NFPA Industrial Technology Roadmap

Meeting Report on Research Areas and Targets

NFPA Industrial Technology Task Force

September 8, 2025

NFPA Industrial Technology Roadmap

The NFPA Industrial Technology Roadmap describes an industry-wide consensus regarding the pre-competitive research and development needs associated with improving the design, manufacture, and function of fluid power components and systems for industrial, or in-plant, applications.

The research and development agenda it describes is focused on advancements that will help the fluid power industry meet the future needs of its customers, expand into new markets, and attract the best and brightest students to the field.

It is used by the NFPA and its academic partners to guide their research efforts, by NFPA members and other industry players to inform decisions about research partnerships and product development, and by academic, government, and other organizations that wish to pursue research and development projects of importance to the fluid power industry.

It is also a key part of NFPA's fluid power technology promotion strategy, as it illuminates places both where fluid power is meeting the needs of its customers and where emerging technologies are being developed and deployed.

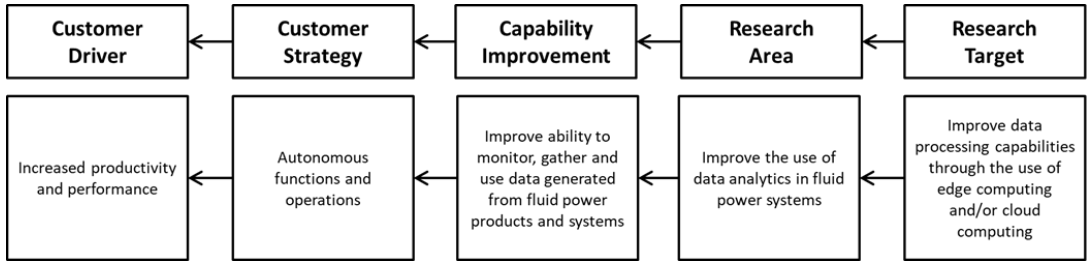
It is updated every four years under the guidance of NFPA's Industrial Technology Task Force.

Roadmap Elements

The NFPA Industrial Technology Roadmap is comprised of five primary elements, each connected to the next in an interdependent chain.

1. **Customer Drivers** are the top-level performance objectives of fluid power customers, the OEMs or machine builders that manufacture machines that often incorporate fluid power systems. Customer Drivers help these machine builders serve the needs of their own customers and are not necessarily connected to their use of fluid power.
2. **Customer Strategies** are the machine-level objectives and technologies that the machine builders have set or are using to help them achieve the top-level performance objectives described by the Customer Drivers. Again, these Customer Strategies are not necessarily connected to their use of fluid power.
3. **Capability Improvements** describe the ways in which fluid power systems must improve if they are to participate or increase their participation in the technology trends described by the Customer Strategies.
4. **Research Areas** are the broad areas of pre-competitive investigation that could assist in bringing about the Capability Improvements.
5. **Research Targets** are the objectives that quantify or otherwise describe successful strategies for pursuing the Research Areas.

EXAMPLE:



2025 Project Process and Timeline

The NFPA Industrial Technology Task Force is following this process and timeline for the 2025 update to the NFPA Industrial Technology Roadmap. This is the report from its meeting on September 8, 2025 to review, harmonize and prioritize Research Areas and Targets.

Phase 1 – Planning and Development (4Q24)

Dec 2024 Task force meeting to review project plan and survey on Customer Drivers and Strategies

Phase 2 – Customer Drivers and Strategies (1Q25)

Jan 2025 Launch of survey on Customer Drivers and Strategies

Feb 2025 Deadline to respond to survey on Deadline to respond to survey on Customer Drivers and Strategies

Mar 2025 Task Force meeting to discuss, define and prioritize Customer Drivers and Strategies, and to review survey on Fluid Power Alignment and Capability Improvements

Meeting report published with prioritized Customer Drivers and Strategies

Phase 3 – Capability Improvements (2Q25)

Apr 2025 Launch of survey on Fluid Power Alignment and Capability Improvements

May 2025 Deadline to respond to survey on Fluid Power Alignment and Capability Improvements

Jun 2025 Task Force meeting to discuss, define and prioritize Capability Improvements, and to review survey on Research Areas and Targets

Meeting report published with prioritized Capability Improvements

Phase 4 – Research Areas and Targets (3Q25)

Jul 2025 Working Groups identified for each Capability Improvement

Launch of survey on Research Areas and Targets

Aug 2025 Deadline to respond to survey on Research Areas and Targets

Working Group meetings to discuss and prioritize Research Areas for each Capability Improvement

Sep 2025 Task Force meeting to review, harmonize and prioritized Research Areas and Targets

Meeting report published with prioritized Research Areas and Targets

Phase 5 – Final Roadmap Document (4Q25)

Oct 2025 Draft Roadmap written and circulated for review and comment

Nov 2025 Deadline to return comments on draft Roadmap

Final Roadmap published and presented

Meeting Participants

- Pete Alles, National Fluid Power Association
- David Blanco, Bosch Rexroth Corporation
- Vonn Bonnema, Continental Hydraulics
- Jeffrey Borchers, ROSS Controls
- Ben Brown, National Fluid Power Association
- John Corona, Nachi America
- T. J. Crenwick, OEM Controls
- Bryan Day, Thermal Transfer Products
- Dale Dietel, DGD Fluid Power
- Robert Forisch, Moog
- Jon Frey, Bosch Rexroth Corporation
- Rick Guidish, VIS Hydraulics
- Bernd Hunger, IC-Fluid Power, Inc.
- Denise Husenica, National Fluid Power Association
- Gajendra Jagatap, Danfoss Power Solutions
- John Jennings, Lexair, Inc.
- Jon Jensen, SMC Corporation of America
- Paul Johnson, Aggressive Hydraulics
- Paul Keating, Certified Power Solutions
- Chris Kolbe, HYDAC
- Eric Lanke, National Fluid Power Association
- Denis Lenoble, Famic Technologies Inc.
- Ada Leung, Anfield Industries
- Michael Magsam, Trelleborg Sealing Solutions
- Steven Meislahn, Helios Technologies
- Paul Michael, Milwaukee School of Engineering
- Michael Miles, KersTech
- Chris Passmore, Flodraulic Group
- Ethan Roth, Vermeer
- Tom Shickel, Bosch Rexroth Corporation
- Dave Tetzlaff, Innovative Hydraulics LLC
- Ben Thomas, OEM Controls
- Joshua Wilson, QCC - Quality Control Corp
- Dan Worden, OEM Controls, Inc.

Fluid Power Capability Improvements

The NFPA Industrial Technology Task Force met on June 9, 2025, to review survey data, discuss, and determine the Fluid Power Capability Improvements that would help frame the 2025 NFPA Industrial Technology Roadmap. The chosen Capability Improvements are shown below.

<u>Capability Improvements</u>

In order to better meet the needs of our customers, fluid power should seek to:

1. **Data.** Improve ability to monitor, gather, and use data generated from fluid power products and/or systems.
2. **Control.** Improve the precision, performance, or ease the application of fluid power control systems.
3. **Energy Efficiency.** Increase the energy efficiency of fluid power products and/or systems.
4. **Environmental Impact.** Reduce the environmental impact of fluid power products and/or systems (i.e., leaks, sustainable materials, damage to environment).
5. **Noise.** Reduce the level and harshness of the noise generated by fluid power products and/or systems.
6. **Power Density.** Increase the power density of fluid power products and/or systems.
7. **Reliability and Durability.** Improve the reliability and/or durability of fluid power products and/or systems.
8. **Safety.** Improve the safe use and application of fluid power products and/or systems.
9. **Service.** Improve the availability of replacement parts or otherwise improve the servicing of the fluid power system on the machine.

Fluid Power Research Areas

Research Areas are the broad areas of pre-competitive investigation that could assist in bringing about the Capability Improvements. At its June 9 meeting, the Task Force reviewed the Research Areas identified as part of the 2023 NFPA Technology Roadmap, the selected the following Research Areas to initially describe in the 2025 NFPA Industrial Technology Roadmap.

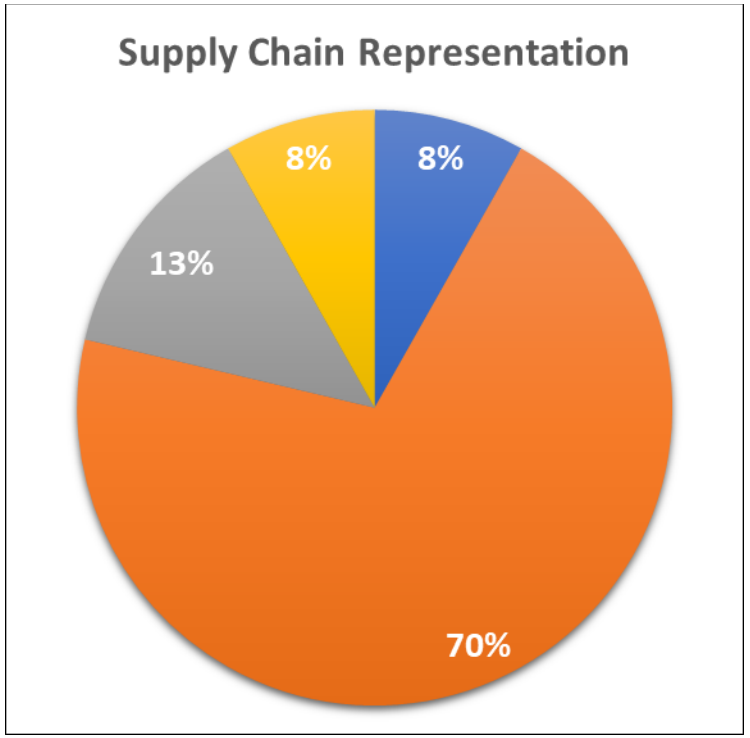
Research Areas

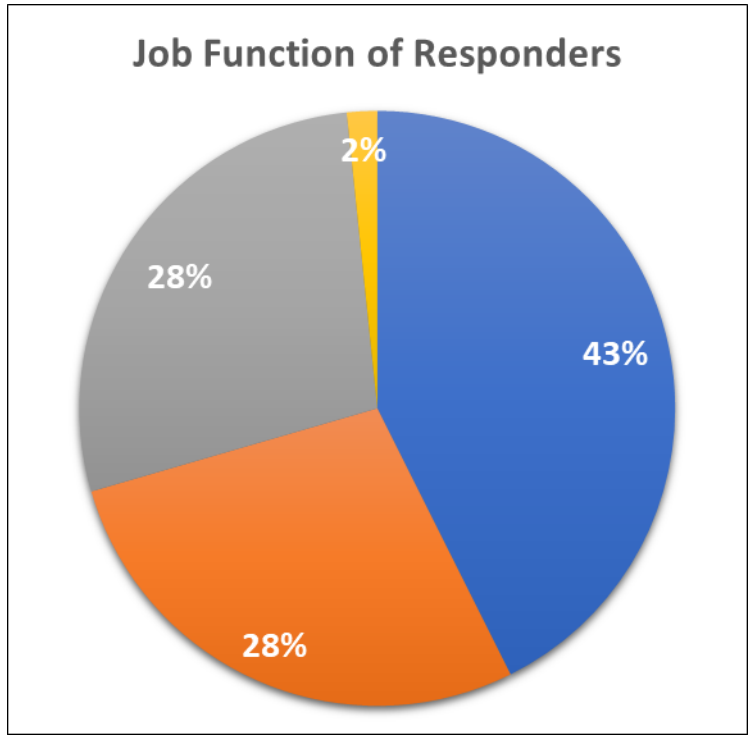
Organizations that wish to pursue research of importance to the fluid power industry should focus on projects that:

1. **Components.** Develop new fluid power components.
2. **Controllability.** Improve the controllability of fluid power systems.
3. **Data Analytics.** Improve use of data analytics in fluid power systems.
4. **Fluids.** Optimize the use of fluids and lubrication in fluid power systems.
5. **Manufacturing Technologies.** Develop/apply new manufacturing technologies for fluid power components and systems.
6. **Materials.** Develop/apply new materials in fluid power components and systems.
7. **Seal Technologies.** Optimize the use of seal technologies in fluid power systems.
8. **Security.** Improve data, cyber or other security needs of fluid power systems.
9. **Sensor Technologies.** Advance sensor technologies used in fluid power systems.
10. **System Architectures.** Explore novel fluid power system architectures.

Survey on Research Areas

The Task Force next reviewed the results of two July 2025 surveys NFPA conducted to assist in assessing the usefulness of these Research Areas in bringing about the improvements described by the 2025 Capability Improvements, and in determining if any new Research Areas had emerged since the time of the 2023 NFPA Technology Roadmap. One survey asked about hydraulic research areas; the other about pneumatic research areas. Together, the surveys received responses from 61 individuals across the fluid power supply chain, including a large percentage from the NFPA Industrial Technology Task Force.





Importance of Hydraulic Research Areas

Survey participants were asked to rate how important each of the Research Areas would be in making a significant impact on each of the Capability Improvements for Hydraulics. The scoring scale was: 5 = Extremely important; 4 = Very important; 3 = Somewhat important; 2 = Not so important; 1 = Not at all important.

CAPABILITY IMPROVEMENTS	N	HYDRAULIC RESEARCH AREAS									
		Components	Controllability	Data Analytics	Fluids	Manufacturing Technologies	Materials	Seal Technologies	Security	Sensor Technologies	System Architectures
Data	38	3.711	4.000	4.000	3.316	3.605	3.263	3.211	3.342	3.974	3.368
Control	34	3.735	4.176	3.882	3.147	3.324	3.265	3.529	3.206	4.029	3.706
Energy Efficiency	32	3.969	4.063	3.844	3.469	3.250	3.375	3.625	2.625	3.875	3.969
Environmental Impact	32	3.594	3.469	2.938	3.719	3.656	3.531	3.906	2.281	3.219	3.594
Noise	32	3.969	3.656	3.125	3.469	3.219	3.438	3.125	2.281	3.313	3.938
Power Density	32	4.156	3.531	3.156	3.500	3.313	4.156	3.688	2.156	3.781	4.125
Reliability and Durability	32	4.000	3.688	3.594	3.719	3.531	3.938	4.000	2.531	3.844	3.875
Safety	32	3.438	3.969	3.500	3.063	3.063	3.406	3.688	3.344	3.969	3.594
Service	33	3.303	2.909	3.424	3.091	3.394	3.273	3.364	2.545	3.182	3.212
All Responses	297	3.761	3.724	3.508	3.384	3.377	3.508	3.562	2.717	3.694	3.700

HYDRAULICS
4.176 to 3.773
3.772 to 3.369
3.368 to 2.965
2.964 to 2.561
2.560 to 2.156

In the aggregate, 91% of the research area choices were rated as at least somewhat important. The color codes categorize the average scores into their quintiles – with dark green and light green representing averages in the upper 40% of the response range.

Importance of Pneumatic Research Areas

Survey participants were asked to rate how important each of the Research Areas would be in making a significant impact on each of the Capability Improvements for Pneumatics. The scoring scale was: 5 = Extremely important; 4 = Very important; 3 = Somewhat important; 2 = Not so important; 1 = Not at all important.

CAPABILITY IMPROVEMENTS	N	PNEUMATIC RESEARCH AREAS									
		Components	Controllability	Data Analytics	Fluids	Manufacturing Technologies	Materials	Seal Technologies	Security	Sensor Technologies	System Architectures
Data	9	3.333	3.889	3.778	2.222	3.444	2.444	2.667	2.889	4.111	3.333
Control	8	3.875	3.625	3.375	2.875	3.500	2.875	2.875	2.750	3.750	3.500
Energy Efficiency	8	3.625	3.750	3.750	3.000	3.000	3.250	3.750	2.375	4.125	3.625
Environmental Impact	7	3.857	4.000	3.429	3.429	3.286	4.143	3.571	2.286	3.857	3.857
Noise	7	3.571	3.286	2.714	3.143	2.857	3.429	3.143	2.000	2.857	3.429
Power Density	7	3.714	3.857	2.571	3.429	3.429	4.000	3.714	1.857	3.000	4.000
Reliability and Durability	7	4.143	3.714	3.143	3.571	3.857	4.143	3.571	1.857	3.571	3.286
Safety	7	3.429	4.143	3.286	2.857	2.429	3.143	2.714	2.571	3.857	3.857
Service	7	3.429	2.714	3.714	2.429	3.286	3.571	2.429	2.286	3.714	2.857
All Responses	67	3.657	3.672	3.328	2.970	3.239	3.403	3.149	2.343	3.672	3.522

PNEUMATICS	
	4.143 to 3.686
	3.685 to 3.229
	3.228 to 2.771
	2.770 to 2.314
	2.313 to 1.857

In the aggregate, only 71% of the research area choices were rated as at least somewhat important. The color codes categorize the average scores into their quintiles – with dark green and light green representing averages in the upper 40% of the response range.

Importance of Fluid Power Research Areas

When we aggregate the hydraulic and pneumatic responses and order the chart from most to least important Research Area, we see the results shown below. The scoring scale was: 5 = Extremely important; 4 = Very important; 3 = Somewhat important; 2 = Not so important; 1 = Not at all important.

CAPABILITY IMPROVEMENTS	N	FLUID POWER RESEARCH AREAS									
		Components	Controllability	Sensor Technologies	System Architectures	Materials	Seal Technologies	Data Analytics	Manufacturing Technologies	Fluids	Security
Data	47	3.638	3.979	4.000	3.362	3.106	3.106	3.957	3.574	3.106	3.255
Control	42	3.762	4.071	3.976	3.667	3.190	3.405	3.786	3.357	3.095	3.119
Energy Efficiency	40	3.900	4.000	3.925	3.900	3.350	3.650	3.825	3.200	3.375	2.575
Environmental Impact	39	3.641	3.564	3.333	3.641	3.641	3.846	3.026	3.590	3.667	2.282
Noise	39	3.897	3.590	3.231	3.846	3.436	3.128	3.051	3.154	3.410	2.231
Power Density	39	4.077	3.590	3.641	4.103	4.128	3.692	3.051	3.333	3.487	2.103
Reliability and Durability	39	4.026	3.692	3.795	3.769	3.974	3.923	3.513	3.590	3.692	2.410
Safety	39	3.436	4.000	3.949	3.641	3.359	3.513	3.462	2.949	3.026	3.205
Service	40	3.325	2.875	3.275	3.150	3.325	3.200	3.475	3.375	2.975	2.500
All Responses	364	3.742	3.714	3.690	3.668	3.489	3.486	3.475	3.352	3.308	2.648

FLUID POWER	
	4.128 to 3.724
	3.723 to 3.319
	3.318 to 2.914
	2.913 to 2.509
	2.508 to 2.103

In the aggregate, 90% of the research areas choices were rated as at least somewhat important. The color codes categorize the average scores into their quintiles – with dark green and light green representing averages in the upper 40% of the response range.

Suggestions for New Research Areas

In addition to rating the importance of the existing Research Areas, participants were also asked to suggest any additional Research Areas that would make a significant impact on each of the hydraulic and pneumatic Capability Improvements. A summary of these suggestions is shown below.

Capability Improvement	Suggested Hydraulic Research Areas	Suggested Pneumatic Research Areas
Data	• Use AI (artificial intelligence) learning from the generated data to predict and make decisions for improving system performance. • Safety related data. • Data exchange approaches between application site, OEM and hydraulic component manufacture. • Standards for control based fault and data reporting. Expand on the J1939 standard. Additional tools to design, transport and implement OEM-specific proprietary PGN/OEM sets. Each OEM will end up with their own set, the industry needs tools to speed that up and make it easier. • Wireless systems for data collection and reliable remote control systems. • Tank design and research for heat exchange and weight reduction. • Use of more analytical tools in design and material science advances.	• Applications that historically pneumatics were not considered for a solution or means of control, there's a lot you can do with pneumatics that engineers forget or do not realize. • Flow, pressure, temp, vibration, position monitoring. • Wireless technologies (5G), Fail-safe communication in industrial automation. • Support of IoT protocols, work should be coordinated with network organizations.
Control	• Safety applications and modes. • Wireless systems. • Electronic control, electrification, and sensor utilization.	• Develop better controls & sensors for very low flow applications, very low flows & pressures are harder to maintain high accuracy's and hysterisis.
Energy Efficiency	• Energy efficiency and electrification is tantamount to success. • Proposal of combination with electronic control and electric drive.	• Self monitoring of pneumatic systems to identify leakage, and reduce or remove pressure when possible to reduce energy consumption.

Suggestions for New Research Areas

In addition to rating the importance of the existing Research Areas, participants were also asked to suggest any additional Research Areas that would make a significant impact on each of the hydraulic and pneumatic Capability Improvements. A summary of these suggestions is shown below.

Capability Improvement	Suggested Hydraulic Research Areas	Suggested Pneumatic Research Areas
Environmental Impact	• Use of biodegradable hydraulic fluids.	
Noise		
Power Density	• Smart systems and components along with higher pressure with robust components. • High efficiency and High pressure.	
Reliability and Durability		
Safety	• Electronic control, and sensor utilization.	
Service		• Make the machine smart enough to tell you which components are reaching a failure point.

Working Group Meetings

The Task Force then acknowledged that the following nine working group meetings had been held, one for each of the nine Capability Improvements, and that each working group had reviewed the data and comments from the survey, and were returning recommendations for updated connections to the Customer Strategies and for a prioritized list of Research Areas and Targets for their Capability Improvement.

Environmental Impact – Mon Aug 4 – 10:00-11:30 AM Central Time
- Francesca Aryee-Dematteis, IMI
- David Coffee, EPCO Zero-Leak
- Matt Grussing, Bailey International
- Christopher Kolbe, HYDAC
- Andy McMichael, JWF Technologies

Data – Mon Aug 4 – 2:00-3:30 PM Central Time
- Tom Carlson, Deltrol Fluid Products
- Chadwick Conte, Peninsular Cylinder Company
- Robert Countiss, AKG of America
- Laszlo Dobo, Continental ContiTech
- Tony Hennum, Nott Company
- Gajendra Japatap, Danfoss Power Solutions
- Kristopher Karbach, Boeing
- Frank Latino, Festo
- Steven Meislahn, Sun Hydraulics
- Paul Michael, Milwaukee School of Engineering
- Mike Minard, Nass Controls
- Andrew Newman, Sun Hydraulics
- Josh Scarbrough, IFP Motion Solutions
- Sam Simons, OEM Controls

Reliability and Durability – Wed Aug 6 – 12:00-1:30 PM Central Time
- Jeffrey Borchers, ROSS Controls
- Greg Broschka, Kepner Products Company
- Bernd Hunger, IC-Fluid Power
- Keith Kushnir, Parker Hannifin
- Denis Lenoble, Famic Technologies
- Bob Mosey, Mosey's Production Machinists
- Tim O'Neill, Kuriyama of America
- Jared Ottman, Pettibone
- Brian Rhode, Afton Chemical
- Ben Thomas, OEM Controls
- Josh Wilson, QCC

Noise – Fri Aug 8 – 8:00-9:30 AM Central Time
- Narendra Gupta, Hyster-Yale Group
- Andy McMichael, JWF Technologies
- Mark Schoessler, Parker Hannifin
- Tom Shickel, Bosch Rexroth

Control – Fri Aug 8 – 10:00-11:30 AM Central Time
- Chandlar Armstrong, IFP Motion Solutions
- Tom Carlson, Deltrol Fluid Products
- T.J. Crenwick, OEM Controls
- Jonathan Gamble, Enfield Technologies
- Sean Howley, Bailey International
- Jeff Keating, Certified Power Solutions
- Daniel Lavelle, Bosch Rexroth
- Andrew Newman, Sun Hydraulics
- Keith Simons, OEM Controls
- Josh Wilson, QCC

Safety – Thu Aug 14 – 8:00-9:30 AM Central Time
- Jon Jensen, SMC
- Tim O'Neill, Kuriyama of America
- Jared Ottman, Pettibone
- Aaron Woynaroski, ROSS Controls

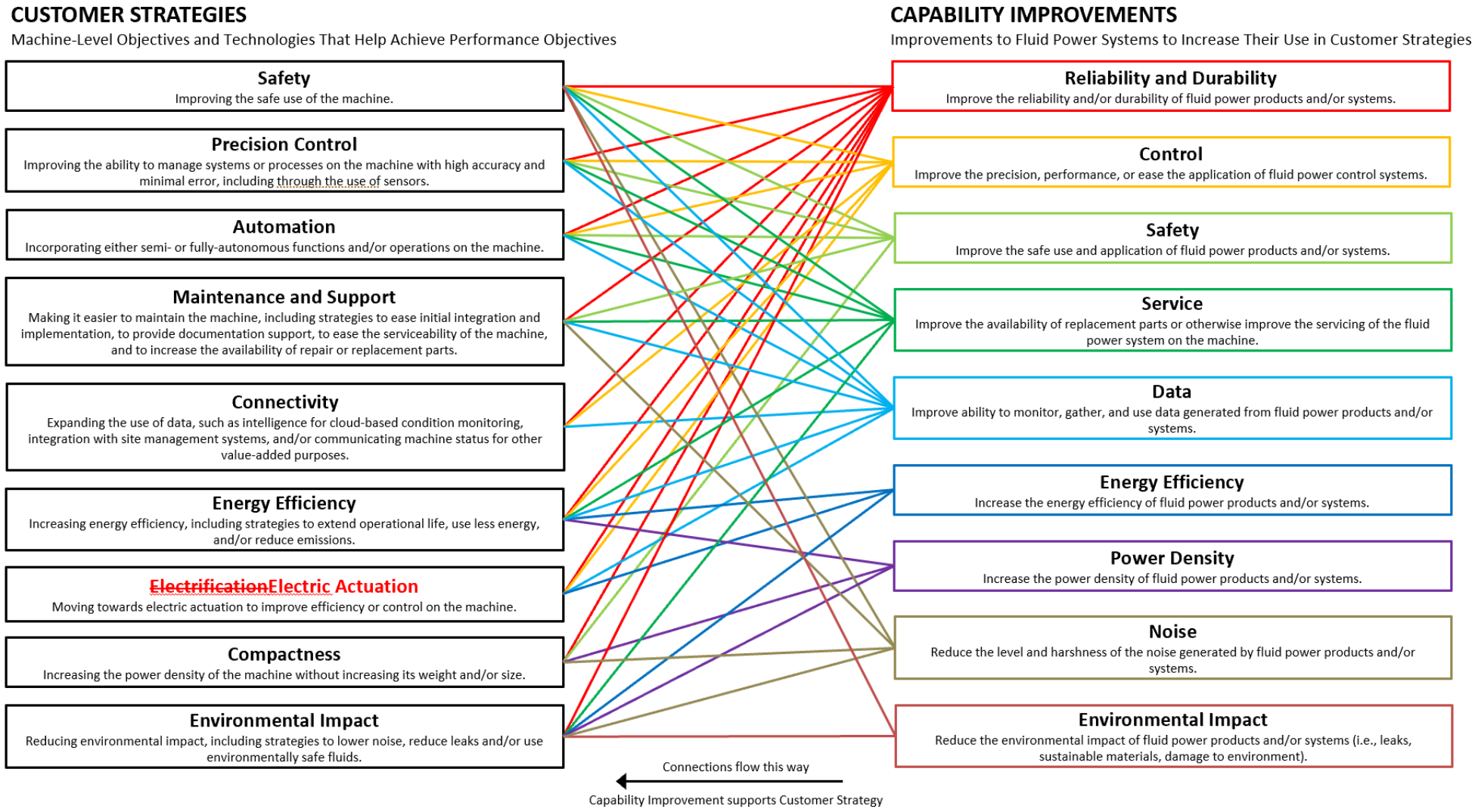
Energy Efficiency – Mon Aug 18 – 12:00-1:30 PM Central Time
- Anant Jain, Danfoss Power Solutions
- Jon Jensen, SMC
- Steve Meislahn, Sun Hydraulics
- Michael Miles, KersTech
- Jared Ottman, Pettibone
- Mark Petit, Evonik Oil Additives
- Brian Rhode, Afton Chemical

Power Density – Tue Aug 19 – 12:00-1:30 PM Central Time
- David Blanco, Bosch Rexroth
- Greg Broschka, Kepner Products
- Mark Schoessler, Parker Hannifin
- Josh Wilson, QCC

Service – Tue Aug 19 – 2:00-3:30 PM Central Time
- Steve Downey, Hydraulex Global
- John Jennings, Lexair
- Josh Wilson, QCC

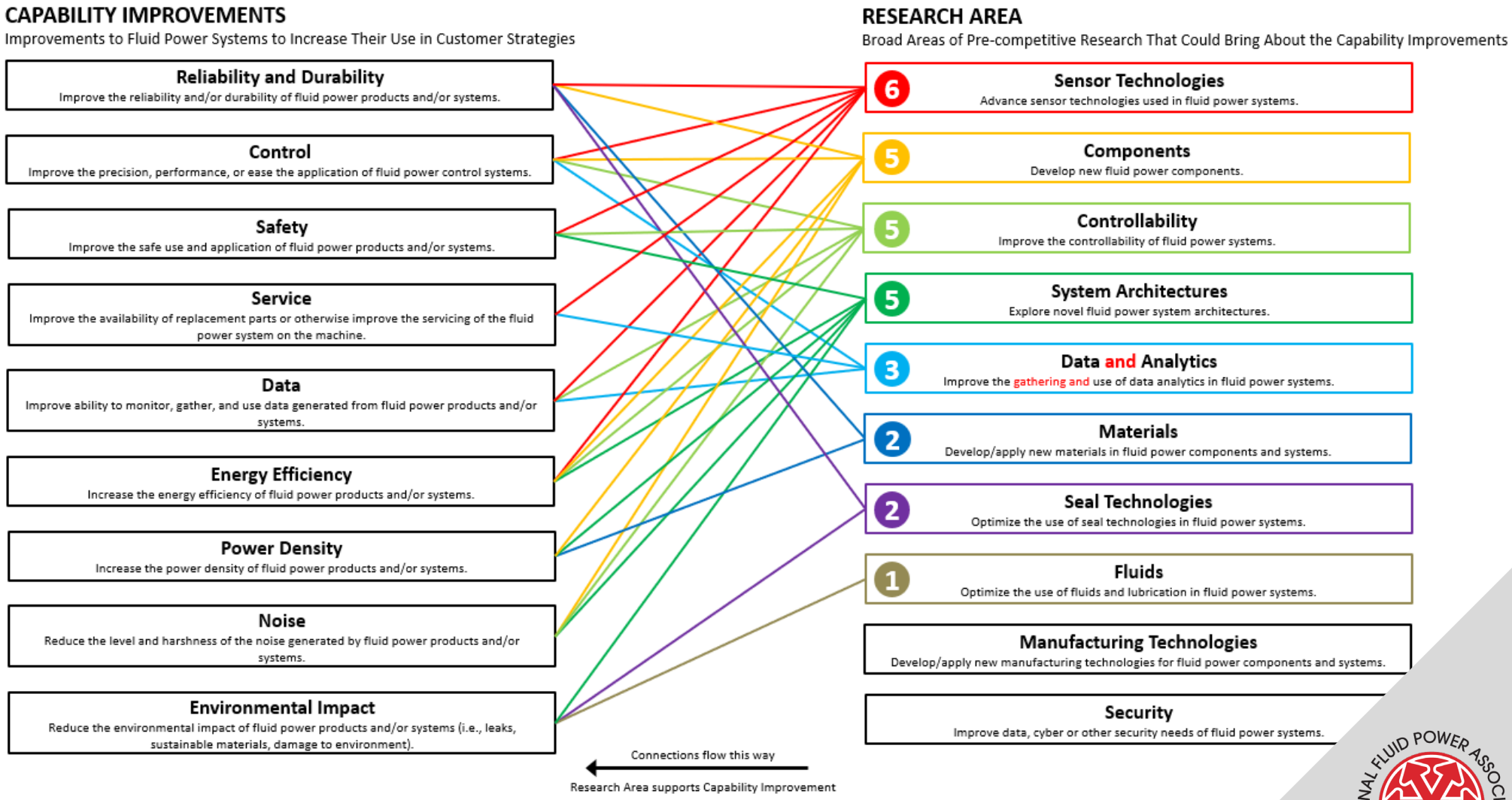
Updated Capability Improvement Connections

A summary of the updated connections from Capability Improvements to Customer Strategies recommended by the working groups is shown at right. Among the changes is the suggestion to rename the “Electrification” Customer Strategy as “Electric Actuation” to more clearly describe that technology strategy. The Task Force reviewed and approved these changes and connections.



Prioritized Research Areas

A summary of the prioritized Research Areas recommended by the working groups is shown at right. Among the changes is the suggestion to rename the “Data Analytics” Research Area as “Data and Analytics” to more clearly describe that investigative area. The Task Force reviewed and approved these changes and connections.



Prioritized Research Targets – Sensor Technologies

The Task Force then reviewed the list of recommended Research Targets from each Working Group for each of its prioritized Research Areas. It was agreed that each list should be reorganized to better clarify which Targets would require new technology development and which would require enhanced market education. In the overall, the Task Force then selected several Targets (shown in bold red) that seem to represent the most impactful Targets for that Research Area.

Sensor Technologies. Advance sensor technologies used in fluid power systems.

DATA:
- Increase the durability and survivability of sensors in harsh environments.
- **Develop sensors that can be more easily applied across the system (i.e., miniaturization, integration of functions - multiple measurements from the same sensor in the same location).**
- Explore “non-traditional” or “new-to-fluid-power sensor modalities for possible application to fluid power objectives (i.e., vibration sensors for maintenance and fault detection).

CONTROL:
- Perform cost-benefit analysis of increased use of sensors and the performance enhancements that they can provide.
- Investigate the potential use of advanced sensors from other industries in fluid power systems (i.e., automotive, aerospace).
- Define and specify existing sensors needed for advanced control strategies (i.e., robust control, adaptive control).

ENERGY EFFICIENCY:
- **Increase use and availability of multi-functional wireless sensors to measure pressure, temperature, and flow (i.e., reduce cost, cybersecurity concerns).**
- Increase the precision and response time of sensors.
- Increase the uniform connectivity of sensors.

RELIABILITY AND DURABILITY:
- Apply sensor technologies to better predict product wear or failure (and make more cost-effective).
- Apply in-line fluid sensors to monitor and act on contamination levels (and make more cost-effective).
- **Explore use of predictive algorithms to monitor and alert on component status.**
- Increase robustness of sensor connections (through proven and standard practices, etc.).

SAFETY:
- Integrate more accurate position sensors into spool-position valves.
- Clarify definition of reliable sensors and requirements for reliable use of sensors in safety systems.
- Develop new or use existing sensors for spray or leak detection.
- Increase robustness of industrial sensors for mobile or other harsh environments.
- Investigate ways to integrate sensors into valves and other components.

SERVICE:
- Technologies needed to perform preventative maintenance is the overarching need.
- Develop new sensing technologies for flow and contamination that don’t require disassembly of the machine.
- Increase the integration of sensors into fluid power components (i.e., measurement ports).

Prioritized Research Targets – Components

The Task Force then reviewed the list of recommended Research Targets from each Working Group for each of its prioritized Research Areas. It was agreed that each list should be reorganized to better clarify which Targets would require new technology development and which would require enhanced market education. In the overall, the Task Force then selected several Targets (shown in bold red) that seem to represent the most impactful Targets for that Research Area.

Components. Develop new fluid power components.

CONTROL:

- **Increase the integration of sensors into components.**
- Integrate more components into the machine network.
- **Investigate the potential for new and needed functions for fluid power components (especially those that address common pain points on the machine).**

ENERGY EFFICIENCY:

- **Find ways to improve the efficiency of individual components (i.e., reducing losses, improving energy conversion, reduce coil wattage in control systems).**

NOISE:

- Design considerations for lower noise into components (i.e., expand flow paths within manifolds, incorporation of noise-dampening materials).
- Define and promote acceptable noise thresholds for components in specific industrial applications.
- Explore 3D-printed component designs, appropriate for a production environment, that reduce noise levels.

POWER DENSITY:

- Operating at higher pressure (need to define - 10,000 PSI or higher?) is the top-level objective. Research areas and targets need to address this. May need a separate survey on this topic to determine current market use and future need.
- Develop components that are smaller and can operate at higher pressure.
- Develop more efficient components (i.e., less internal leakage).
- Develop more durable components (i.e., longer service life).

RELIABILITY AND DURABILITY:

- Develop bearing-free components or that utilize other alternatives to bearings.
- Develop components that are more resistant to contamination (i.e., servo valves, manifolds).
- Educate and accelerate evolution towards O-ring seals and away from tapered threads.
- Increase use of on-board electronics to provide component data for better system integration.

Prioritized Research Targets – Controllability

The Task Force then reviewed the list of recommended Research Targets from each Working Group for each of its prioritized Research Areas. It was agreed that each list should be reorganized to better clarify which Targets would require new technology development and which would require enhanced market education. In the overall, the Task Force then selected several Targets (shown in bold red) that seem to represent the most impactful Targets for that Research Area.

Controllability. Improve the controllability of fluid power systems.

DATA:

- **Simplify the application of advanced control architectures.**
- **Increase the use of wireless systems for data collection and reliable remote control systems.**
- **Explore the use of digital twins and related simulation technologies to test and validate improved control of fluid power components.**

CONTROL:

- Review emerging safety requirements (i.e., European, Asian) and educate the marketplace with specific future timeline of impacts on the North American market of fluid power control systems.
- Increase the application of advanced concepts for fluid power control (i.e., closed loop control, position sensing).
- Increase translation of “academic” control strategies to real-world application (i.e., robust control, adaptive control).

ENERGY EFFICIENCY:

- Improve the ability of control to reduce losses in the fluid power system (i.e., utilizing sensors to minimize the pressure and flow required to perform needed work).
- **Develop accurate model-based simulations for control systems and components (i.e., digital twins, improvements in the characterization of components to accomplish this).**

NOISE:

- Define and promote best practices for control strategies that reduce the level and harshness of noise (i.e., dither adjustment, use of proportional valves, use of feedback to monitor case flow, spool position, optimizing hysteresis).
- **Increase use of sensors in fluid power systems to monitor and reduce vibration and noise levels (i.e., reducing cavitation and entrained air).**

SAFETY:

- Create and/or disseminate “handy reference guides” for handling of stored energy in ways that comply with ISO and ANSI standards.
- Engage more fluid power experts in the efforts to update relevant standards for safe use of fluid power (i.e., ANSI B1126, ISO 4413,4414, ISO 14839).
- Improve integration between machine controls and safety-related fluid power control systems.

Prioritized Research Targets – System Architectures

The Task Force then reviewed the list of recommended Research Targets from each Working Group for each of its prioritized Research Areas. It was agreed that each list should be reorganized to better clarify which Targets would require new technology development and which would require enhanced market education. In the overall, the Task Force then selected several Targets (shown in bold red) that seem to represent the most impactful Targets for that Research Area.

System Architectures. Explore novel fluid power system architectures.

ENERGY EFFICIENCY:

- **Utilize active displacement control to use only the fluid flow needed.**
- **Utilize distributed subsystems to customize pressure and flow to individual work circuits.**
- **Develop methods to recover energy from the system and use for additional work.**

ENVIRONMENTAL IMPACT:

- Produce a system design guide that focuses on strategies that can reduce environmental impact (i.e., reduce the number of connections, shape and configuration of fluid conduits, integrates components, properly regulates pressure, reduces the volume of fluid, thermal conditioning of fluid, properly sizes the system to the application).

NOISE:

- Define and promote best practices for system architectures that reduce the level and harshness of noise (i.e., proper line sizing, flexible connections to prime movers, utilization of dampening materials, sizing components to energy needed).
- Investigate the application of active noise cancellation technologies to fluid power systems.
- Evaluate the external environment and implement strategies that reduce perceived levels of noise.

POWER DENSITY:

- Operating at higher pressure (need to define - 10,000 PSI or higher?) is the top-level objective. Research areas and targets need to address this. May need a separate survey on this topic to determine current market use and future need.
- Analyze and address the system development and safety needs associated with higher pressure (i.e., cost/benefit analysis, thermal management, new standards development).

SAFETY:

- Educate the equipment OEM on safety standards and requirements to increase incorporation into system design.
- Improve integration of less leak-prone fittings into hydraulic systems.
- Develop new or improve existing technologies/architectures to safely relieve pressure in hydraulic systems.

Prioritized Research Targets – Data and Analytics/Materials

The Task Force then reviewed the list of recommended Research Targets from each Working Group for each of its prioritized Research Areas. It was agreed that each list should be reorganized to better clarify which Targets would require new technology development and which would require enhanced market education. In the overall, the Task Force then selected several Targets (shown in bold red) that seem to represent the most impactful Targets for that Research Area.

Data and Analytics. Improve the gathering and use of data analytics in fluid power systems.

DATA:

- **Ensure compliance with industry standard communication protocols.**
- **Ensure compliance with data protection regulations (CA, Europe, etc.)**
- Increase the standardization of data formats across systems and components.
- **Explore the use of AI (artificial intelligence) to predict and make decisions for improving system performance.**

CONTROL:

- Define and describe effective data analysis strategies that improve the control of fluid power systems (i.e., monitoring and refining cyclical processes), especially in ways that compare favorably to the control of electromechanical systems.
- Analyze electromechanical control systems and adopt/educate on similar strategies for fluid power systems (i.e., for improved precision and accuracy).

SERVICE:

- **Technologies needed to perform preventative maintenance is the overarching need.**
- Quantify the impact of preventative maintenance strategies (i.e., performance, financial).
- **Provide guidance to system integrators on what sensors are needed, what they detect, and the service opportunities that they reveal (can be component-specific and dependent; can also be hydraulic or pneumatic-specific).**

Materials. Develop/apply new materials in fluid power components and systems.

POWER DENSITY:

- Operating at higher pressure (need to define - 10,000 PSI or higher?) is the top-level objective. Research areas and targets need to address this. May need a separate survey on this topic to determine current market use and future need.
- Develop higher strength materials for fluid power components (including seals, hoses).
- Optimize designs and materials used for additive manufacturing for higher pressure or smaller fluid power applications.

RELIABILITY AND DURABILITY:

- Investigate the use of materials processing less prone to leaks (i.e., castings, 3D-printing, injection-molding).
- **Investigate the use of new materials (i.e., lead-free brass and steel, composites, PFAS-free).**
- Develop and apply coatings and heat-treat processes that increase resistance to wear-and-tear.

Prioritized Research Targets – Seal Technologies/Fluids

The Task Force then reviewed the list of recommended Research Targets from each Working Group for each of its prioritized Research Areas. It was agreed that each list should be reorganized to better clarify which Targets would require new technology development and which would require enhanced market education. In the overall, the Task Force then selected several Targets (shown in bold red) that seem to represent the most impactful Targets for that Research Area.

Seal Technologies. Optimize the use of seal technologies in fluid power systems.

ENVIRONMENTAL IMPACT:

- **Define, assess current use of, and educate market on best practices (including surface finishes, side loading, external temperature) for seal and connection types.**

RELIABILITY AND DURABILITY:

- Increase alignment between existing seal technologies and the application (materials, geometries, etc.).
- Improve and increase use of predictive models for seal failures.
- **Develop seal technologies that are more resistant to cutting or scratching during assembly.**

Fluids. Optimize the use of fluids and lubrication in fluid power systems.

ENVIRONMENTAL IMPACT:

- **Develop biodegradable fluids that have lower cost, greater lubricity, greater seal compatibility, and can operate at a wider temperature range.**

Fluid power is a modern and thriving technology.

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