National Aeronautics and Space Administration

Transformational Tools and Technologies (T^3) Project

Capturing, Analyzing, Maintaining, and Disseminating Experimental Data in a Robust Material Information Management System

Brandon Hearley, Steve Arnold
NASA Glenn Research Center

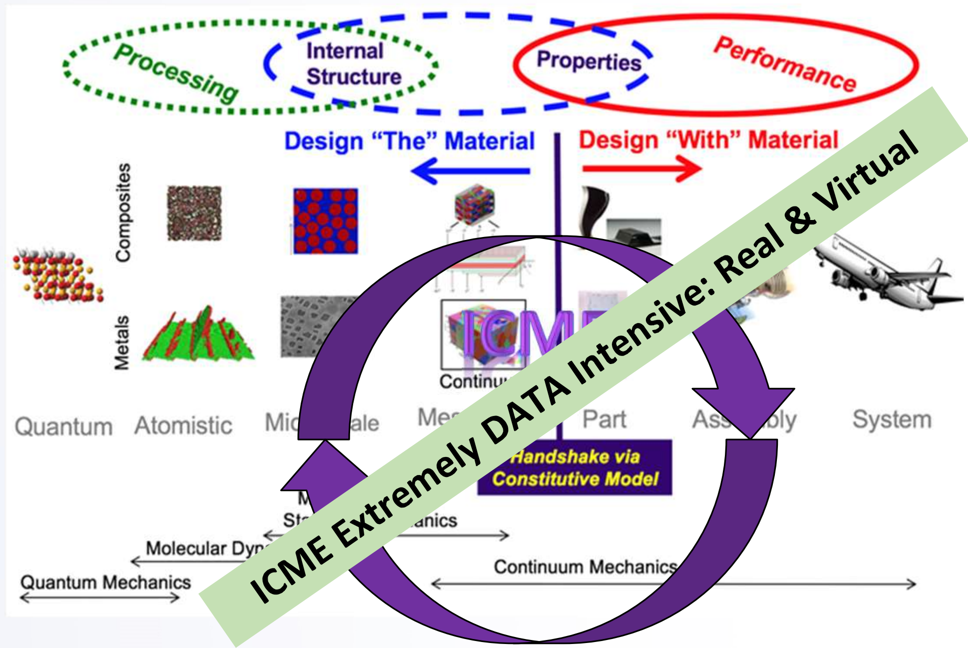
Innovative solutions through foundational research and cross-cutting tools

3rd International Conference on Mechanics of Advanced Materials and Structures, Aug 8-10

www.nasa.gov

Integrated Computational Materials Engineering (ICME) Enables Innovation

- Top performing organizations rate **New Materials** as one of **THE MOST IMPORTANT** factors in meeting their <u>innovation goals</u> (Historically new materials ≥ 20 years)
- Integrated Computation Materials Engineering (ICME) looks to bridge the gap between the "Design-the-Material" (Material Science) and "Design-with-the-Material" (Structural) viewpoints
  - Enables design of 'fit-for-purpose' materials
- Requirements for ICME
  - Experimentally validated materials models at multiple length scales
  - Understanding processing-structure-properties-performance relationships
  - Integrated framework that can automatically pass information across scales during design optimization
  - Manufacturing capability to achieve desired microstructure at any location in an application



Vision 2040 has identified
Data, Informatics, & Visualization
as a Key Element Discipline Area

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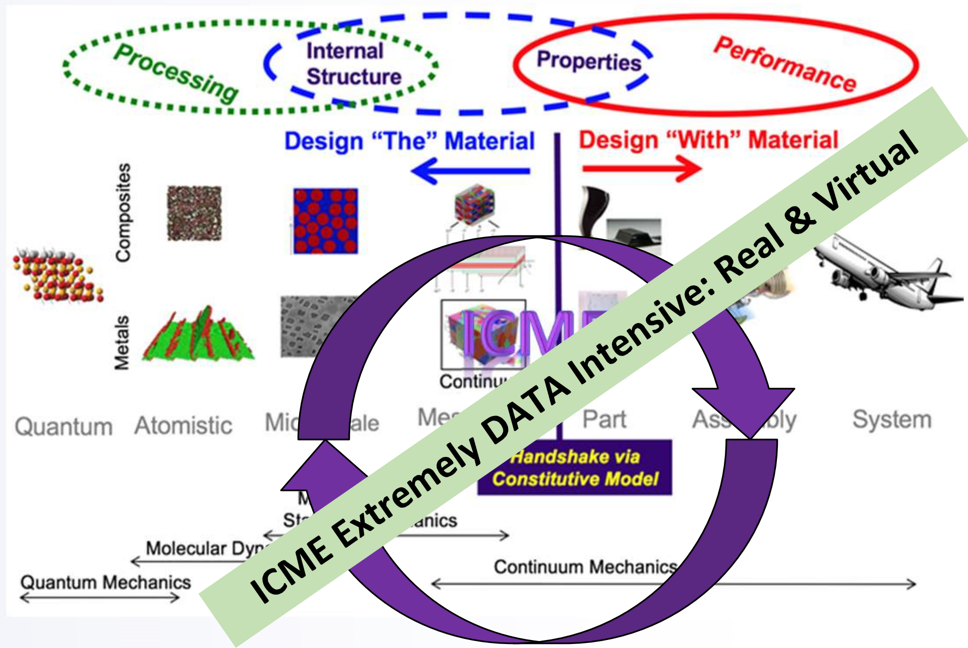

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Why Does Material Information Management Matter?

50% of Engineers spend *at least* ONE HOUR per week looking for material data

Cost $3K/

33% of organizations DUPLICATE *at le*

Represent Millions $ in unnecessary costs

VERY COSTLY PROBLEM

% of Test data is used once then lost
(not captured for re-use)

Cost Millions $/year

David Meza: Head of Knowledge Management at NASA, JSC
Status Quo of Collaboration

- "Most engineers have to look at 13 different sources to find the information they are looking for"
- "46% of workers can't find the information about half the time"
- "30% of total R&D funds are spent to redo what we've already done once before"
- "54% of our decisions are made with inconsistent or incomplete, or inadequate information"

https://www.youtube.com/watch?v=QEBVoultYJg

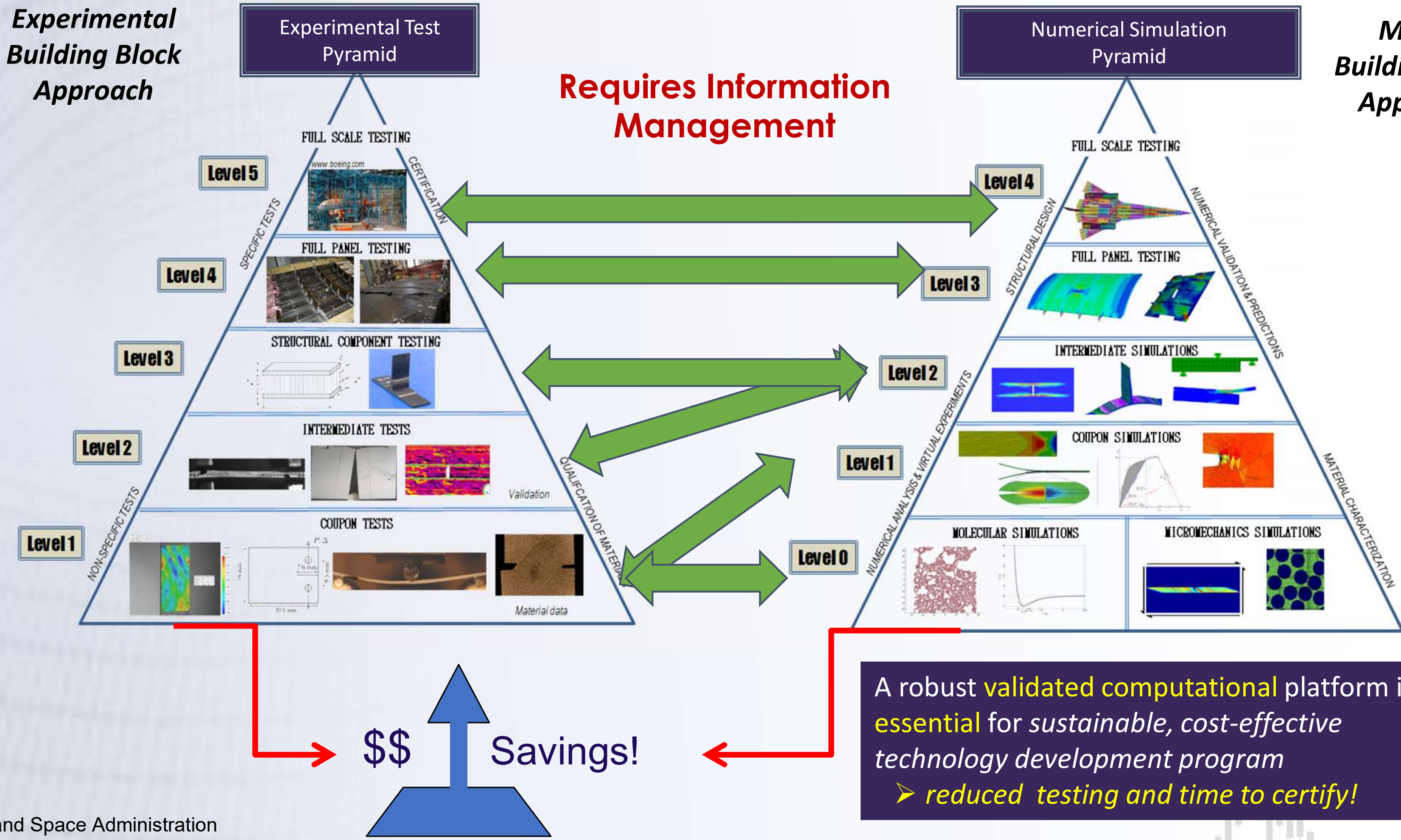
Axel Reichwein, June 5, 2018

Data from July 2012 survey of 350 Granta customers/contacts; 35% N America, 45% Europe, 20% elsewhere; 25% current customers, 75% not customers

Virtual Testing Can Enable Significant Cost Savings in Certification Process

Experimental Building Block Approach

Model Building Block Approach



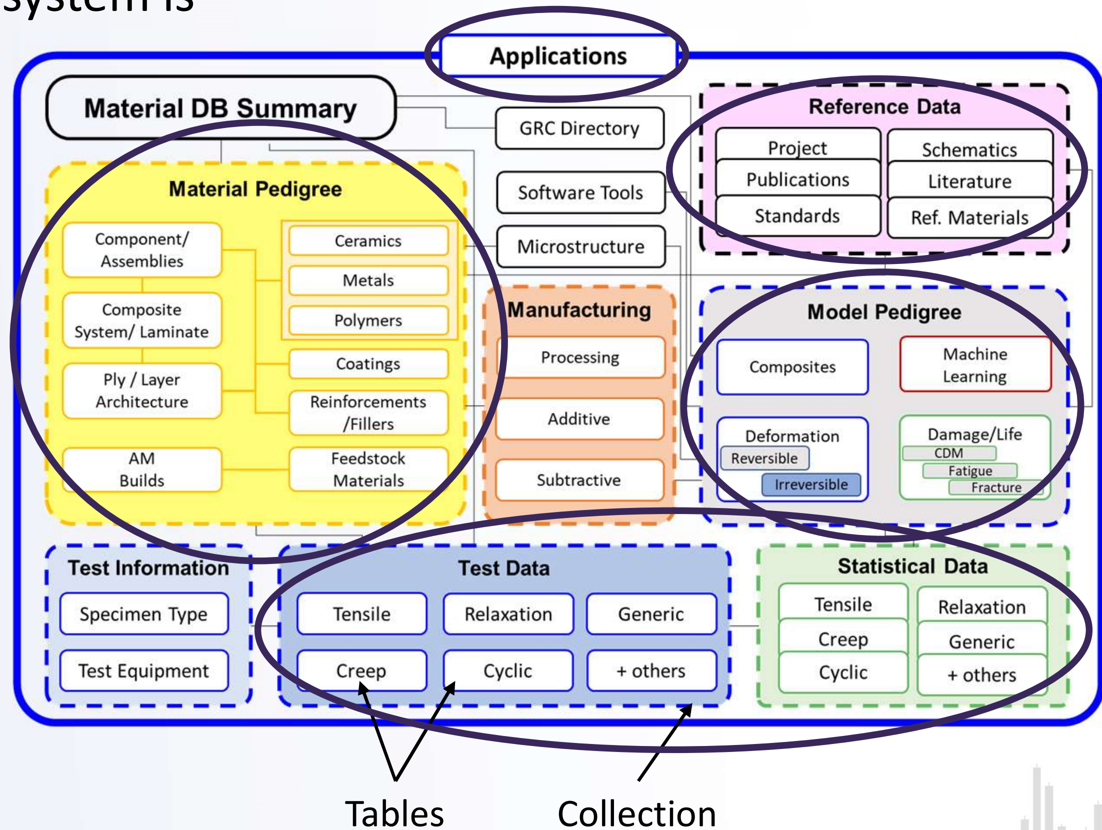
A robust validated computational platform is essential for *sustainable, cost-effective technology development program*

- *reduced testing and time to certify!*

NASA GRC ICME Schema

A robust material information management system is **essential** for fit-for-purpose material design

- Developed the NASA GRC ICME Schema within the Granta MI Material Information Management Platform
- Contains *collections* of *tables*, where each table has its own schema (i.e., attributes, layout, linking behavior, security controls, etc.)
  - Material Pedigree: Store material source information, properties, etc.
  - Test Data/Statistical Data: Store in-house experimental data and summarize into material properties
  - Model Pedigree: Store material models developed from experimental and virtual data (machine learning)
  - Reference Data: Store references, literature data, virtual data, etc.
  - Application Table: Link material models to parts for digital thread maintenance



Benefits of Effective Data Management

Benefits

- Maintain institutional knowledge
  - Prevent recapturing/recreating data
  - Maintain pedigree/metadata on all data previously capture

ID	Alloy	XX	YY	ZZ	Base
144	HOS-875	1	1	1	Iron-base
356	Kanthal A-1	1	1	2	Iron-base
357	GE-1541	1	1	3	Iron-base
358	GE-2541	1	1	4	Iron-base
488	FeCrAlY MA-956	1	1	5	Iron-base
410	Allegheny Lud. A-1	1	1	6	Iron-base
728	Fontana - O.S.U.	1	1	7	Iron-base
773	Fecralloy A	1	1	8	Iron-base
783	NOZZL-(10 Ni)	1	1	9	Iron-base
586	NOZZI-Zr(10 Ni)	1	1	10	Iron-base
550	Fe-15Cr-5Al-10Ni (Scratch)	1	1	11	Iron-base
551	Fe-15Cr-5Al-20Ni (Scratch)	1	1	12	Iron-base
552	Fe-15Cr-5Al-30Ni (Scratch)	1	1	13	Iron-base

Base ??? Alloy ID

Oxidation Test Matrix from 1980's lack of documentation → Loss of organizational data

Benefits of Effective Data Management

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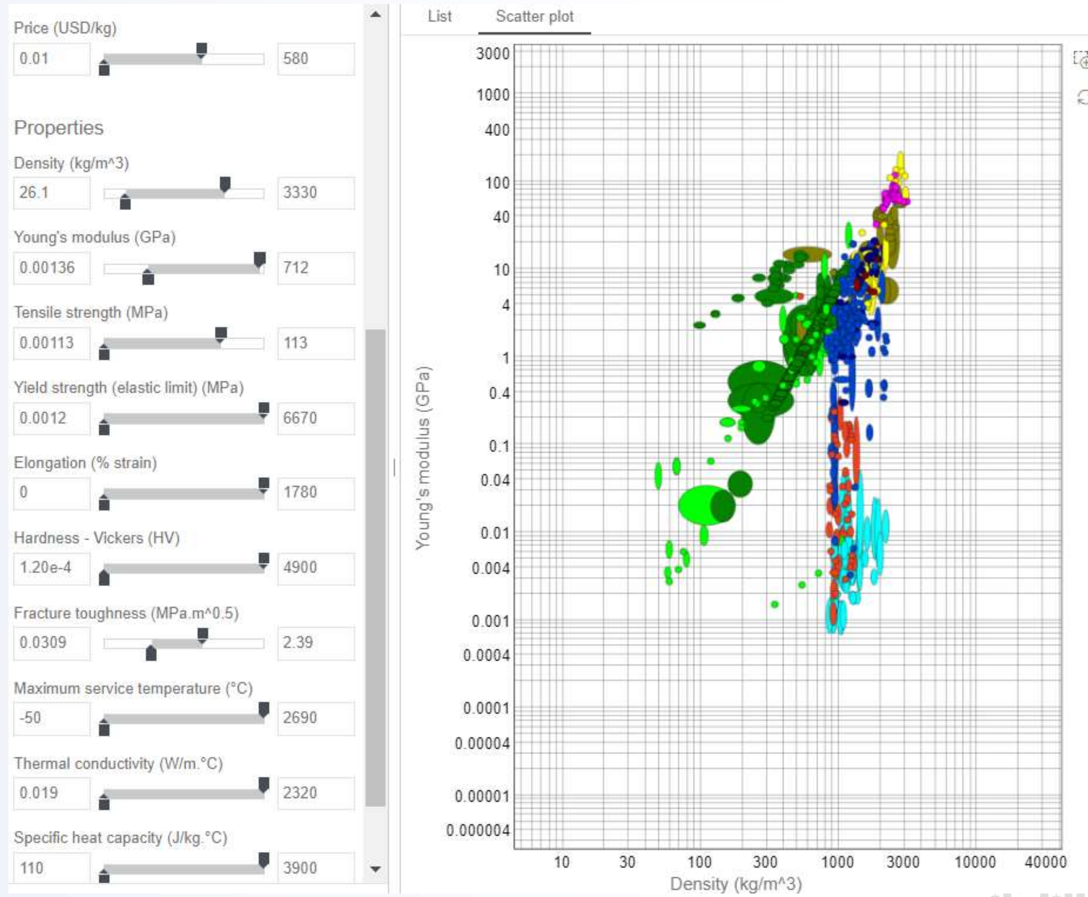
- Reduce time for:
  - Finding what materials have been characterized
  - Finding what tests have been performed
  - Material selection for a specific application



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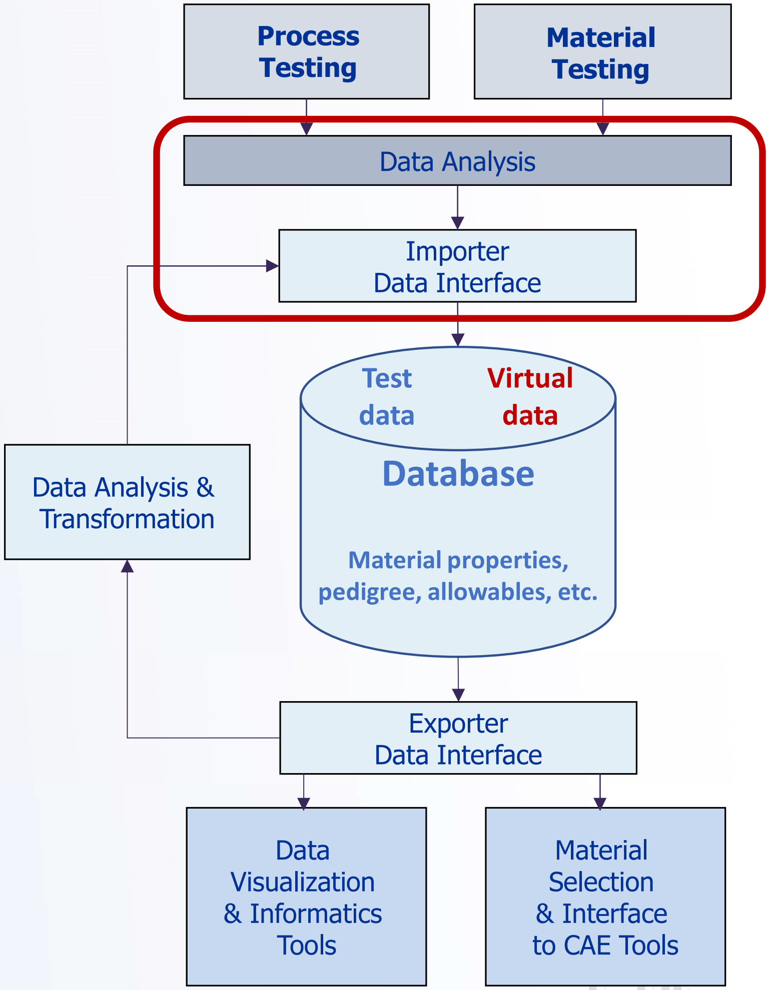
  - Assign ITAR, Gov. only, etc. restrictions on an attribute-by-attribute basis



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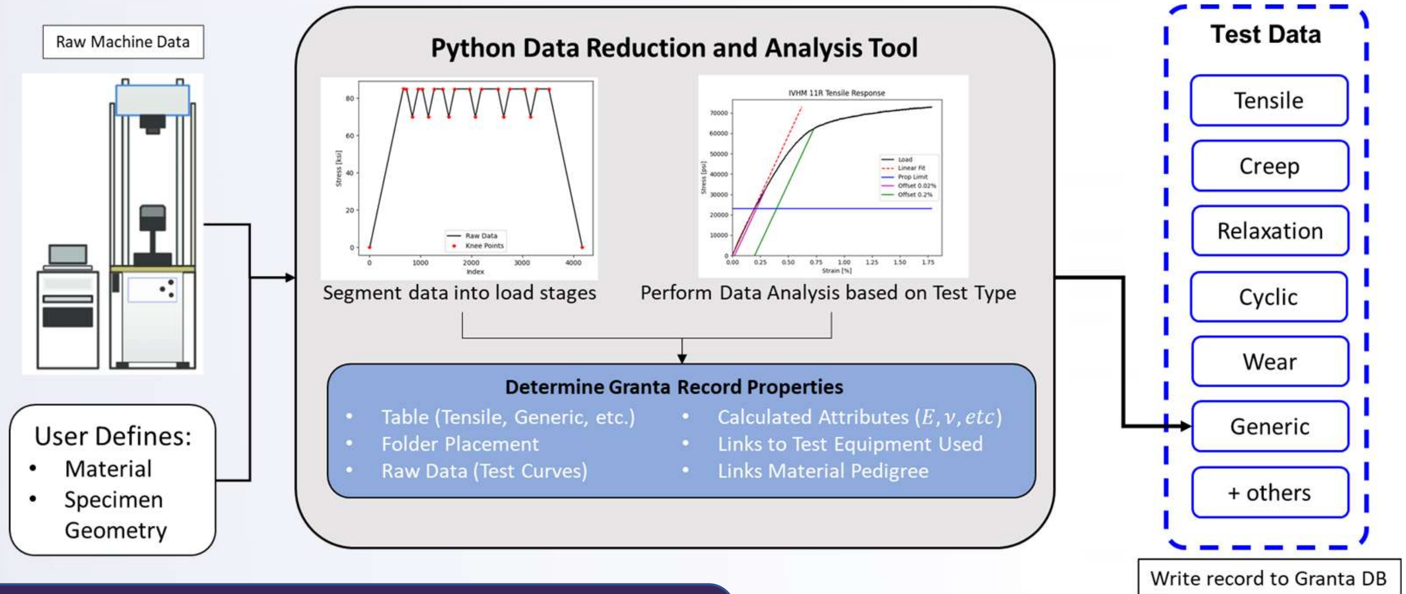
  - Material selection for a specific application
- Security
  - Assign ITAR, Gov. only, etc. restrictions on an attribute-by-attribute basis
- Consistent/Up-to-Date data
  - Automatic linking and ability to connect user subroutines allows for automation to provide consistent properties across the organization

Efficient Data Analysis and Importing is Critical to Effective Data Management

- **Goal:** Develop and automatic framework to capture analyze, and store **bulk** experimental test data in the NASA GRC ICME Schema
- Benefits
  1. Reduce User Effort for Data Management
  2. Provide traceability between test machine calibration and test performance
  3. Consistency in data analysis and reduction



Automatic Placement + Data Analysis → Higher likelihood of organizational adoption

Experimental Data Automatic Import Tool:
Selecting Data

- To begin the bulk analysis and import process, the user is asked to supply:
  1. An Excel File containing data information that applies to all tests performed (1st Sheet) and individual test data not stored in the raw output from the machine (2nd Sheet)
  2. A folder containing the raw machine data from each test
     - Because the output format of different test machines (i.e., Instron, MTS, etc.) is different, all raw data is passed through a *machine specific* subroutine to convert it to a standard format for analysis and importing

1st Sheet

Test Series Information

Project Name	IVHM
Project Code	
Testing Organisation	NASA GRC
Funding Organization	Aeronautics
Data Ownership	Government
Data Ownership (Other)	
Distribution Category	Publicly Available
Testing Standards	NASA FAST Lab Standards
Institutional Standards	
Contact Information	
Testing Contract	
Report Number	
Testing Source Notes	Tested in bldg. 49, room 100
Operator	Brad Lerch
Alloy	Ti-6Al-4V

Measurment Information

Temperature Measurement Method	Thermocouple
Mode of Heating	Direct Induction
Mode of Heating Test Equipment	Direct Induction Heater
Test Environment	Air
Load Measurement Method	Load Cell
Load Measurement Test Equipment	TMD #1
Strain Measurement Method	Extensometer
Strain Measurement Test Equipment	Axial Exten: 632-53&54
Strain Measurement (Other)	Optical micrometer (transverse)

Specimen Information

Specimen Orientation	L
Orientation (Θ) (°)	0
Specimen Location	all from one plate location
Gauge Cross-Section Geometry	Circular
Machining Method	Turned
Surface Finish	Polished
Surface Finish (Other)	final polishing parallel to spec. axis
Batch Number	8-46-707-2
Product Thickness (mil)	625

2nd Sheet

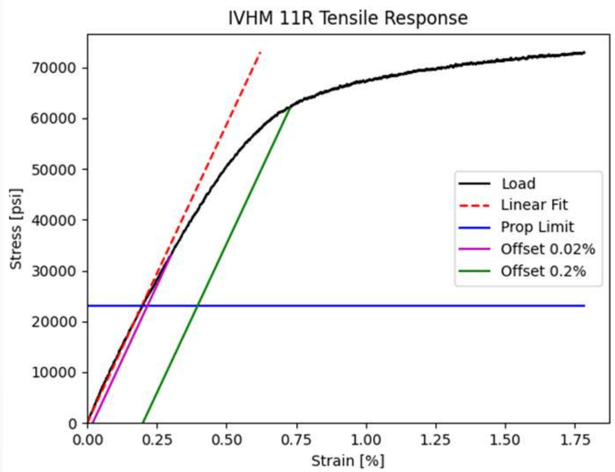
Sample Information			Test Information		Sample Specifications					Other
Specimen ID	Original Data Filename	Date	Test Type	Test Temperature (°F)	Gauge Area (in^2)	Gauge Length (mil)	Gauge Outer Diameter (mil)	Tested To Failure?	Valid Test?	Additional Information
IVHM427-35	IVHM427-35.xls		Generic	800	0.0497	750	252	No	Yes	No transverse strain
IVHM316-17	IVHM316-17.xls		Creep	600	0.0498	750	250	No	Yes	
IVHM538-23	IVHM538-23.xls		Tensile	1000	0.0501	750	249	No	Yes	

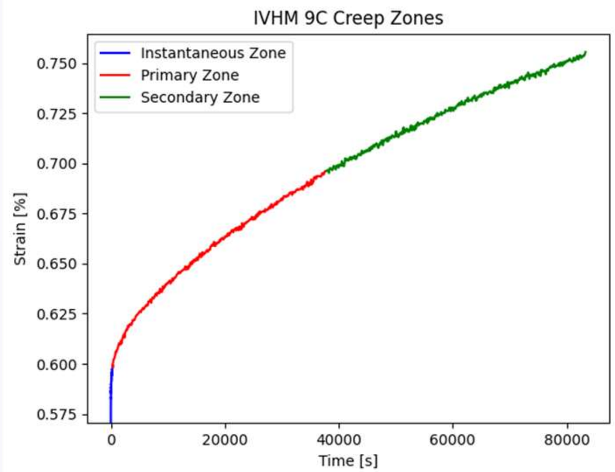
Experimental Data Automatic Import Tool:
Data Analysis for Standard Tests

- Test data is categorized as either Standard or Generic
  - Standard – Tensile, Relaxation, Creep
  - Generic – Combination of various standard test stages
- For each Standard Test, data analysis of raw data performed
  - Tensile – Modulus, Yield
  - Creep – Creep Zones, Creep Stress
  - Relaxation – Relaxation Stress, Loading/Unloading behavior
- Specific subroutines written for each test to perform the data analysis/parameter extraction
  - Store how parameters were calculated and write to each record to maintain material/test pedigree

Modulus Calculation Range

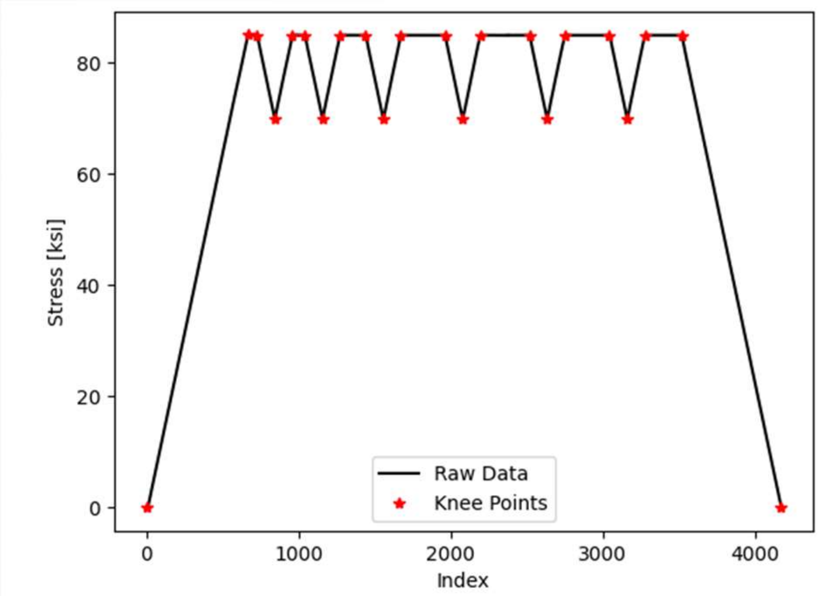
- Loading Modulus calculated using datapoints from 5% to 25% of maximum stress, calculated using Linear Fit method (R2 = 1.00)





Experimental Data Automatic Import Tool:
Defining Generic Tests

- Generic Tests contain various stages of one of the standard test types
  - Stages endpoints are automatically recognized by implementing a knee-point algorithm
  - Control Modes are determined from analyzing the stress-time and strain-time behavior of each stage
  - Stage Type is determined using the table below

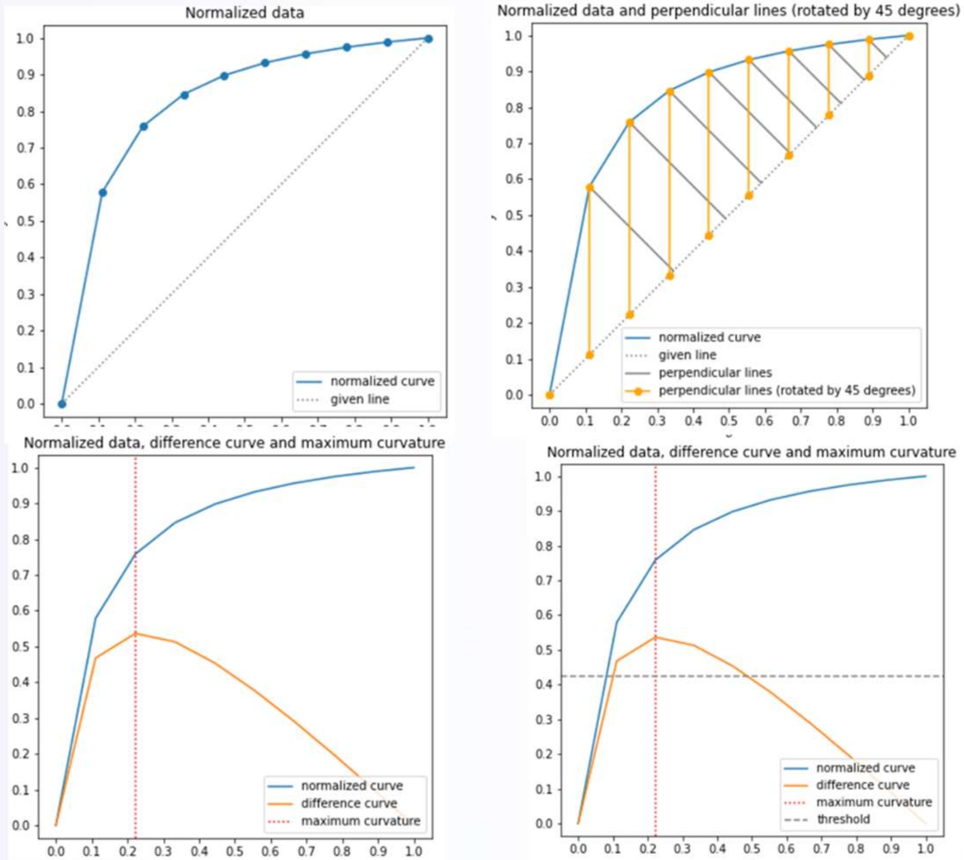


Control Mode	Rule	Stage Type
Stress	$\lvert\dot{\sigma}\rvert < 10^{-3}\ ksi/s$	Creep
Strain	$\dot{\varepsilon} < 10^{-8}\ \%/s$	Relaxation
Stress or Strain	$\dot{\sigma} > 0$ and $\sigma_{end} > 0$ or $\dot{\varepsilon} > 0$ and $\varepsilon_{end} > 0$	Tensile Loading
Stress or Strain	$\dot{\sigma} < 0$ and $\sigma_{end} > 0$ or $\dot{\varepsilon} < 0$ and $\varepsilon_{end} > 0$	Tensile Unloading
Stress or Strain	$\dot{\sigma} < 0$ and $\sigma_{end} < 0$ or $\dot{\varepsilon} < 0$ and $\varepsilon_{end} < 0$	Compressive Loading
Stress or Strain	$\dot{\sigma} > 0$ and $\sigma_{end} < 0$ or $\dot{\varepsilon} > 0$ and $\varepsilon_{end} < 0$	Compressive Unloading

Experimental Data Automatic Import Tool:
Knee Point Algorithm

- Knee point algorithm finds the turn point in series data
  - Use the Kneed python package/Kneedle algorithm developed by Satopa et. Al
- Kneedle Algorithm

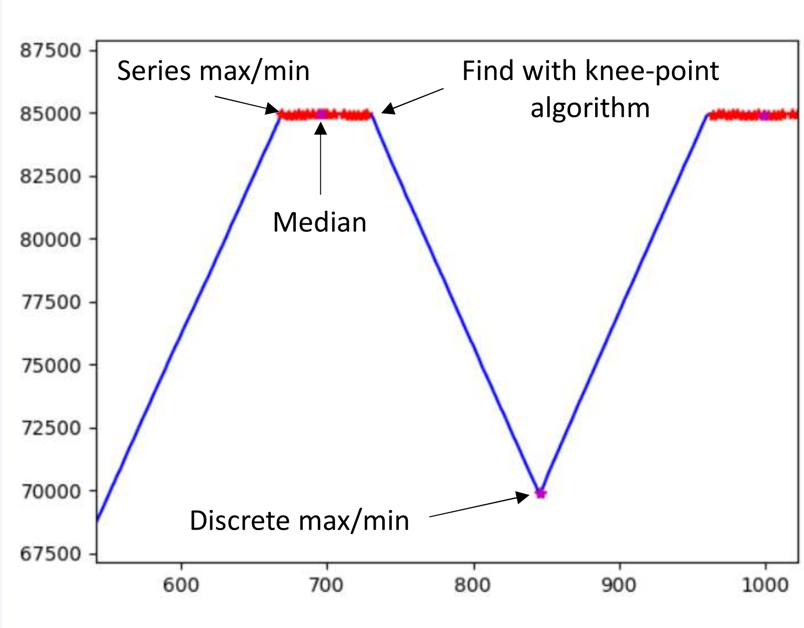
1. Use a spline to smooth the data
2. Normalize between 0 and 1
3. Calculate the perpendicular distance of each point and rotate lines 45°
4. Calculate the local maxima of the difference curve
5. Calculate the threshold for each local maximum in the difference curve
6. Compare difference value to threshold to determine knee



Klein, D, "Detecting knee-/elbow points in a graph of a function", *Towards Data Science*. (2021)

Experimental Data Automatic Import Tool:
Automatic Stage Recognition

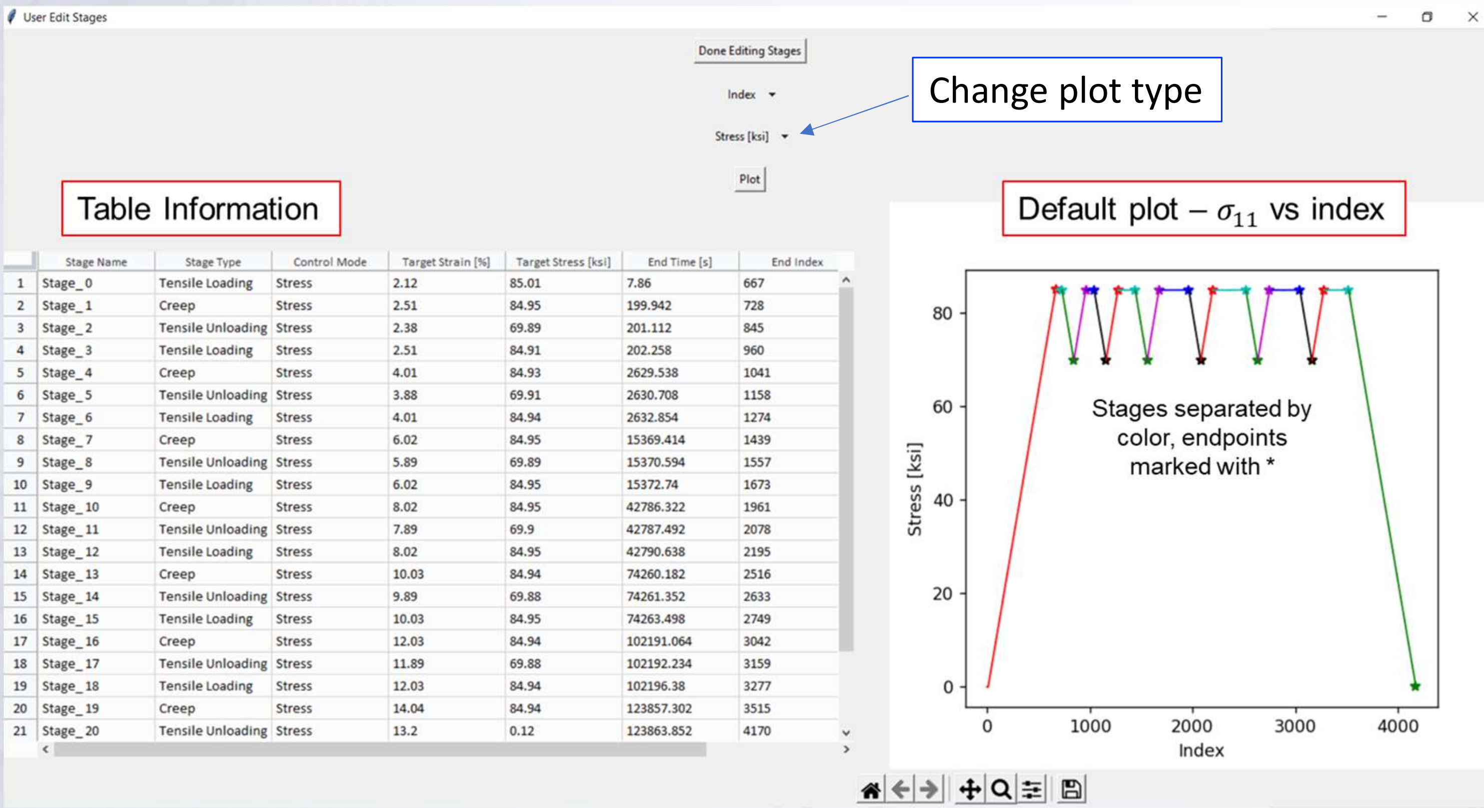
- To find the beginning and end of each stage automatically:
  - Find the local maximum and minimum on stress (force) vs time data
    - Discrete points are assumed to be the beginning/end
    - Due to noise, flat sections will have many local max/min. If flat section is found:
      - Find the median value
      - If a median value exists between discrete points → run the knee point algorithm to find the stage beginning/end



* Local max/min

Experimental Data Automatic Import Tool:
Manual Stage Editing

- Users can edit the stages manually through the GUI if desired



	Stage Name	Stage Type	Control Mode	Target Strain [%]	Target Stress [ksi]	End Time [s]	End Index
1	Stage_0	Tensile Loading	Stress	2.12	85.01	7.86	667
2	Stage_1	Creep	Stress	2.51	84.95	199.942	728
3	Stage_2	Tensile Unloading	Stress	2.38	69.89	201.112	845
4	Stage_3	Tensile Loading	Stress	2.51	84.91	202.258	960
5	Stage_4	Creep	Stress	4.01	84.93	2629.538	1041
6	Stage_5	Tensile Unloading	Stress	3.88	69.91	2630.708	1158
7	Stage_6	Tensile Loading	Stress	4.01	84.94	2632.854	1274
8	Stage_7	Creep	Stress	6.02	84.95	15369.414	1439
9	Stage_8	Tensile Unloading	Stress	5.89	69.89	15370.594	1557
10	Stage_9	Tensile Loading	Stress	6.02	84.95	15372.74	1673
11	Stage_10	Creep	Stress	8.02	84.95	42786.322	1961
12	Stage_11	Tensile Unloading	Stress	7.89	69.9	42787.492	2078
13	Stage_12	Tensile Loading	Stress	8.02	84.95	42790.638	2195
14	Stage_13	Creep	Stress	10.03	84.94	74260.182	2516
15	Stage_14	Tensile Unloading	Stress	9.89	69.88	74261.352	2633
16	Stage_15	Tensile Loading	Stress	10.03	84.95	74263.498	2749
17	Stage_16	Creep	Stress	12.03	84.94	102191.064	3042
18	Stage_17	Tensile Unloading	Stress	11.89	69.88	102192.234	3159
19	Stage_18	Tensile Loading	Stress	12.03	84.94	102196.38	3277
20	Stage_19	Creep	Stress	14.04	84.94	123857.302	3515
21	Stage_20	Tensile Unloading	Stress	13.2	0.12	123863.852	4170

Experimental Data Automatic Import Tool:
Manual Stage Editing

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Add/Delete stages through the table

	Stage Name	Stage Type	Control Mode	Target Strain [%]	Target Stress [ksi]	End Time [s]	End Index
	Stage_0	Tensile Loading	Stress	2.12	85.01	7.86	667
	Stage_1	Creep	Stress	2.51	84.95	199.942	728
3	Stage_2	Tensile Unloading	Stress	2.38	69.89	201.112	845
4							
		g	Stress	2.51	84.91	202.258	960
			Stress	4.01	84.93	2629.538	1041
		ling	Stress	3.88	69.91	2630.708	1158
		g	Stress	4.01	84.94	2632.854	1274
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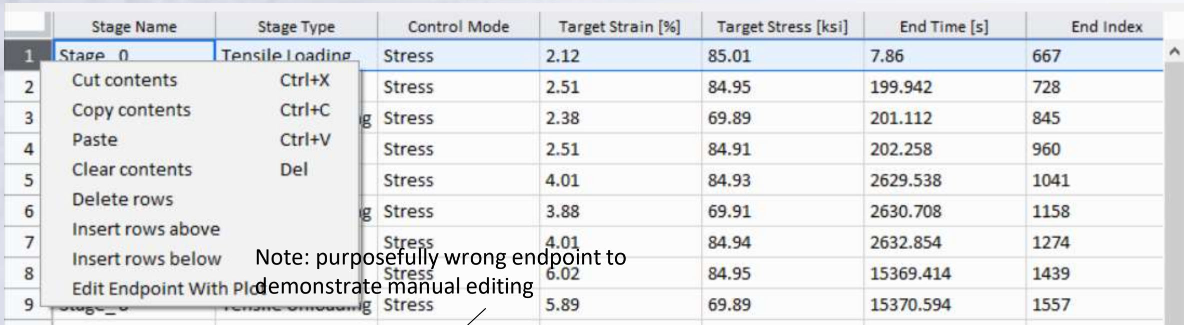
Cut contents Ctrl+X
Copy contents Ctrl+C
Paste Ctrl+V
Clear contents Del
Delete rows
Insert rows above
Insert rows below
Edit Endpoint With Plot

Only need to fill in end time or index → program will add the rest

Experimental Data Automatic Import Tool:
Manual Stage Editing

- Endpoints can be edited through the graph as well



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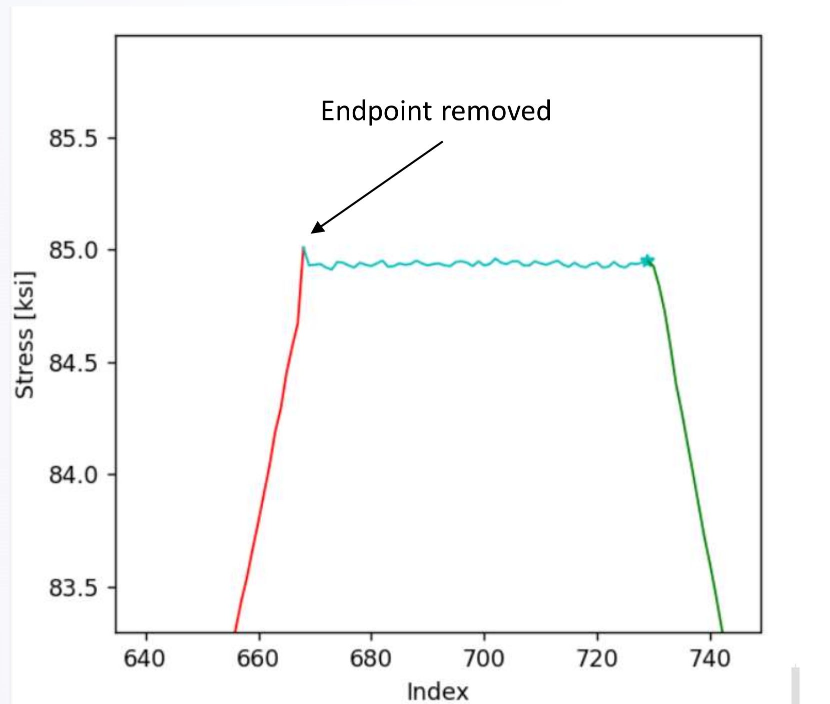
9		g	Stress	5.89	69.89	15370.594	1557

Custom button added to the right click popup menu

- Highlight row you want to edit with the plot and right click
- Select “Edit Endpoint With Plot”
- Previous endpoint on the plot is removed
- Use to toolbar to zoom/pan to stage endpoint
  - Press “Enter” to continue



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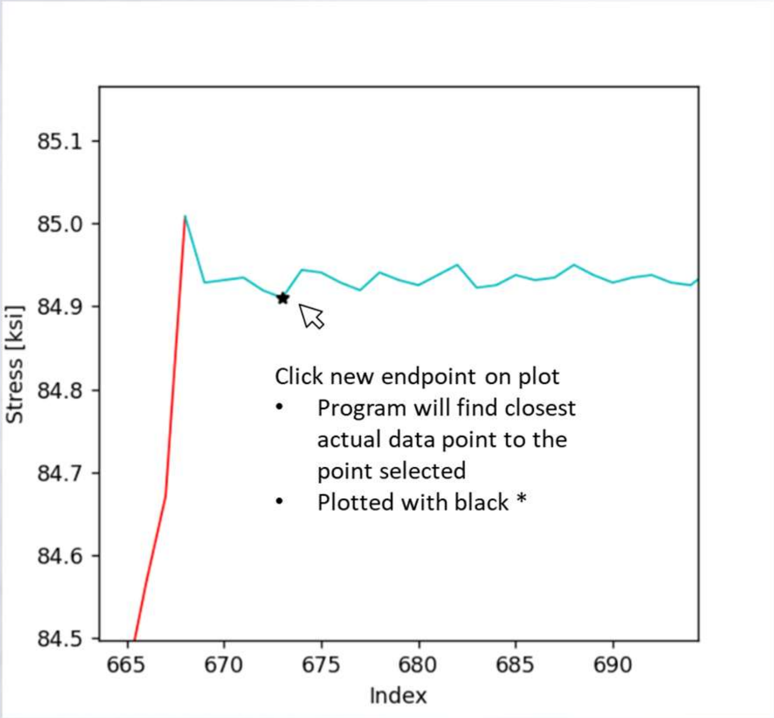

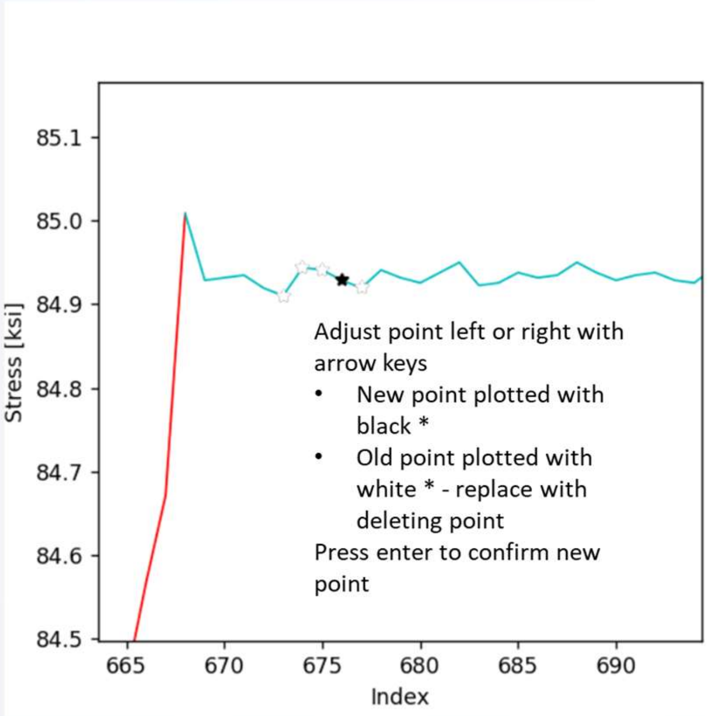

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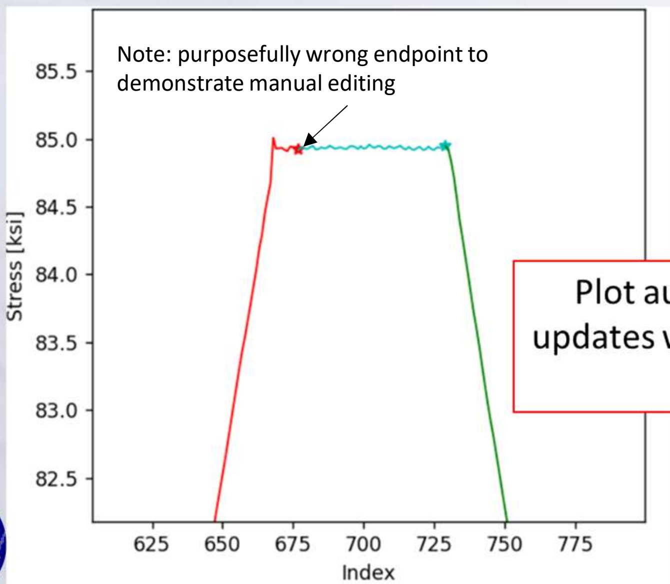
Old

	Stage Name	Stage Type	Control Mode	Target Strain [%]	Target Stress [ksi]	End Time [s]	End Index
1	Stage_0	Tensile Loading	Stress	2.12	85.01	7.86	667

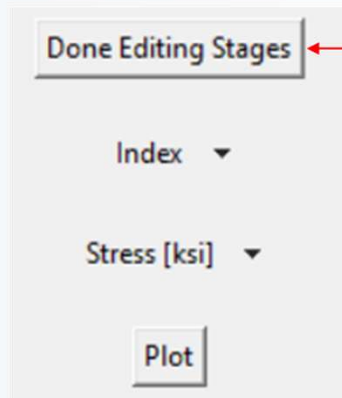
New

	Stage Name	Stage Type	Control Mode	Target Strain [%]	Target Stress [ksi]	End Time [s]	End Index
1	Stage_0	Tensile Loading	Stress	2.18	84.92	16.86	677

Table automatically updates values



Plot automatically updates with new point



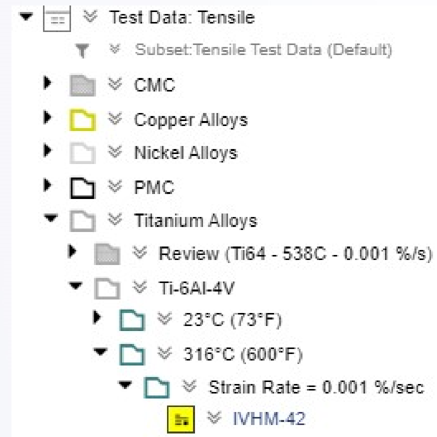
Manual editing exited with "Done Editing Stages" Button

When stage editing is done, the program begins the import process to the database

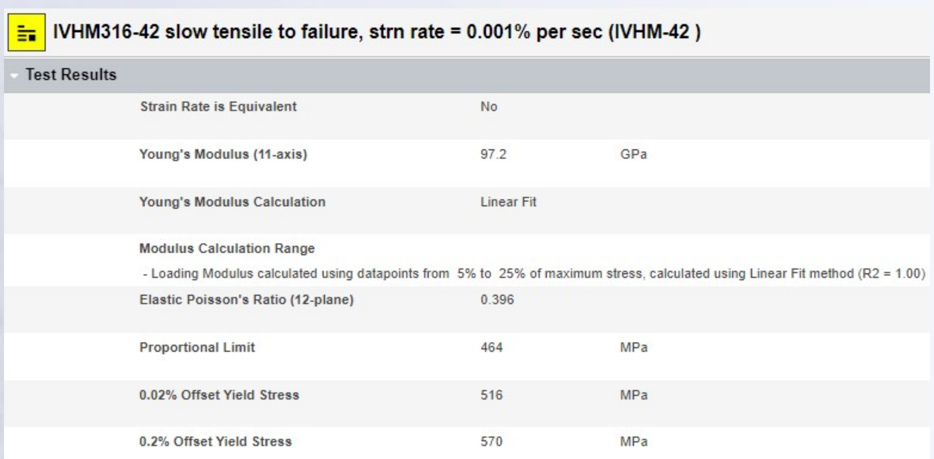
Importing Test Data to Granta

- Records are automatically placed in the database according to the GRC ICME schema

Table (Test Type)
└→ Material Class
  └→ Material
    └→ Test Temperature
      └→ Test Parameter (Strain Rate, Creep Stress, etc.)
        └→ Test Record

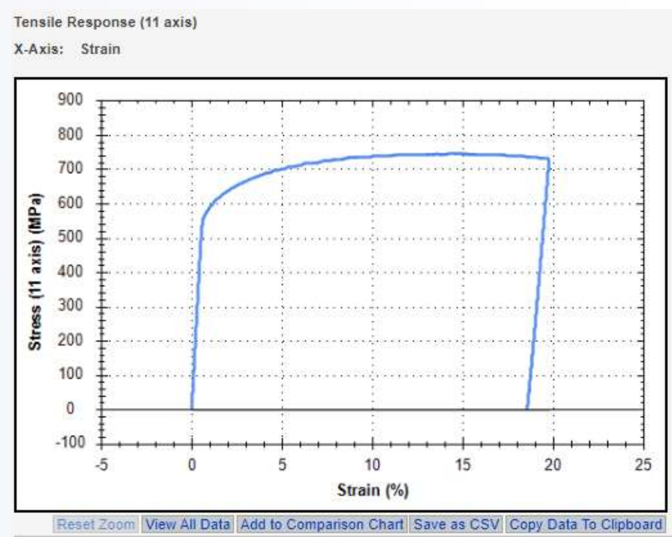


- Store user defined data, calculated parameters, and raw functional data curves



IVHM316-42 slow tensile to failure, strn rate = 0.001% per sec (IVHM-42)

Test Results		
Strain Rate is Equivalent	No	
Young's Modulus (11-axis)	97.2	GPa
Young's Modulus Calculation	Linear Fit	
Modulus Calculation Range - Loading Modulus calculated using datapoints from 5% to 25% of maximum stress, calculated using Linear Fit method (R2 = 1.00)		
Elastic Poisson's Ratio (12-plane)	0.396	
Proportional Limit	464	MPa
0.02% Offset Yield Stress	516	MPa
0.2% Offset Yield Stress	570	MPa



Importing Generic Test Data to Granta

- Generic test records also store the stage information

Stage Information

Test Summary

# Stages	Stage Types	Test Duration (s)	Max Stress Rate 11 (MPa/s)	Strain Rates 11 (%/s)	Max Stress 11 (MPa)	Max Strain 11 (%)
21	Tensile Loading Creep Tensile Unloading	124000	91	0.148 0.00206 -0.105 0.106 0.000683 -0.108 0.109 0.000169 -0.113 0.113 0.0000742 -0.118 0.106 0.0000635 -0.123 0.123 0.0000708 -0.126 0.089 0.0000898 -0.129	586	14

Hide full table

Summary table automatically generated by Granta

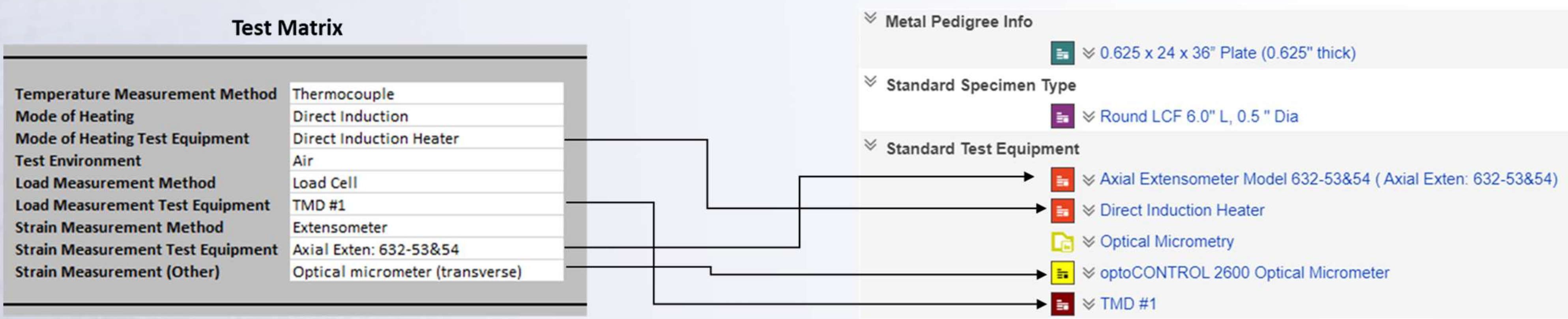
Importer populates the stage table

Save as CSV | Copy To Clipboard

Stage Name	Stage Type	Control Mode	End Time (s)	Stress Rate (11-axis) (MPa/s)	Strain Rate (11-axis) (%/s)	Target Stress (11-axis) (MPa)	Target Strain (11-axis) (%)	Notes
Stage_ 0	Tensile Loading	Stress	7.86	89.2	0.148	586	2.12	Both Stress and Strain Rates are calculated from a linear fit the entire data set in this stage
Stage_ 1	Creep	Stress	200	-0.000152	0.00206	586	2.51	Both Stress and Strain Rates are calculated from a linear fit the entire data set in this stage
Stage_ 2	Tensile Unloading	Stress	201	-89.9	-0.105	482	2.38	Both Stress and Strain Rates are calculated from a linear fit the entire data set in this stage
Stage_ 3	Tensile Loading	Stress	202	90.3	0.106	585	2.51	Both Stress and Strain Rates are calculated from a linear fit the entire data set in this stage
Stage_ 4	Creep	Stress	2630	-2.15e-7	0.000683	586	4.01	Both Stress and Strain Rates are calculated from a linear fit the entire data set in this stage
Stage_ 5	Tensile Unloading	Stress	2630	-90.1	-0.108	482	3.88	Both Stress and Strain Rates are calculated from a linear fit the entire data set in this stage
Stage_ 6	Tensile Loading	Stress	2630	90.4	0.109	586	4.01	Both Stress and Strain Rates are calculated from a linear fit the entire data set in this stage
Stage_ 7	Creep	Stress	15400	-1.89e-7	0.000169	586	6.02	Both Stress and Strain Rates are calculated from a linear fit the entire data set in this stage
Stage_ 8	Tensile Unloading	Stress	15400	-90.1	-0.113	482	5.89	Both Stress and Strain Rates are calculated from a linear fit the entire data set in this stage

Automatic Linking Capability Enables Pedigree Maintenance

- From the information defined in the Excel Test Matrix supplied by the user, links to other records in the database are automatically populated
  - Automatic links to the test equipment and measurement devices ensure that *how* the data was captured is maintained in the database
  - If a test is out of spec. or the machine is found to be out of calibration, automatic linking can provide a list of potentially effected records to ensure that the data in the database is correct



Summary

- Data Informatics and Effective Data Management are critical to enabling ICME and achieving the NASA Vision 2040
  - Ensure the integrity of our data, prevent loss of institutional knowledge, and trust that our data is protected
- Granta MI offers a commercial, robust tool for effective information management
  - Connect to the database through Python scripting for advanced/customizable data analytics and importing
  - Utilize well-developed export tools to get data out to the correct people
- Developed a Python-based GUI that performs data analysis and automatic importing of data to Granta MI
  - Fast, consistent data reduction and analysis from machine raw data
  - Reduce the time to analyze complex test data and import to the database → promote organizational adoption

Thank You for Your Attention

Integrate Don't Duplicate