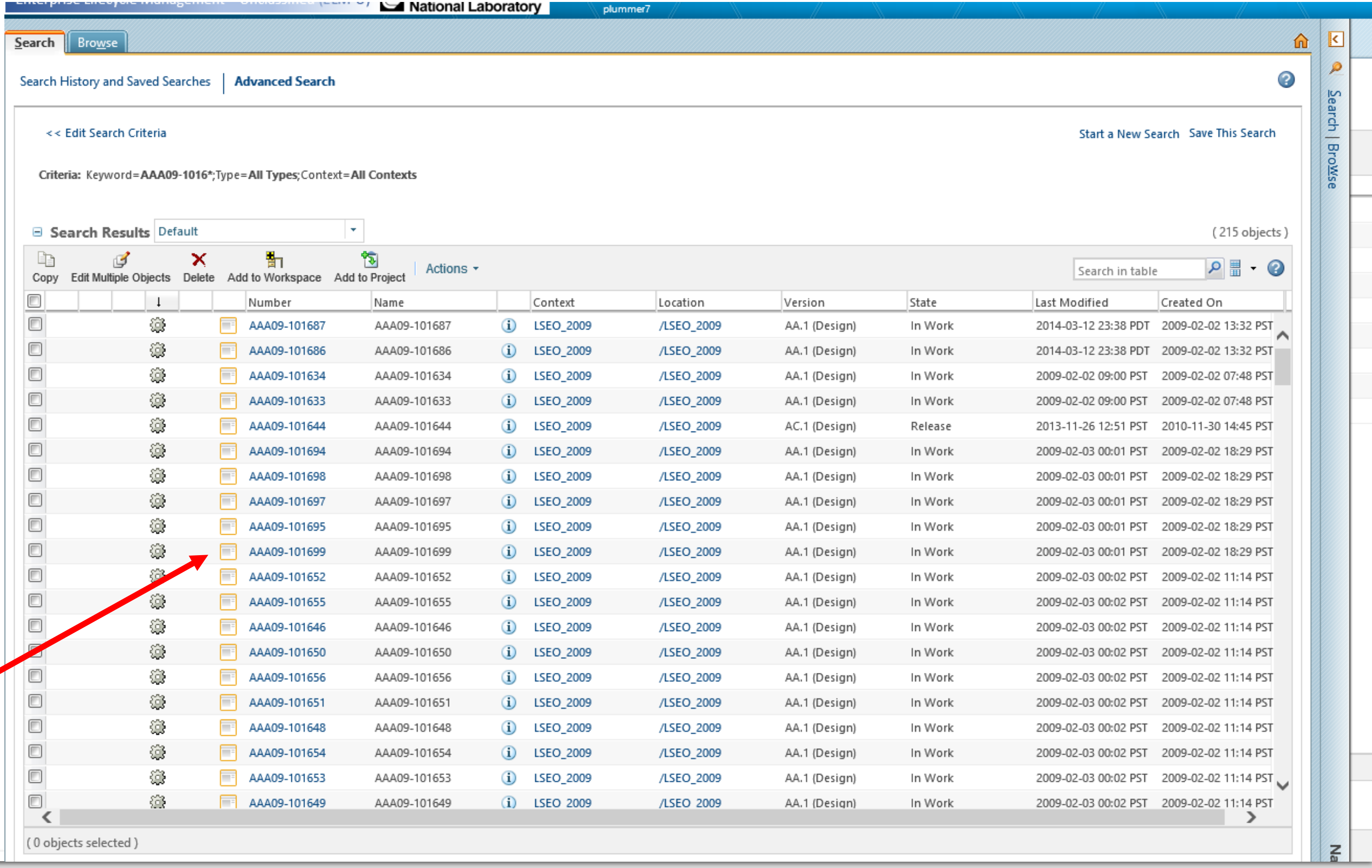
Requirement Name	5502527-OA
SDR/SSDR Basis	0000439-OC
Date of Last State Change	,
Requirement Verification	
Keywords	Optical
Project/Program	NIF - NIF Requirement
USH	

Text

Requirements are an OUTCOME of the SE process, *not* the beginning of the project

Configuration management platform for all system documents

- Revision control
- Workflow approvals
- Check-in/check-out system



Number	Name	Context	Location	Version	State	Last Modified	Created On
AAA09-101687	AAA09-101687	LSEO_2009	/LSEO_2009	AA.1 (Design)	In Work	2014-03-12 23:38 PDT	2009-02-02 13:32 PST
AAA09-101686	AAA09-101686	LSEO_2009	/LSEO_2009	AA.1 (Design)	In Work	2014-03-12 23:38 PDT	2009-02-02 13:32 PST
AAA09-101634	AAA09-101634	LSEO_2009	/LSEO_2009	AA.1 (Design)	In Work	2009-02-02 09:00 PST	2009-02-02 07:48 PST
AAA09-101633	AAA09-101633	LSEO_2009	/LSEO_2009	AA.1 (Design)	In Work	2009-02-02 09:00 PST	2009-02-02 07:48 PST
AAA09-101644	AAA09-101644	LSEO_2009	/LSEO_2009	AC.1 (Design)	Release	2013-11-26 12:51 PST	2010-11-30 14:45 PST
AAA09-101694	AAA09-101694	LSEO_2009	/LSEO_2009	AA.1 (Design)	In Work	2009-02-03 00:01 PST	2009-02-02 18:29 PST
AAA09-101698	AAA09-101698	LSEO_2009	/LSEO_2009	AA.1 (Design)	In Work	2009-02-03 00:01 PST	2009-02-02 18:29 PST
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AAA09-101699	AAA09-101699	LSEO_2009	/LSEO_2009	AA.1 (Design)	In Work	2009-02-03 00:01 PST	2009-02-02 18:29 PST
AAA09-101652	AAA09-101652	LSEO_2009	/LSEO_2009	AA.1 (Design)	In Work	2009-02-03 00:02 PST	2009-02-02 11:14 PST
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AAA09-101649	AAA09-101649	LSEO_2009	/LSEO_2009	AA.1 (Design)	In Work	2009-02-03 00:02 PST	2009-02-02 11:14 PST

Drawings, procedures, memos, test plans and reports, risk assessments, design reviews, etc.

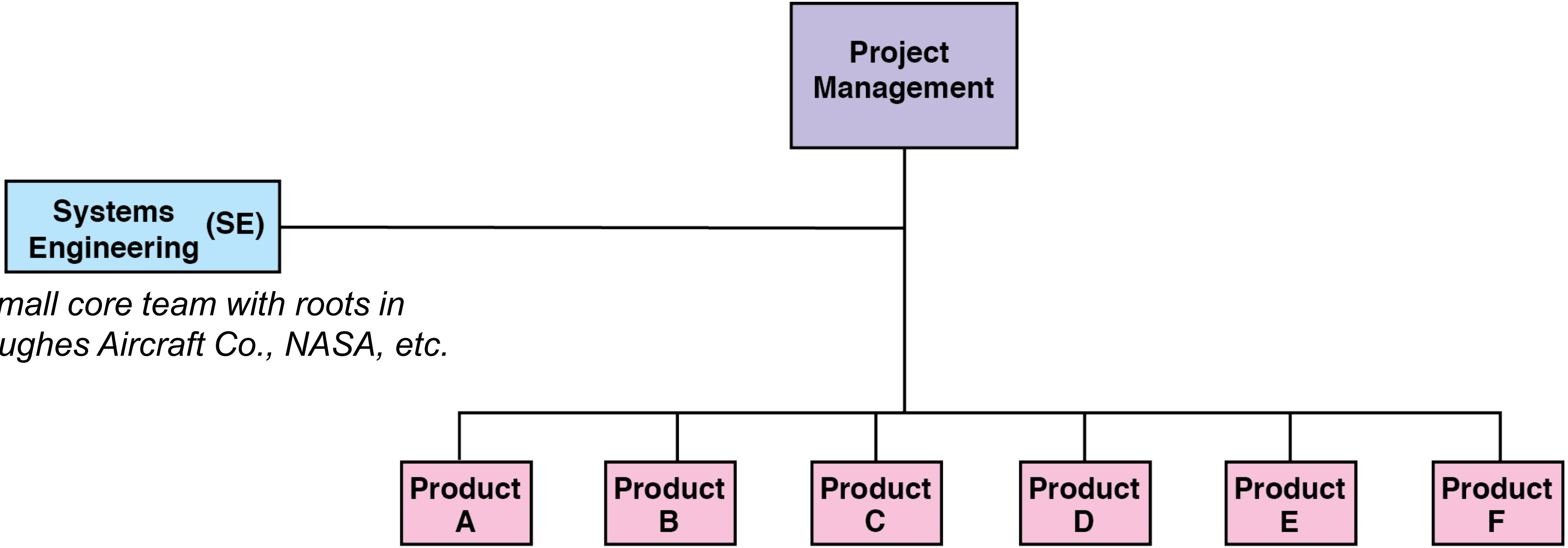
Once design lifecycle completed, authorization to field on NIF granted through Work Authorization Process (WAP) or Point

Work Authorization Point Checklist		**WAP Activity:**			
		AI:	AI		
Phase 1: Ready for Installation	Need by	**RSE {RI/SM}:**	RSE		
Phase 2: Ready for IQ	Need by	**RS:**			
Phase 3: Ready for OQ	Need by				
Phase 4: Ready for Ride-a-long Shots (RI required during operations, withTAO support provided)	Need by				
Phase 5: Ready for turnover to operations	Need by				
Last Updated:					

Standard Checklist Documentation	Deliverables	Provider	Phase Req'd	Reviewer	Approval
Management Oversight					
Work Authorization Scope	Scope Summary / Checklist	RSE	1	AI	
Work Authorization Scope Review	Scope Summary / Checklist	S&PRB Coordinator	1	S&PRB Reader	
Authorized Safety Basis	SBCC Checklist	RSE	1	Safety Analyst (Watson)	
Facility Schedule	Integrated Work Schedule Planned (SubFLIP & TAO Daily Plan)	RSE	1	Facility Coordinator (Cox)	
Draft Work Permit	Scope of work and procedures	RSE	1	AI	

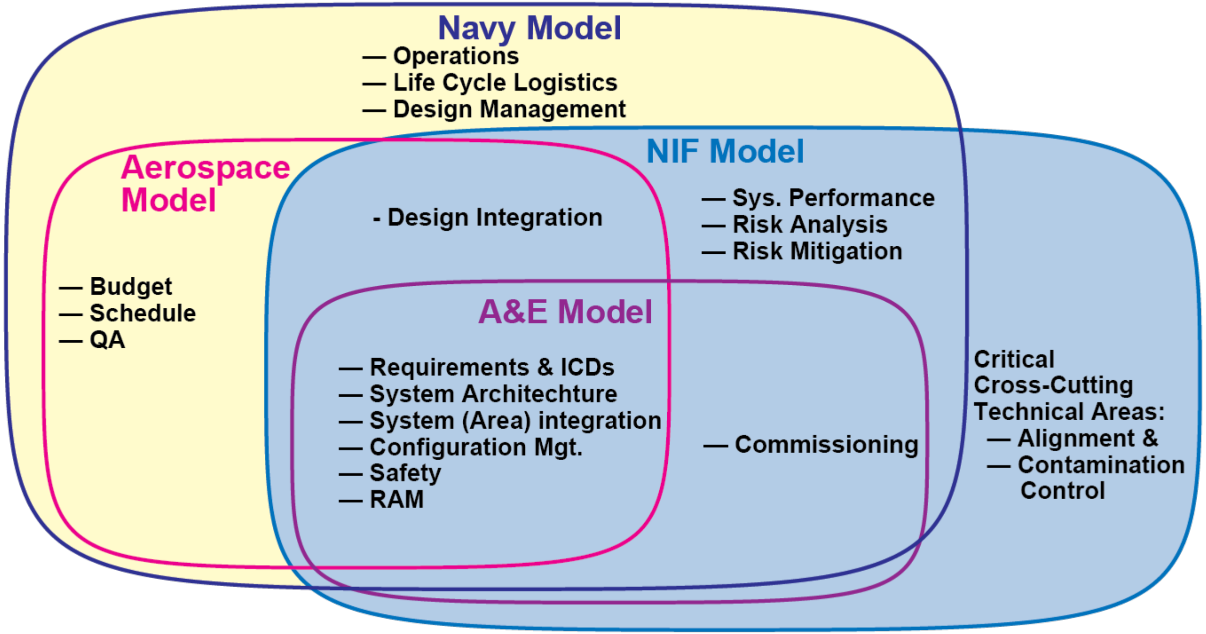
Used widely for shot campaigns, construction projects, diagnostic instruments, etc.

Following reorg in 2000, SE was introduced as critical oversight and support function for overall NIF program



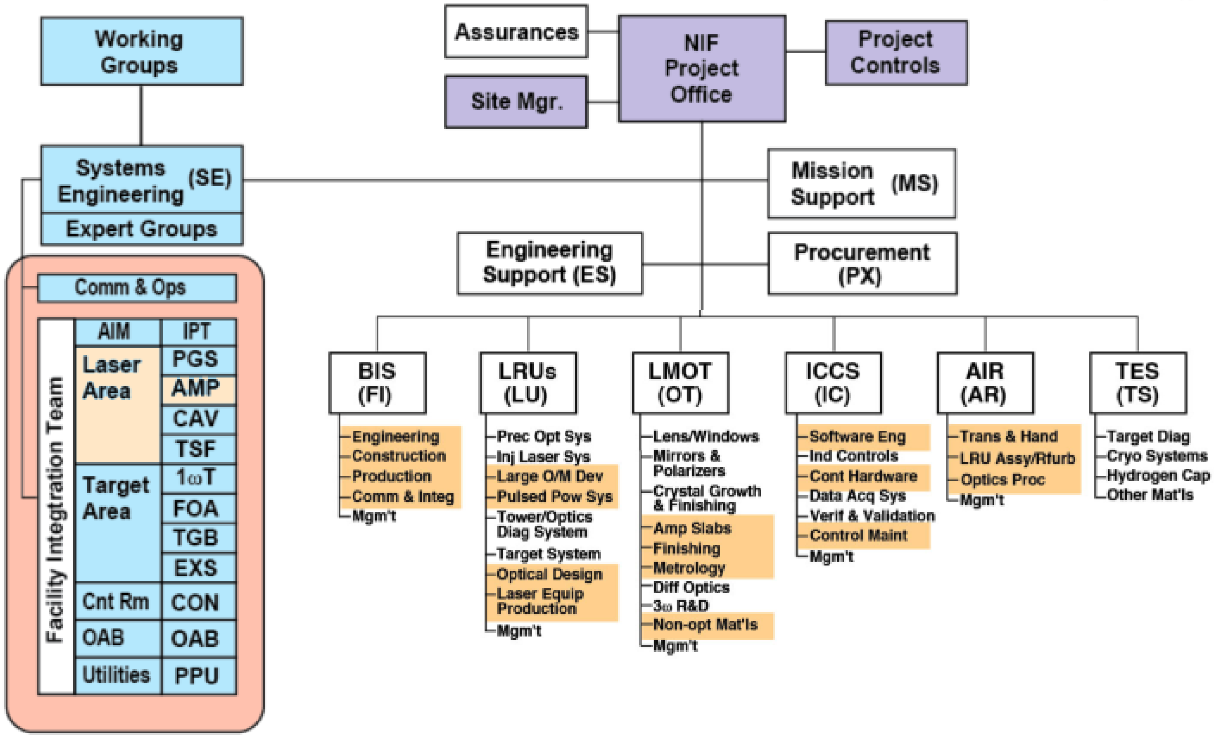
Small core team with roots in Hughes Aircraft Co., NASA, etc.

Conscious decisions were made w.r.t. responsibilities based on numerous models; PM intentionally separated from SE



Much like today, early SE at NIF was part discipline, part creativity

SE provided expert groups and IPT functions to solve cross-cutting challenges within infrastructure, optics, materials, controls, laser, and targets



<u>SE IPTs maintained</u>

- Requirements flow-down and interfaces
- Technically responsibility

Some key elements of NIF's historical SE culture

Part discipline, part creativity

Discipline

- Requirements management and change control
  - Verification & validation testing
  - Discipline for documentation
- *Daily* integration and planning coupled with Work Authorization Process
- Reward people for broaching project risk and failure modes
  - Maintained 300-item risk register with mitigation strategies
  - ~$200M scope associated with risk mitigations

Creativity

- Dynamic, organizational flexibility to manage extraordinary risk (e.g., IPTs, expert groups)
- Innovate solution and paradigm shift for grand challenges (e.g., optics refurbishment loop, optomechanics)

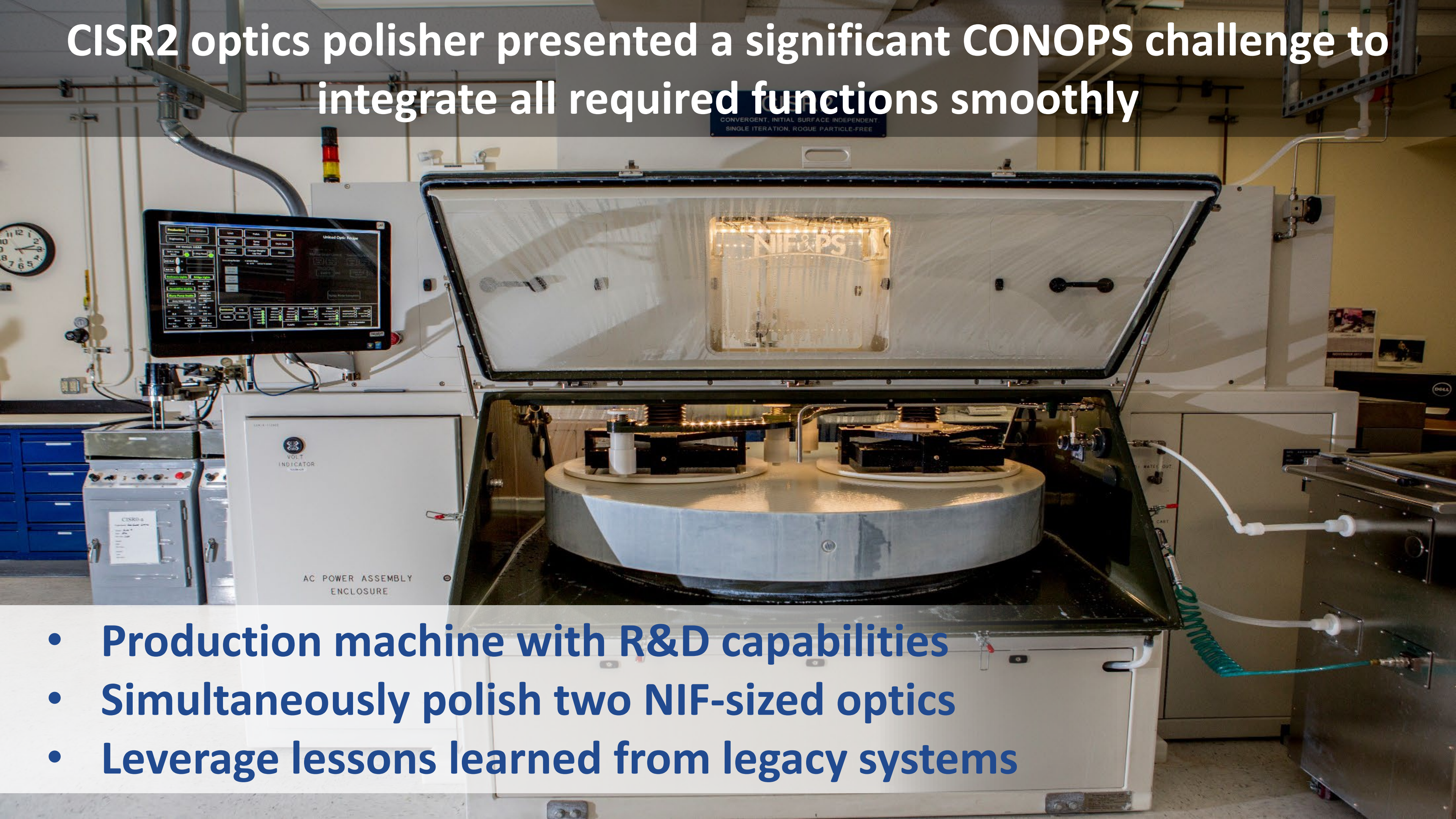
Real systems engineering at NIF

NIF optics recycling loop employs System of 50+ Systems (SoS) to characterize, mitigate, and repair damage on optics

In-situ inspection

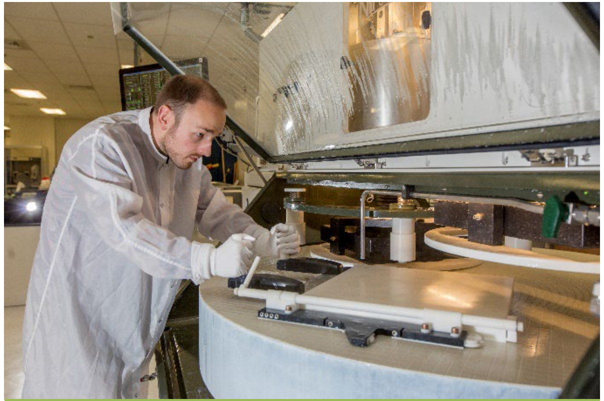
Significant challenge to integrate SoS interfaces across multiple design teams and years

CISR2 optics polisher presented a significant CONOPS challenge to integrate all required functions smoothly

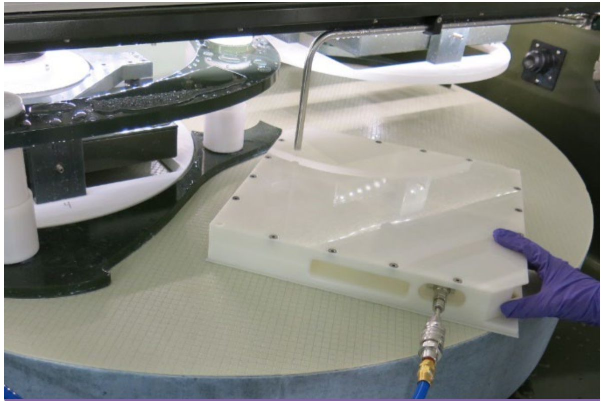


- **Production machine with R&D capabilities**
- **Simultaneously polish two NIF-sized optics**
- **Leverage lessons learned from legacy systems**

A mature CONOPS drove several innovative design solutions



"Pizza peel" to safely remove optics under suspended load

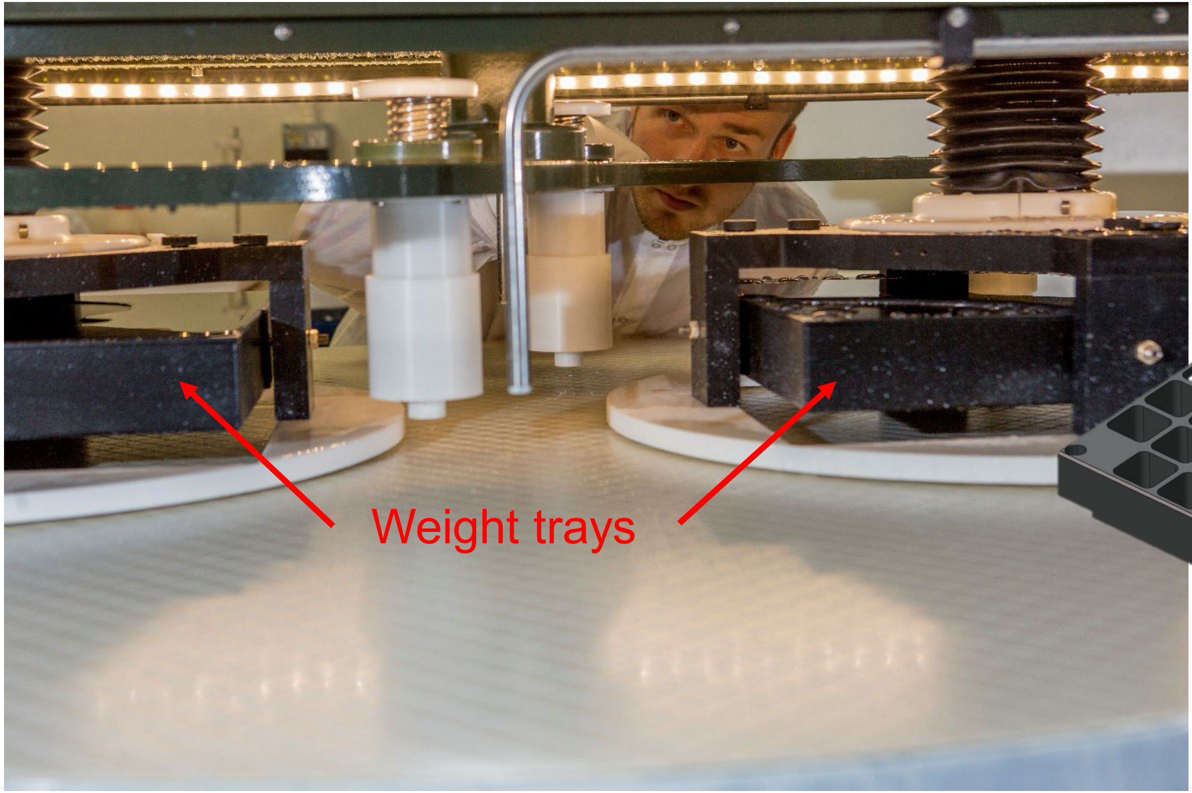


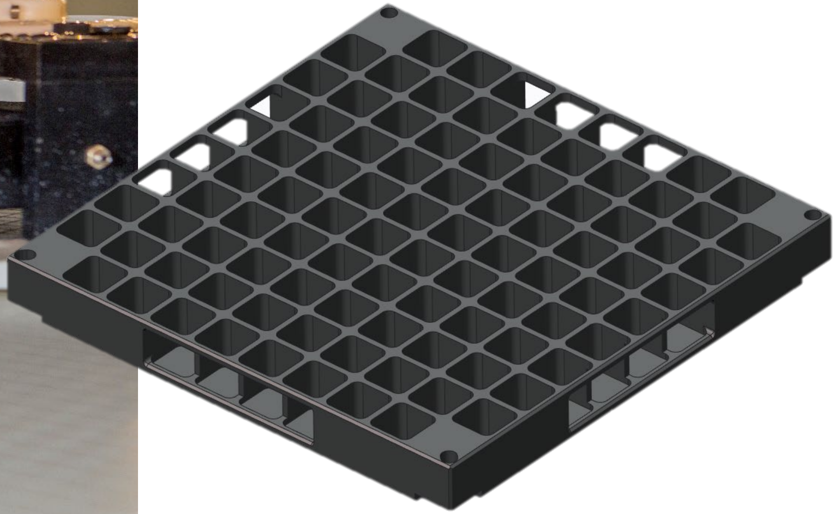
Air-bearing loader to change polishing pressure weights

Modular add-on assemblies for ultrasonication and pad conditioning

CONOPS was developed after 6 dedicated user interviews focusing on legacy system use cases

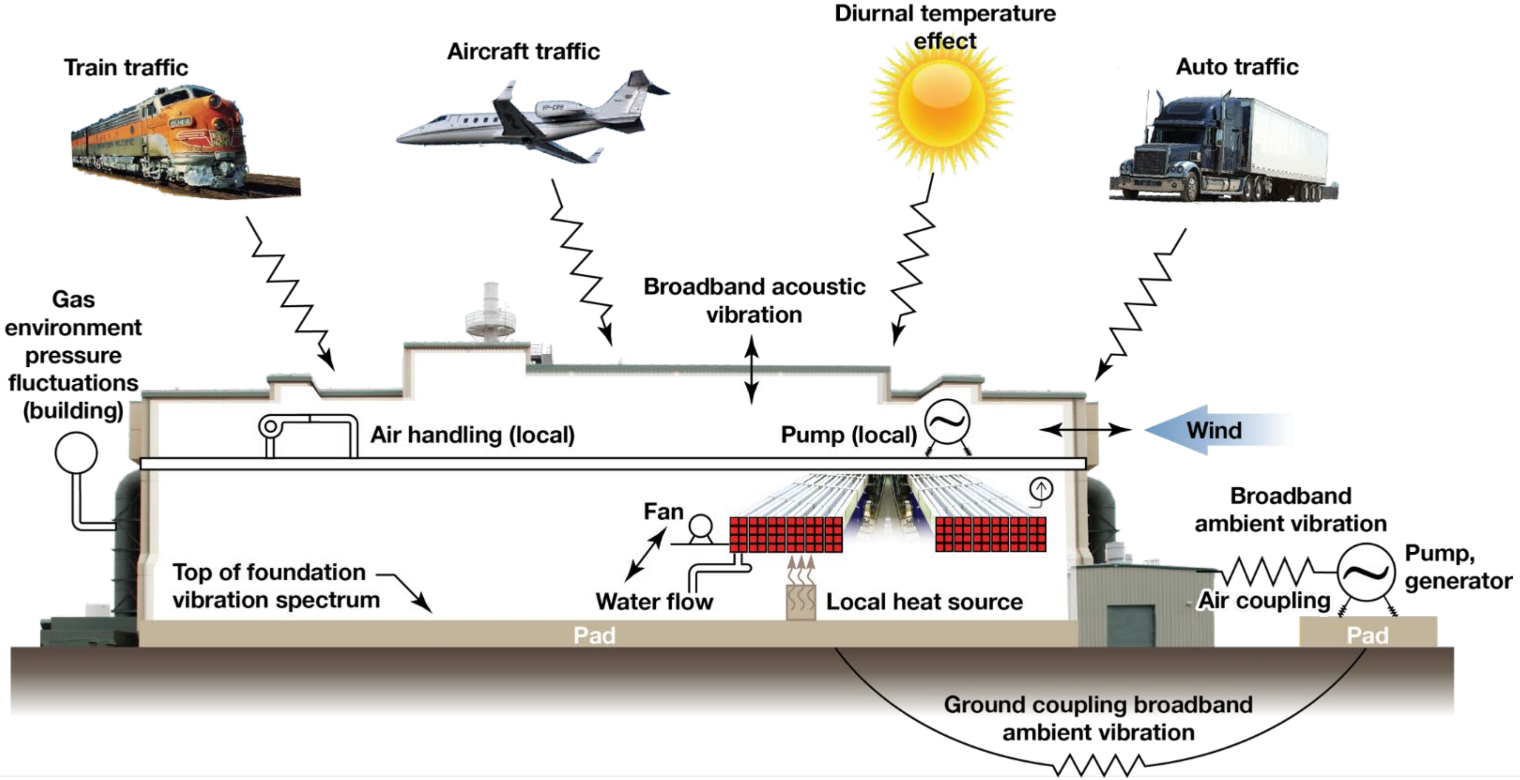
Critical decision made early to raise enclosure 3” to account for unknown design of optic backing plate



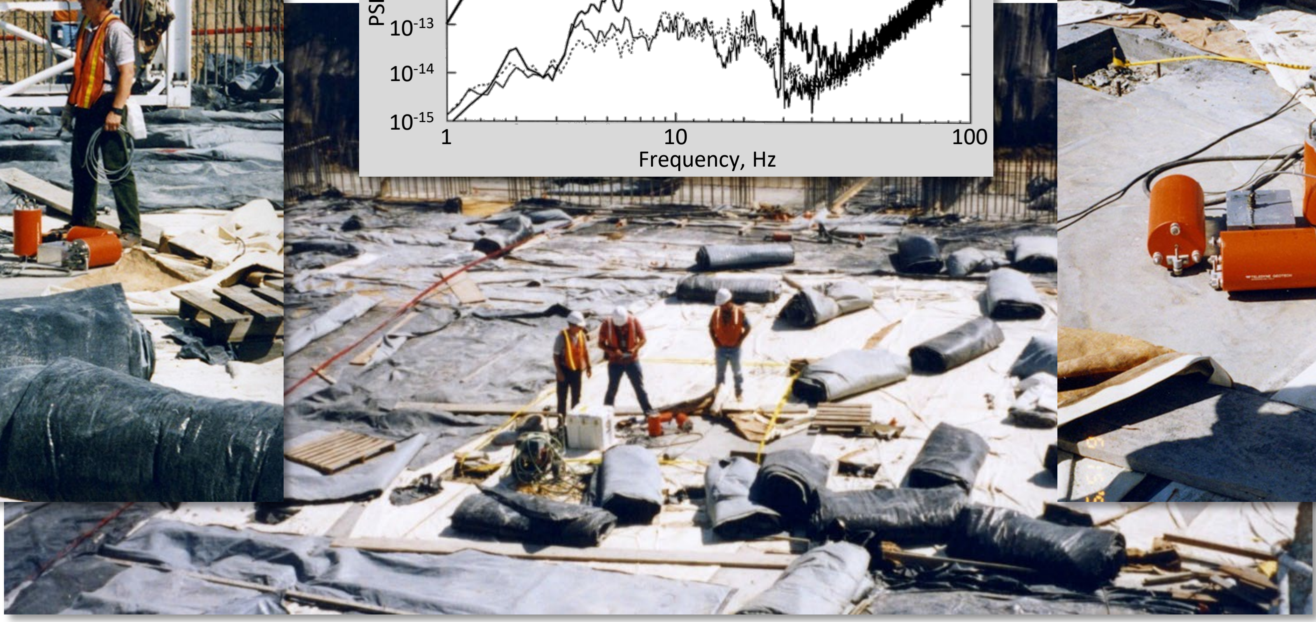


Optic backing plate

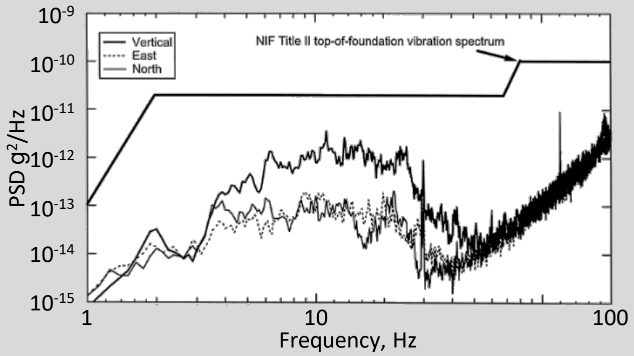
Prior to NIF construction, systems level assessment was performed of the many sources that affect NIF optical motion

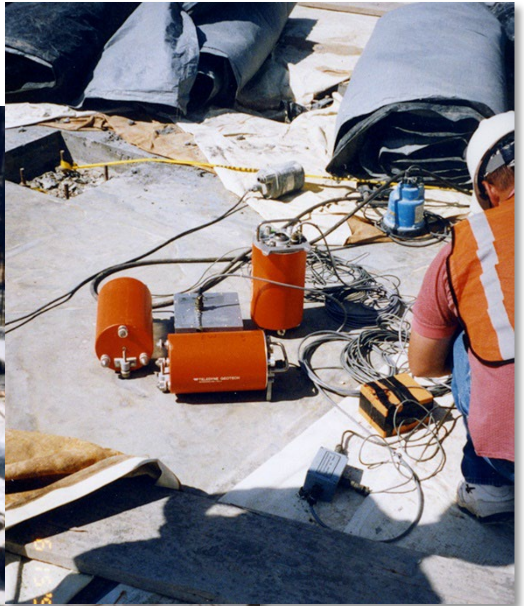


Ambient vibration measurements were performed



Laser Bay Foundation

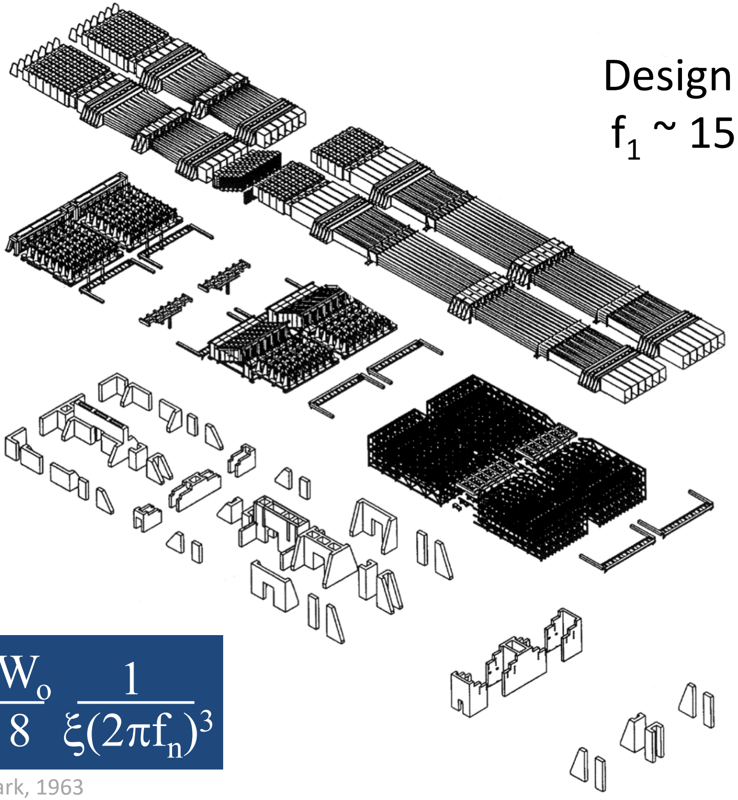




Hybrid reinforced concrete and steel optical support structures were designed to enhance vibrational stability

Steel support frames

Reinforced concrete pedestals



Design for $f_1 \sim 15$ hz

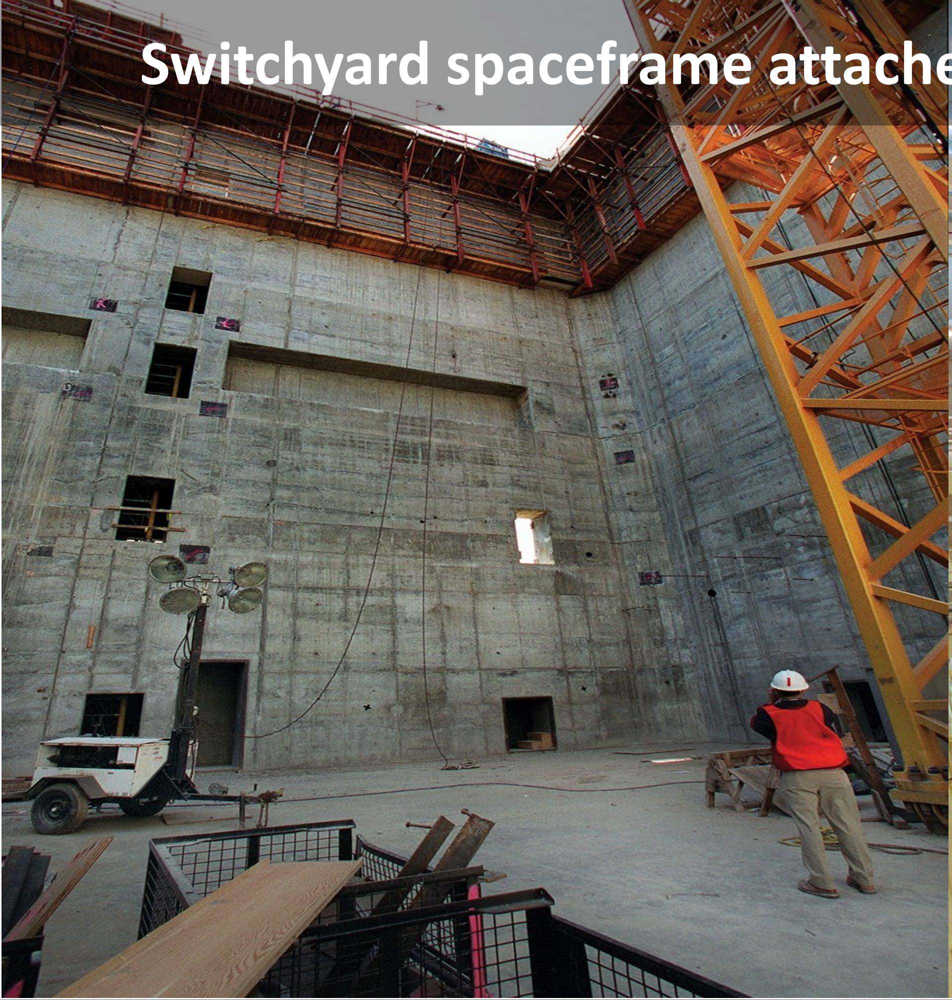
Mechanical design flexibility

Stable optic bench

$$E[y^2] = \frac{W_o}{8} \frac{1}{\xi(2\pi f_n)^3}$$

Crandall and Mark, 1963

Switchyard spaceframe attaches to the corners of the building



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